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XLVIII ANNUAL SYMPOSIUM ON OPTICAL MATERIALS FOR HIGH-POWER LASERS

TECHNICAL
ABSTRACT BOOK

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Millennium Harvest House Hotel
Boulder, Colorado, USA

Conference
25–28 September 2016

SPIE. LASER DAMAGE

XLVIII ANNUAL SYMPOSIUM ON OPTICAL MATERIALS FOR HIGH-POWER LASERS

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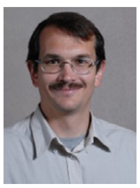

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SPIE. LASER DAMAGE

XLVIII ANNUAL SYMPOSIUM ON OPTICAL MATERIALS FOR HIGH-POWER LASERS

SUNDAY 25 SEPTEMBER

Tutorial on Advanced Materials for High Laser-Damage Resistance

6:00 to 7:00 pm
Location: Grand Ballroom

Dr. Marco Jupé
Laser Zentrum Hannover (Germany)

This tutorial is focused on the interplay of three major topics of this symposium: optical materials, thin films for optical coatings, and fundamental mechanisms of ultrafast laser-material interactions. This tutorial will address the influence of fundamental material aspects on laser-induced damage. Thereby, the properties of different coating materials and the application of mixture and structuring as well as the laser stack design on the damage are discussed. The main objective is focused on the electronic aspects of laser induced damage.

Welcome and Social Mixer

7:00 to 8:30 pm
Location: Pavilion Gardens
Join your colleagues for light refreshments and mingling. Guest tickets are available onsite for purchase, $30.

Registration Material Pick-up will available until 8:30 pm.

SPECIAL EVENTS

MONDAY 26 SEPTEMBER

Poster Overviews

10:10 to 10:40 am
Location: Grand Ballroom

Poster authors are asked to give a 2-minutes/2-viewgraph overview of their posters in the order that they appear in the poster sessions.

Poster Viewing and Refreshment Breaks

10:40 to 11:40 am and 3:40 to 4:30 pm
Location: Century Room

Conference attendees are invited to attend the Poster Sessions to review poster papers and interact with the authors who will be at their posters during both sessions.

Please be sure to wear your registration badge.

Standardization Round-Table Discussion

1:20 to 2:15 pm
Location: Millennium Room

This workshop is dedicated to recent developments in the field of International Standardization for optics characterization. Especially ISO 21254, the International Standard for the measurement of Laser Induced Damage Thresholds, is presently subject of a major revision activity within the corresponding Working Group ISO TC 172/SC 9/WG 1 "Terminology and test methods for electro-optical systems." There will be a brief introduction into the present state of the standard and some other standards of interest elaborated within ISO, followed by a discussion of what alterations will be necessary in the present version of ISO 21254 and how it can be adapted to the present needs in practice. Also, further requirements on standardization activities within the community will be considered. Duration about 1 hour.

Sign-up Sheet, and optional boxed lunches will be available for purchase onsite.

Open House and Reception

6:30 to 8:00 pm

Come, relax, and join your colleagues at Research Electro-Optics, Inc. for an enjoyable evening of refreshments and pleasant conversation.

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TUESDAY 27 SEPTEMBER

Poster Overviews

10:00 to 10:30 am
Location: Grand Ballroom

Poster authors are asked to give a 2-minutes/2-viewgraph overview of their posters in the order that they appear in the poster sessions.

Poster Viewing and Refreshment Breaks

10:30 to 11:30 am and 3:40 to 4:30 pm
Location: Century Room

Conference attendees are invited to attend the Poster Sessions and review poster papers and interact with the authors who will be at their posters during both sessions.

Please be sure to wear your registration badge.

Wine and Cheese Tasting Reception at NCAR

6:30 to 8:00 pm
Location: NCAR, 1850 Table Mesa Dr., Boulder, CO

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All attendees are invited to join us for an enjoyable evening of wine tasting, local brews, and a selection of cheese appetizers.

Guest tickets are available for purchase, $30 (USD). Available at registration desk.

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DAILY EVENT SCHEDULE

SUNDAY 25 September	MONDAY 26 September	TUESDAY 27 September	WEDNESDAY 28 September
SPIE LASER DAMAGE 2016			
REGISTRATION MATERIAL PICK-UP, 5:30 to 8:30 pm	**REGISTRATION MATERIAL PICK-UP,** 7:30 am to 4:00 pm	**REGISTRATION MATERIAL PICK-UP,** 7:30 am to 4:00 pm	**REGISTRATION MATERIAL PICK-UP,** 7:30 am to 3:00 pm
TUTORIAL Advanced Materials for High Laser-Damage Resistance (Chaired by: Dr. Marco Jupé), 6:00 to 7:00 pm	**Poster Placement,** 7:50 to 8:20 am	**Poster Placement,** 7:50 to 8:20 am	
Welcome and Social Mixer 7:00 to 8:30 pm *Registration Material Pick-up continues until 8:30 pm*	**Opening Remarks and Award Presentations** 8:20 to 8:50 am **Best Oral Presentation and Best Poster Presentation**	**SESSION 5 Materials and Measurements I,** 8:20 to 10:00 am	**SESSION 9 Mini-Symposium: Review of Large-Scale, High-Power Laser Facility Projects I,** 8:00 to 10:00 am
	SESSION 1 Surfaces, Mirrors, and Contamination I, 8:50 to 10:10 am		**Refreshment Break,** 10:00 to 10:30 am
	Monday Poster Overview, 10:10 to 10:40 am	**Tuesday Poster Overview,** 10:00 to 10:30 am	**SESSION 10 Mini-Symposium: Review of Large-Scale, High-Power Laser Facility Projects II,** 10:30 am to 12:30 pm
	Poster Viewing and Refreshment Break, 10:40 to 11:40 am	**Poster Viewing and Refreshment Break,** 10:30 to 11:30 am	
	SESSION 2 Surfaces, Mirrors, and Contamination II, 11:40 am to 1:00 pm	**SESSION 6 Materials and Measurements II,** 11:30 am to 12:50 pm	
	Lunch Break 1:00 to 2:20 pm	**Lunch Break** 12:50 to 2:20 pm	**Lunch Break** 12:30 to 1:40 pm
	STANDARDIZATION ROUND TABLE DISCUSSION, 1:20 to 2:15 pm		
	SESSION 3 Thin Films I, 2:20 to 3:40 pm	**SESSION 7 Materials and Measurements III,** 2:20 to 3:40 pm	**SESSION 11 Fundamental Mechanisms I,** 1:40 to 4:00 pm
	Poster Viewing and Refreshment Break, 3:40 to 4:30 pm	**Poster Viewing and Refreshment Break,** 3:40 to 4:30 pm	**Refreshment Break,** 4:00 to 4:30 pm
	SESSION 4 Thin Films II, 4:30 to 6:10 pm	**SESSION 8 Materials and Measurements IV,** 4:30 to 5:50 pm	**SESSION 12 Fundamental Mechanisms II,** 4:30 to 6:30 pm
	Closing Remarks, 6:10 to 6:20 pm	**Closing Remarks,** 5:50 to 6:00 pm	**Closing Remarks,** 6:30 to 6:45 pm
	OPEN HOUSE AND RECEPTION, 6:30 to 8:00 pm	**WINE AND CHEESE TASTING RECEPTION,** 6:30 to 8:00 pm	

10014-1, SESSION 1

Laser-matter coupling mechanisms governing particulate-induced damage on optical surfaces *(Keynote Presentation)*

Manyalibo J. Matthews, Eyal Feigenbaum, Stavros G. Demos, Rajesh N. Raman, Roger Qiu, Nan Shen, Candace D. Harris, Raluca A. Negres, Mary A. Norton, David A. Cross, Christopher W. Carr, Jeffrey D. Bude, Alexander M. Rubenchik, Lawrence Livermore National Lab. (United States)

SPEAKER BIOGRAPHY: Manyalibo (Ibo) J. Matthews currently serves as Deputy Group Leader in the Optical Materials and Target Science group in the Materials Science Division of the Physical & Life Science Directorate at Lawrence Livermore National Laboratory. He holds a PhD in Physics from MIT, and a BS in Applied Physics from UC Davis. His research interests at LLNL include novel applications in laser-assisted material processing (e.g. metal additive manufacturing, laser-based CVD, nano-coarsening of metal films, non-contact laser polishing of glass), optical damage science, vibrational spectroscopy and in situ optical characterization of transient processes. Prior to LLNL he was a Member of Technical Staff at Bell Labs and worked on materials characterization of optical devices using novel spectroscopic techniques, stress-induced birefringence management in planar optical devices and research in advanced broadband access networks.

ABSTRACT TEXT: Surface contamination has long been recognized as a performance-limiting issue in many areas of technology from microelectronics, nuclear reactors and optics.[1] While debris accumulation on optical surfaces is generally problematic because of light scattering, diffraction and obscuration, the impact to performance takes on new dimensions when considering optics for high power laser systems. In these systems, contamination on surfaces generated through optical processing and handling can lead to damage initiation and local fracture that, if left uncorrected, can limit optic lifetime in a pulsed laser system after several successive laser shots. The laser processing of large optics and optical damage cross-contamination can also introduce debris, compounding the issue further. In addition to local damage initiated at the site of the debris and leading to failure,[2] non-local mechanisms associated with contamination have been recognized wherein particles on the entrance surface of optics can lead to Fresnel diffraction of incident light and damage on the exit surface.[3] Similar effects have also been associated with SiO_2/HfO_2 multilayer stacks used as high reflector (HR) optics as well.[4] Indeed, because many HR transport optics exist in open atmosphere conditions in lasers like NIF, introduction of particulates from the environment can be especially problematic and can lead to mirror damage. Although numerous efforts to understand particle-surface interactions under intense pulsed laser light have been undertaken, the exact dynamics of these interactions remain unclear and can be very complex.[5] The dynamics of the interaction involve high gradients of pressure, temperature and corresponding changes to thermodynamic material properties, plasma formation and aerodynamic effects. Particle ablation induces a recoil momentum that pushes the particle along the beam. In addition, the formed plasma can interact with the laser pulse while the melted material layer on the particle is ejected and thus be the source of secondary contamination/surface pitting. To the best of our knowledge, these important processes involved in the laser-particle interaction have not been adequately resolved.

In this talk, we investigate the interaction of micro-scale, metallic and glass particles bound to optical surfaces with nanosecond and picosecond laser pulses at 1064- and 355-nm. Our in situ experimental platform allows direct measurements of the particle velocity, plasma formation, and the kinetics of the ejected molten material. Large aperture damage tests were also performed to assess damage probabilities and probe the stochastic nature of particle-induced damage events. We use FDTD, Fourier beam propagation and ray tracing to understand the effect of particle shape and particle-induced surface pitting on beam propagation. By varying the combination of particle and substrate materials, we are able to gain important insights to the governing mechanisms of laser-particle interactions which could lead to improvements in high power laser optics designs.

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344. We would like to acknowledge the funding from Laboratory Directed Research and Development grant 14-ERD-098.

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[1] J. Honig, M. A. Norton, W. G. Hollingsworth, E. E. Donohue and M. A. Johnson, SPIE 5647, 129-135 (2005).

[2] R. N. Raman, S. G. Demos, N. Shen, E. Feigenbaum, R. A. Negres, S. Elhadj, A. M. Rubenchik and M. J. Matthews, Optics Express 24 (3), 2634-2647 (2016).

[3] M. J. Matthews, N. Shen, J. Honig, J. D. Bude and A. M. Rubenchik, Journal of the Optical Society of America B 30 (12), 3233-3242 (2013).

[4] S. R. Qiu, M. A. Norton, R. N. Raman, A. M. Rubenchik, C. D. Boley, A. Rigatti, P. B. Mirkarimi, C. J. Stolz and M. J. Matthews, Applied Optics 54 (29), 8607-8616 (2015).

[5] S. G. Demos, R. A. Negres, R. N. Raman, N. Shen, A. M. Rubenchik and M. J. Matthews, Optics Express 24 (7), 7792-7815 (2016).

KEYWORDS: Contamination, Damage, Plasma generation, Particle ejection, Energy coupling mechanisms, Pulsed lasers, Surfaces, Light scattering

10014-2, SESSION 1

Study of the laser damage growth in the short-pulse regime

Martin Sozet, Jérôme Néauport, Eric A. G. Lavastre, Nadja Roquin, Commissariat à l'Énergie Atomique (France); **Laurent Gallais,** Institut Fresnel (France); **Laurent Lamaignère,** Commissariat à l'Énergie Atomique (France)

SPEAKER BIOGRAPHY: Not Available

ABSTRACT TEXT: Laser-induced damage resistance is a key factor for the improvement of high power laser system. PETAL facilty is one of them, developed by the French Commissariat à l'Energie Atomique et aux Energies Alternatives (CEA CESTA, Bordeaux), that provides multi-petawatt laser irradiations. This facility uses meter scale reflective optics to compress, transport and focalize sub-picosecond laser pulse at 1053nm with high-energy. When damage occurs on these optical components, subsequent laser irradiations may cause an increase of the damage area. This detrimental phenomenon strongly reduces the functional lifetime of optics. Moreover, the formation of damage on optical components can upset the laser beam propagation by generating modulations in the spatial profile. It may trigger damage on downstream optics in the laser system. For that purpose, we have investigated the laser-induced damage growth in the sub-picosecond regime with a near-infrared beam. Experiments have been carried out on a high reflective mirror to study the damage growth effect as well as the growth probability for different growth fluences and different initial damage sites. A growth threshold set at 50% of the intrinsic damage threshold of the component has been evidences. A general behavior for the evolution of damage area as function of the number of laser irradiations has been observed.

KEYWORDS: Laser damage, Sub-picosecond, Damage growth, Mirrors, Thin films

10014-3, SESSION 1

Entry and exit facet laser damage of optical windows with random antireflective surface structures

Gopal Sapkota, Jason R. Case, Matthew G. Potter, The Univ. of North Carolina at Charlotte (United States); **Lynda E. Busse, L. Brandon Shaw, Jasbinder S. Sanghera,** U.S. Naval Research Lab. (United States); **Ishwar D. Aggarwal, Menelaos K. Poutous,** The Univ. of North Carolina at Charlotte (United States)

SPEAKER BIOGRAPHY: Not Available

ABSTRACT TEXT: Nanosecond duration, high intensity and high average power laser pulses induce damage on uncoated optics, due to localized field enhancement at the exit surface of the components. Anti-reflection (AR) coated optics, due to their (multiple) thin film boundaries, have similar field enhancement regions, which lead to laser damage on both entry and exit sides. Nano-scale structured optical interfaces with AR performance (ARSS) have been widely demonstrated, and found to have higher laser damage resistance than conventional AR coatings. Comprehensive tests of optical entry and exit structured-surface laser damage using nanosecond pulses for ARSS are not widely available.

We measured the laser damage of random anti-reflective surface structures (rARSS), on planar, optical quality, fused silica substrates, using single 6-10ns duration pulses at 1064 nm wavelength. The single-sided rARSS substrates were optimized for Fresnel reflectance suppression at 1064 nm, and the measured transmittance at normal incidence was increased by 3.2%, with a possible theoretical maximum of 3.5%. The high energy laser beam was focused to increase the incident intensity, in order to probe values above and below the damage thresholds reported in the literature. The source laser Q-switch durations were used to directly control incident fluence. Multiple locations were tested for each Q-switch setting, to build a statistical relationship between the fluence and damaging events. Single-sided, AR random surface structured substrates were tested, using entry and exit side orientations, to determine any effects the random structures may have in the damage induced by the field enhancement on the exit side. We found that the AR randomly structured surfaces have a higher resistance, to the onset of laser damage, when they are located at the entry (structured) side of the substrates. In comparison, when the same AR random structures are in the beam exit side of the substrates, the onset of laser damage occurs at lower fluence values. All tests resulting in damage of the optical-quality polished fused silica substrates, and those with the structures on the exit side of the samples, are ballistic in nature, showing surface cracks and outward-directed debris craters, all occurring at the beam exit facet. Of interest are the results from tests completed with the rARSS located on the beam entry side; the damage caused by these tests was not typically ballistic in nature (inward directed craters) and occurred on the structured side of the samples.

KEYWORDS: Subwavelength structures, Anti-reflection surfaces, Laser induced surface damage, Laser damage threshold, Random structures, Fused silica nanostructures

10014-51, SESSION PS1

In-situ laser-induced micro-damage monitoring using long-distance microscope

Joana C. Alves, European Space Agency (Netherlands); **Markus Hippler, Helmut B. Schröder,** Deutsches Zentrum für Luft- und Raumfahrt e.V. (Germany); **Alessandra Ciapponi,** European Space Agency (Netherlands); **Paul Allenspacher, Wolfgang Riede,** Deutsches Zentrum für Luft- und Raumfahrt e.V. (Germany); **Clemens Heese,** European Space Agency (Netherlands)

SPEAKER BIOGRAPHY: Not Available

ABSTRACT TEXT: Long term high-power space operations require reliable characterization of the damage threshold of the optics and understanding the conditions associated to damage growth is of main importance. In this paper micro-damage growth on high-reflective (AR) coated optics is investigated in two similar setups for UV irradiation of 355 nm at 100 Hz under high vacuum conditions. The investigated AR optics were coated by ion beam sputtering (IBS) and are originating from the same batch. In-situ observation of induced damage was performed using a long distance microscope for long-term exposure. Ex-situ characterization of deposits and damage morphology was performed by differential interference contrast microscopy. The damage growth observed with two types of 355 nm Q-switched nanosecond lasers will be presented.

KEYWORDS: Laser-induced damage threshold, Anti-reflective optics, Coating techniques, Long distance microscope

10014-52, SESSION PS1

Characterization of the polishing-induced contamination of fused silica optics

Mathilde Pfiffer, Jean-Louis Longuet, Commissariat à l'Énergie Atomique (France); **Christine Labrugère,** Ctr. National de la Recherche Scientifique (France); **Evelyne Fargin,** Institut de Chimie de la Matière Condensée de Bordeaux (France); **Bruno Bousquet,** Ctr. Lasers Intenses et Applications (France); **Marc Dussauze,** Univ. Bordeaux 1 (France); **Sebastien Lambert, Philippe Cormont, Jérôme Néauport,** Commissariat à l'Énergie Atomique (France)

SPEAKER BIOGRAPHY: Not Available

ABSTRACT TEXT: One of the most specific features concerning glass polishing is the formation of a thin layer on the surface which is due to chemical reactions between the surface and the polishing slurry. These chemical reactions are responsible for the contamination of the surface by impurities initially contained in the slurry. In the case of high power laser optics components operating in the ultraviolet, these impurities can trigger laser damage. Hence getting a detailed knowledge of impurities distribution in the interface is a key factor to improve laser damage performance. The aim of the study is to get a better knowledge of contamination depth penetration and concentration on a fused silica polished surface by using various characterization methods. Another goal is to point out that they bring complementary information on the interface composition. The surface characterization was performed by Secondary Ion Mass Spectroscopy (SIMS), Electron Microprobe Analyzer (EMPA), X-Ray Photoelectron Spectroscopy (XPS) and Inductively Coupled Plasma – Optical Emission Spectroscopy (ICP-OES). Samples were prepared using a magnetorheological polishing machine and a cerium-based slurry consequently we focused on cerium and iron contamination. We analysed the depth penetration as well as homogeneity on the surface.

This work confirms that the fused silica polished surface contamination is composed of alkali and metallic elements from the polishing fluid. The cerium and iron penetration and concentration were measured in the surface out of defects. Cerium is embedded at the surface in a 50nm layer and concentrated at 1200ppm in this layer while iron concentration falls down at 30nm. Spatial distribution and homogeneity of the pollution was also studied in the scratches and the bevel using SIMS and EMPA techniques. We evidence that surface defects such as scratches are specific places that hold the pollutants. This overconcentration is also observed in the chamfer. These new insights into the polishing induced contamination of fused silica optics and its repartition have been obtained using various characterization methods. These further techniques were essential to study the pollution induced by polishing and it should be emphasized that none technique could provide alone a complete description.

KEYWORDS: fused silica, polishing, contamination

10014-53, SESSION PS1

Laser removal of PVP without causing laser-induced surface damage

Kosuke Nuno, Takanobu Yamashiro, Singo Tuzimoto, Osaka Institute of Technology (Japan); **Ryosuke Nakamura,** Osaka Univ. (Japan); **Seizi Takagi, Takashi Nishiyama, Hideo Horibe,** Osaka City Univ. (Japan); **Tomosumi Kamimura,** Osaka Institute of Technology (Japan)

SPEAKER BIOGRAPHY: Not Available

ABSTRACT TEXT: To reduce environmental risks in semiconductor manufacturing, removal of the resist by laser irradiation instead of chemicals is an attractive method. An advanced laser resist stripping method for the positive-tone diazonaphthoquinone (DNQ) / novolak resist was developed without causing the laser damage to the Si wafer. A scanning removal of the highly ion-implanted resist was successfully stripped by using an optimized irradiation condition. In this study, we investigated the removal technology of polyvinyl phenol (PVP) using laser irradiation. The PVP prepared this time is a base polymer of the KrF resist. The flexibility of resist removal technology is expanded by adapting itself to other materials except the novolak resist.

The second harmonics (532 nm) of a pulsed Nd:YAG (Y3Al5O12) laser was irradiated to the PVP in a normal atmosphere and in water. The PVP stripping threshold and the surface laser damage threshold of Si wafer were evaluated in this experiment. The laser irradiation in the water can improve the PVP stripping effect, compared with that of normal atmosphere irradiation. The surface laser damage threshold of Si wafer was 0.13 J/cm^2, and the PVP stripping threshold was 0.06 J/cm^2. The PVP is stripped from the Si wafer as in a positive-tone DNQ / novolak resist. However, the removal efficiency decreased at a larger irradiation beam diameter. By the irradiation at the large beam diameter, laser damage became easy to occur to a Si wafer. It means that the stripped area decreases in scale at a beam diameter of 1.5mm or more. Irradiation with multiple laser beam by smaller beam diameter will be performed to improve a stripping rate with high efficiency.

KEYWORDS: resist stripping, highly ion-implanted resist, positive-tone diazonaphthoquinone, novolak resist, laser irradiation, laser damage, silicon wafer

10014-75, SESSION PS1

Damage behavior of Nd:glass of high-power disk amplifier medium in ICF Facility

Shaobo He, Univ. of Electric Science and Technology of China (China) and China Academy of Engineering Physics (China); **Lin Chen, Xiaodong Yuan, Yuanbin Chen, Xiaofeng Cheng, Xudong Xie, Wenyi Wang,** China Academy of Engineering Physics (China); **Xiaotao Zu,** Univ. of Electronic Science and Technology of China (China)

SPEAKER BIOGRAPHY: Not Available

ABSTRACT TEXT: Large aperture disk Nd:glass is often used as the amplifier medium in the inertial confinement fusion (ICF) facilities. The typical size of Nd:glass is up to 810mm×460mm×40mm and more than 3,000 Nd:glass components are needed in the ICF facility. At present, the 3ω fused silica glass and DKDP crystal are mainly responsible for the damage of driver used for ICF. However, with the enlargement of the facility and increase of laser shot number, the laser damage of Nd:glass at 1ω waveband is still an important problem to limit the stable operation of facility and improvement of laser beam quality. In this work, the influence of Nd:glass material itself, mechanical processing, service environment, and laser beam quality on its damage behavior is investigated experimentally and theoretically. The results and conclusions can be summarized as follows: (1) It is very important to control the concentration of platinum impurity particles during melting and the sputtering effect of the cladding materials. (2) The number and length of fractural and brittle scratches should be strictly suppressed during mechanical processing of Nd:glass. (3) The B-integral of high power laser beam should be rigorously controlled. Particularly, the top shape of pulses must be well controlled when operating at high peak laser power. (4) The service environment should be well managed to make sure the cleanness of the surface of Nd:glass better than 100/A level during mounting and running. (5) The service environment and beam quality should be monitored during operation.

KEYWORDS: Not Available

10014-54, SESSION PS2

Characterization of laser-beam ablation profile on PMMA material as a function of practical and theoretical parameters

Luis Alberto V. Carvalho, Univ. de São Paulo (Brazil) and Wavetek Technologies Ltda. (Brazil)

SPEAKER BIOGRAPHY: Luis has a degree in Physics (1993) and a master's (1996) in Experimental and Theoretical Physics applied to optics from the Institute of Physics of São Carlos, University of Sao Paulo (USP), a PhD in Applied Physics from the same institute (2000) with sandwich (1998-1999) at the University of California Berkeley (USA). He has a total of 3 Post-doctorals: (1) Paulista School of Medicine, UNIFESP (2001-2004), (2) University of Rochester, New York (2005-2006) and (3) Ophthalmic optics laboratory at USP (3). Today he is assistant professor at UNIFESP, founder and president of Wavetek Technologies (www.wavetek.com.br), a leading medical technology company in South America. He has extensive experience in the area of Biomedical Engineering, more than 100 papers published in indexed Journals and Conferences, 17 chapters in international books. Luis is inventor of 12+instruments / techniques in the medical field with registered patents, and is also reviewer of many scientific journals.

ABSTRACT TEXT: Many practical and theoretical studies on the ideal refractive laser profile and algorithm in order to obtain optimal corneal ablations and lower residual spherical aberrations have been implemented. Nevertheless, on the theoretical studies not all practical variables are available and on the practical studies, commercial lasers and non-disclosed algorithms are used. The lack of a better theoretical and practical ablation model has resulted in greater practical spherical aberration outcomes. In this study we have conciliated the theoretical and practical advances into empirical formulas which relate the ablation profile with variables such as beam diameter, fluency, material and angle of incidence. In this work an excimer laser (Coherent Xantos XS 500, wavelength = 193 nm) exhibiting a top-hat beam profile with different diameters (300-500 μm) and pulse energies (1-5 mJ), operating at a repetition rate of 1 Hz was used to ablate polymethylmethacrylate (PMMA) plates placed at different angles with respect to the beam direction. High-resolution measurements of the ablated zone (1mJ, 30-50 pulses, 1 Hz) were performed via confocal microscopy (Carl Zeiss LSM780, λ = 405 nm) and the 3D ablation patterns were obtained by a non-contact high resolution optical profilometer. A theoretical equation was obtained using Matlab fitting algorithms using the practical ablation profiles. The results presented here is a useful tool in conjunction to other theoretical and practical methods in the literature in order to improve laser calibration and manufacture's ablation algorithms in order to reduce undesired residual aberrations.

KEYWORDS: Laser Beam Ablation, PMMA, Excimer Laser, Refractive Surgery

10014-55, SESSION PS2

Laser-induced bulk damage of silica glass at 355nm and 266nm

Reina Kashiwagi, Shunsuke Aramomi, Nikon Corp. (Japan)

SPEAKER BIOGRAPHY: Not Available

ABSTRACT TEXT: Nd:YAG lasers are widely used in material processing applications. Recently, laser processing machines using Nd:YAG 3rd harmonic wave (355 nm) and 4th harmonic wave (266 nm) have been developed and put into practical use. UV Lasers have higher energy than VIS and IR lasers and can perform fine processing without the damaging effects of heat. Due to this, optical elements with high laser durability to 355 nm and 266 nm are required.

Laser-induced damage threshold (LIDT) is one of the key indexes for laser durability. In regards to silica glass, research of laser-induced surface damage has been studied in detail. Results have shown that the surface of silica glass is typically damaged more easily than the bulk in general. However, we have not acquired significant knowledge of laser-induced bulk damage. Therefore, we studied the laser durability of a variety of silica glass samples by 1-on-1 and S-on-1 laser-induced bulk damage threshold at 355 nm and 266 nm. We observed that the LIDT of all samples decreased as the shot count increased with each silica glass sample having different LIDT results. In addition, we observed that 10000-on-1 LIDT depended on hydrogen concentration and hydroxyl content at 266 nm. LIDT became higher in accordance with an increase of hydrogen under constant hydroxyl concentration. A decrease of hydroxyl content also made LIDT higher under constant hydrogen concentration.

KEYWORDS: silica glass, laser-induced bulk damage threshold (LIDT), Nd:YAG laser

10014-56, SESSION PS2

Investigation of laser-induced ablation of ceramic materials for space-borne applications

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SPEAKER BIOGRAPHY: Helmut Schröder studied physics at the University of Göttingen and got his diploma degree in 1981 and his Ph.D. in 1985. In 1986 he joined the German Aerospace Center (DLR) in Stuttgart. His main interest is the qualification of optical components for space applications with main focus on laser induced contamination.

ABSTRACT TEXT: Space-borne laser systems have to meet high requirements concerning reliability, precision, lifetime and damage threshold of optical components. This applies not only to coatings and substrate materials of optics but also to beam dumps, pin holes and apertures. These elements typically consist of metallic or ceramic materials and they should have a high ablation threshold. Otherwise, emitted particles could redeposit on optical components of the system and deteriorate their functionality. In this work the laser-induced ablation of different ceramic materials, e.g. oxides, nitrides and carbides is investigated. Tests were performed with a pulsed ns-laser at UV, visible and infrared wavelength. Samples were irradiated under high vacuum conditions to simulate space environment. The dynamics of the ablation process were monitored online with a long distance microscope. The morphologies of the ablation spots were investigated by scanning-electron microscopy for determination of even minor surface modifications. From the experiments, recommendations on the preparation and selection of materials for long term stable operation can be deduced.

KEYWORDS: pulsed laser-induced ablation, ceramic, ablation threshold, space-borne lasers

10014-57, SESSION PS2

Investigation of the ageing effects exhibited by AR coatings exposed to UV-laser irradiation

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SPEAKER BIOGRAPHY: Roelene Botha received a Master's degree in electrical/electronic engineering from the Rand Afrikaans University in 2005. She obtained her PhD degree in Applied Physics at the Laboratory for Physics of Interfaces and Thin Films (LPICM) at Ecole Polytechique, Palaiseau (France) in 2008. The subject of her thesis was on the deposition of dielectric materials in an MDECR deposition system. Her industry experience includes work on the process integration and production of thin film solar cells using PECVD systems, the development and production of photo-lithographically structured coated optical components and as a production line manager for cleanroom processes. Since November 2014 she is a senior research engineer at the Institute for Production Metrology, Materials and Optics (PWO) at NTB in Buchs, Switzerland and a technical project manager at RhySearch. She is responsible for the LIDT and CRD measurement systems and the build-up of the RhySearch optical coating lab.

ABSTRACT TEXT: Optical coatings used in UV-applications are often exposed to harsh environments operating at elevated temperatures. In order to study the impact of the ageing effects optical coatings experience at various operating temperatures, an ultraviolet laser-induced degradation test system has been developed. It allows for flexible use in both a long-term stability test bench as well as in an LIDT measurement system. This paper contains the preliminary results of optical degradation ageing tests at 355 nm performed on anti-reflective coatings. Tests from room temperature up to 250°C were performed. As a subsequent step, the LIDT of the samples were measured using a Q-Switched Nd:YAG laser.

KEYWORDS: Laser damage, laser conditioning, optical degradation, ageing, environmental effects, dielectric filters

10014-58, SESSION PS2

Assessment of laser damage resistance in the sub-picosecond regime

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SPEAKER BIOGRAPHY: Not Available

ABSTRACT TEXT: In the case of defect-free material, the laser-induced damage in the femtosecond and the sub-picosecond regimes is known to be deterministic and the damage threshold depends on the electronic structure of the irradiated materials, the pulse duration and the electric-fields enhancement in thin film coatings. Based on these considerations, a mono-shot technique has been investigated to assess the intrinsic damage resistance of optical component with only one laser shot. Mono-shot method is a time and space saving test protocol with regards to standard protocol. On the other hand, while considering real optical components, manufacturing processes necessarily insert nanoscale defects in the functional coating. The origin of these defects embedded of optics has been widely studied in the past few decades. It has been shown in previous works that these defects can be ejected when irradiated and strongly reduce the laser damage resistance of optics: a rasterscan procedure has been developed to determine defect-induced damage densities as a function of the fluence of test in the short pulse regime. These densities are found to be high even for fluences as low as 20% of the intrinsic Laser-Induced Damage Threshold and they can increase catastrophically with the fluence. These experiments allow to better estimate the functional lifetime of an optic in its operating conditions and bring new information on its characteristics in the short pulse regime.

KEYWORDS: Laser damage, Sub-picosecond, Thin film, mirror

10014-59, SESSION PS2

Characterization of NLO crystal absorption for wavelengths 1 to 4

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SPEAKER BIOGRAPHY: Not Available

ABSTRACT TEXT: We present an overview of the characteristic features for the sandwich concept used for NLO crystal absorption measurements. The sandwich concept is a photo-thermal absorption measurement concept based on the laser induced deflection (LID) technique. Besides a strong sensitivity enhancement for photo-thermally insensitive materials, the focus of the presentation is on the absolute calibration, one of the key criteria for photo-thermal techniques. Based on experimental results we prove that absolute bulk absorption calibration can be simplified by using the sandwich concept since it is insensitive to sample orientation or dopants. Furthermore, experimental results on a variety of materials reveal that in general the bulk absorption calibration sample can be made of just one material. We chose Aluminum due to its easy mechanical handling. Finally, the sandwich concept is applied to characterize the bulk absorption of different nonlinear crystals at the wavelengths 1064, 532, 355 and 266nm.

KEYWORDS: Absorption, Nonlinear optical materials, Instrumentation, measurements, and metrology, Photo-thermal effects

10014-60, SESSION PS2

Damage resistance of wide-bandgap nonlinear crystals for femtosecond mid-infrared spectrometer using chirped-pulse upconversion

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SPEAKER BIOGRAPHY: Not Available

ABSTRACT TEXT: Femtosecond time-resolved mid-infrared (MIR) spectroscopy has been a powerful tool for gaining insight into biochemical processes such as photoisomerization, bond formation and dissociation, and protein folding. MIR probe pulses are upconverted to the visible regime via sum-frequency mixing with highly chirped pulses in a nonlinear crystal. One of the key elements determining sensitivity, bandwidth, and spectral resolution of the upconversion system is the nonlinear crystal. In this study, we evaluated wide-bandgap nonlinear crystals and its damage threshold. For this purpose, AgGaGeS4 and LiGaS2 crystals were prepared as efficient materials for the upconversion from the MIR into the visible.

The MIR pulses were generated in a type-I AgGaS2 crystal by different frequency mixing of the signal and idler pulses from the optical parametric amplifier. The MIR pulses were upconverted into the visible using the chirped pulses at 806 nm with a FWHM of 150 ps. The LiGaS2 (thickness: 1 mm) crystal was transparent in 0.32 – 11.6 m, and showed high efficiency below 2000 cm-1. Laser-induced damage was not observed in the crystal at the chirped-pulse energy up to 100 J/mm2. However, for the slightly long-term upconversion, laser damage occurred on the AR coating of the crystal surface. In contrast, AgGaGeS4 (thickness: 0.2 mm) was transparent in 0.45 – 12.1 m, and showed higher efficiency than LiGaS2 in the frequency above 1700 cm-1. However, the efficiency significantly decreased below 1700 cm-1. At the upconverted wavenumber of 1600 cm-1, laser damage occurred at an energy density of 280 J/mm2. These results indicate that LiGaS2 is an efficient upconversion medium in the 1300 – 2200 cm-1 region where many important vibrational modes of organic molecules exist.

KEYWORDS: wide-bandgap nonlinear crystal, upconversion, AgGaGeS4, LiGaS2, laser damage

10014-61, SESSION PS2

An empirical investigation of the laser survivability curve: VII-summary

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SPEAKER BIOGRAPHY: Jonathan Arenberg has been with Northrop Grumman Aerospace Systems since 1989 having started his career with Hughes Aircraft Company in 1982. His work experience includes optical, space and laser systems, working on such astronomical programs as the Chandra X-ray Observatory, James Webb Space Telescope and is developing the Starshade concept for the direct imaging of extra-solar planets, which he co-invented. He has worked on major high-energy and tactical laser systems, laser component engineering, metrology and optical inspection issues. Dr. Arenberg is currently the Chief Engineer for the James Webb Space Telescope and Space Science Missions at Northrop Grumman and an SPIE Fellow.

ABSTRACT TEXT: We report on a continuing multi-year empirical investigation into the nature of the laser survivability curve. In this year's poster we summarize the results uncovered over the last years of this effort. In particular we review the scaling that was found to work well in the nano-second regime pulsewidths but not at femto-seconds. This scaling is applied to the samples tested at atmospheric pressure and vacuum. We summarize the results of this investigation with a particular goal or making recommendations to those involved in the periodic review of ISO 21254.

KEYWORDS: Laser damage testing, Laser optics qualification, S on 1 testing, ISO 21254-2, Life testing, Scaling

10014-62, SESSION PS2

Laser remote heating in vacuum environment to study temperature dependence of optical properties for bulk and thin film materials

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Laurent Gallais, Institut Fresnel (France)

SPEAKER BIOGRAPHY: Not Available

ABSTRACT TEXT: The optical properties of materials used for high power laser applications (metallic materials used as reflectors, semiconductor or dielectric materials for windows, lenses or coatings) are generally strongly dependent on temperature. Moreover in many cases these dependencies are not well documented, particularly at very high temperature that can be reached in the case of laser damage under high power irradiation. Any fundamental understanding or simulations of laser material interactions require the knowledge of these optical properties and their dependence with temperature. It is indeed the basis for numerical simulations taking into account the thermal non-linearity of the laser material interaction process and for an accurate evaluation of the amount of energy deposited on a sample during laser irradiation.

In order to gain this knowledge, we are currently developing a system to measure the temperature dependence of the reflection coefficient of optical materials, from the ambient to high temperatures (>2000 K). The present contribution is a report on the status and first results obtained with this system.

The experimental setup includes a fiber-coupled high power laser diodes system operating at 800 nm with output power up to 200W used for controlled remote heating, a supercontinuum source (450-2400 nm) as probing beam, a fiber-optic spectrometer to measure reflected light, a high speed optical pyrometer for temperature monitoring.

We report on experiments that have been conducted on different metallic or semi-conductor materials (W,Si, SiC, Ge, Au...) for assessment of the system and comparison to bibliographic inputs. As a perspective of the work, first results obtained on dielectric films will be also presented and discussed.

KEYWORDS: high temperature optical properties, high power lasers

10014-63, SESSION PS2

1064nm CW damage threshold of chalcogenide and ZnS materials

John E. McElhenny, Richard L. Tober, U.S. Army Research Lab. (United States)

SPEAKER BIOGRAPHY: John McElhenny is a physicist at the U.S. Army Research Laboratory. He is the cw laser protection expert in the Laser Protection Branch headed by Andrew Mott.

ABSTRACT TEXT: The laser-induced damage threshold (LIDT) has been assessed in the pulsed-regime for many materials. In the continuous wave (cw) regime, due to lack of access to high power cw lasers, the LIDT of optics is less well studied. We have conducted experiments to determine the cw LIDT of chalcogenide and zinc sulfide optics according to ISO 21254 standards.

KEYWORDS: continuous wave, laser induced damage threshold, chalcogenide, zinc sulfide, ZnS, damage threshold, optical materials, optics

10014-4, SESSION 2

Effects of chemical etching on the surface quality and the laser-induced damage threshold of scratched fused silica optics

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SPEAKER BIOGRAPHY: I'm a PhD student in a French university. I'm working for the high power laser named Laser MegaJoules. My goal is to improve the optics components laser induced damage threshold (LIDT) with a wet etching.

ABSTRACT TEXT: Fused silica components for high power fusion class laser systems operate under high UV fluences, i.e. more than 10J/cm^2 for 3ns pulse at 355nm. Polished silica surface can have much higher laser induced damage threshold than 10 J/cm^2 but surface defects such as small scratches coming from polishing or handling are weak area that can trigger damage. Most of scratches initiate laser damage sites under low fluences in the range of some J/cm?. The impact of scratches can be reduced with a wet etching step introduced after the polishing step in the fabrication process of the optics.

Our goal is to improve the laser damage resistance of the scratches by chemical etching while preserving the characteristics of the surface, as the roughness and the surface texture. Engineered scratches were performed on fused silica samples. Different wet etching processes were performed and compared. The evolution of scratch morphology, damage threshold and surface roughness is studied. We notice that the widening is different from expectation when the etching removal depth increases.

KEYWORDS: fused silica, optics components, etching, laser damage

10014-5, SESSION 2

Laser-induced Hertzian fractures on the exit surface of silica glass deposited with metal microspheres

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SPEAKER BIOGRAPHY: Not Available

ABSTRACT TEXT: The need for optics that can sustain higher laser fluences grows as new technological advancements drive increases in peak power of energetic laser systems. This has motivated a substantial effort in the last decade on mitigating damage sites initiation and growth in high power lasers optics [1,2]. These growing damage sites can be characterized by their complex fracture-dominated morphologies and while only a few tens of microns in depth they have the potential to limit optics lifetime. In contrast, another type of artifact initiated by the presence of metal particle contamination on the exit surface of silica is sub-micron deep laser-induced shallow pits (LSPs) [3,4]. These LSPs are free of fracture and appear on optics in high densities, however do not tend to grow. They result from incident laser beam interaction within the skin depth of the particle resulting in heat deposition, which in turn ejects a plasma plume towards the substrate surface, propelling the particle away from the substrate, and etching a LSP into it [5]. Here we report that at higher incidence fluence the emitted plasma pushing on the silica surface can result in surface damage with potentially growing Hertzian fractures surrounding the particle locations.

Two types of metal micro-spheres (Al and stainless-steel (SS)) were deposited on well-separated patches of a silica slab and then exposed separately to an ultraviolet (λ=351 nm) 5 ns flat-top laser pulses at an average fluence of 15 J/cm2 with the particles on the exit surface of the sample. Bright-field images of the samples from before and after the shot were acquired and registered with the captured beam fluence map. Based on statistical analysis comparing sample morphologies before and after the shot, we calculate the Hertzian fracture initiation probability as a function of incidence fluence. Hertzian fracture initiation threshold fluence of 11.1 J/cm2 and 16.5 J/cm2 for the SS and Al particles, are obtained accordingly. We then repeat the methodology for a reference sample patch (without deposited particles) to calculate the native damage density curve. Based on this data we then calculate the modified damage density curve of silica when a given population of particulates is introduced to its exit surface. The modified damage density curves yield a 'hump' feature with characteristics determined by the surface-bound particles population. We extract from the data the momentum coupling coefficient linking the incident energy on the metal particle and the force applied by the expanding laser-induced plasma on the silica surface. We will present the model which includes analytic relations based on the underlying mechanisms, and the resulting calculated values for the different particles. The results of this study suggest that the presence of exit surface-bound metal particles, which result in non-growing shallow pits at low fluences, could lead to Hertzian fractures at higher fluences. This could help guide damage initiation predictions useful for designing next generation laser systems.

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344. We would like to acknowledge the funding from Laboratory Directed Research and Development grant 14-ERD-098. LLNL-CONF-691138.

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KEYWORDS: Laser damage, Silica

10014-6, SESSION 2

Development of a laser damage growth mitigation process based on CO_2 laser scanning for the laser MegaJoule fused silica optics

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SPEAKER BIOGRAPHY: Not Available

ABSTRACT TEXT: Laser damage of optical components is a main issue for high power laser systems. Particularly for Inertial Confinement Fusion class lasers (Laser MegaJoule, LMJ, in France or National Ignition Facility, NIF, in USA), the laser damage resistance of fused silica surfaces at 351 nm in the nanosecond regime is a major concern. Under successive nanosecond laser irradiations, an initiated damage can grow which can make the component unsuitable. The localized CO_2 laser processing has demonstrated its ability to mitigate (stopping) laser damage growth. In order to mitigate large damage sites (millimetric), a method based on fast micro-ablation of silica has been proposed by Bass et al. [BASS2010]. This is accomplished by scanning of the CO_2 laser spot with a fast galvanometer beam scanner to form a crater with a typical conical shape.

In this context, the objective of the present work is to develop a similar fast micro-ablation process for application to the Laser MegaJoule optical components. We present in this paper the developed experimental system and process. We describe also the characterization tools used in this study for shape measurements which are critical for the application. Particularly, we detail and evaluate a method based on quantitative phase imaging to obtain fast and accurate 3D topographies of the crater. The morphologies obtain through different processes are then studied based on an empirical approach, the characterization techniques and validation criteria of the procedure which are the laser damage resistance and the downstream intensification level. Mitigation of sub-millimetric nanosecond damages are demonstrated through different examples. Experimental and numerical studies of the downstream intensifications, resulting of cone formation on the fused silica surface, are presented. The experimental results are compared to numerical simulations for different crater shapes in order to find optimal process conditions to minimize the intensifications in the LMJ configuration. We show the laser damage test experimental conditions and procedures to evaluate the laser damage resistance of the mitigated sites and discuss the efficiency of the process for our application.

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KEYWORDS: laser damage mitigation, silica, CO_2 laser, laser material interactions, laser micro processing

10014-7, SESSION 2

Verification for robustness to laser-induced damage for the Aladin instrument on the ADM-Aeolus satellite

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SPEAKER BIOGRAPHY: Denny Wernham is the Instrument Manager of the European Space Agency's ADM-Aeolus satellite.

ABSTRACT TEXT: The Aladin instrument will fly on the European Space Agency's ADM Aeolus satellite. The instrument is a Doppler wind LIDAR, primarily designed to measure global wind profiles to improve the accuracy of numerical weather prediction models. At the heart of the instrument, is a frequency stabilized 355nm laser which will emit approximately 100mJ of energy in the form of 20ns pulses with a fluence around 1Jcm-2. The pulse repetition frequency is 50Hz meaning that Aladin will eventually have to accumulate 5Gshots over its 3 year planned lifetime in orbit. Due to anomalies that have occurred on previous space-borne lasers, as well as a number of failures that we have observed in previous tests, an extensive development and verification campaign was undertaken in order to ensure that the Aladin instrument is robust enough to survive the mission. In this paper, we shall report the logic and the results of this verification campaign.

The verification logic for laser damage was based upon a bottom-up approach. Firstly, optics from different suppliers were filtered using a classical 10k-on-1 test which allowed derivation of the optics which were likely to survive. More than 150 such tests were performed. Secondly, from those optics which passed the S-on-1 tests with sufficient margins, defect densities were detected using the raster scan technique. This covered and area more representative of the Aladin laser beam and captured those defects which would have otherwise have been missed by the S-on-1 test due to a lack of areal coverage. After the raster scan had been successfully completed at sample level, the actual flight parts were raster scanned in order to capture any manufacturing variations.The next stage was to perform burn-in tests on the optics in an ambient environment followed by similar tests at subsystem level. Finally the optics that had successfully made it through all of the previous stages were subjected to a life test in conditions representative of those in-orbit.

Results of the various tests will be presented along with the lessons learned in the long campaign to obtain optics robust enough to withstand the ADM Aeolus mission.

KEYWORDS: laser damage, space optics, coating defects, contamination, lifetime tests

10014-8, SESSION 3

Nanosecond laser-induced damage of high-reflection coatings: NUV through NIR *(Keynote Presentation)*

Zhanshan Wang, Jinlong Zhang, Pengfei He, Bin Ma, Hongfei Jiao, Xinbin Cheng, Tongji Univ. (China)

SPEAKER BIOGRAPHY: Zhanshan Wang Received PhD in 1996 from Shanghai institute of Optics and Fine Mechanics, Chinese Academy of Sciences. He is a professor for Optics at Tongji University. He acts as the director of the Institute of Precision Optical Engineering and an executive deputy-director of Advanced Institute of Technology at Tongji University. He is mainly engaged in the research of the micro-imaging system from XUV to infrared range, and in the research of the design, fabrication and characterization of multilayer optical elements from XUV to near infrared region.

ABSTRACT TEXT: High reflection (HR) coatings are one of the key components in high power laser systems, their damage characteristics from near ultraviolet (NUV) to near infrared (NIR) are discussed in this paper. Defects in HR coatings are a major factor degrading their performance. Based on the nature of defects, they can be classified into two categories: nodules and nano-sized absorbers. As the working wavelength varies from NUV to NIR, the most limiting defects in HR coatings also change. For the NIR HR coatings, nodules decrease the laser damage resistance. The research progress of laser-induced damage (LID) in nodules is given with an emphasis on the experimental and theoretical studies using artificial defects. With a deepened understanding of the origins and the damage mechanisms of nodules, the approaches that control the nodules to improve the laser damage resistance are presented. Except for the LID at nodules, interfacial damage that is initiated from nano-sized absorbers at interfaces of coatings is also observed. But the influence at which the interfacial damage occurs is usually much higher than that of nodules. So less attention is paid to the interfacial damage in NIR HR coatings. Whereas, for the NUV HR coatings, the nodules are no longer the limiting defects, but the nano-sized absorbers at the interfaces of coatings are considered as the most problematic defects that trigger LID. Several approaches, such as decreasing the electric-filed at the interface, improving the interface quality using mixed materials, have been proposed to improve the laser damage resistance. We used a different way to reduce the electric-filed at the interface by increasing the incident angle of the s-polarized light. Compared to normal incidence, the 65 degree incidence reduced the E-field by a factor of 4. The damage testing were performed using small beam size (tens of micrometer) and bigger beam size (hundreds of micrometer). For small beam size, the HR coating working at 65 degree showed higher laser damage resistance as expected. Whereas, for big beam size, the HR coating working at 65 degree showed abnormally lower laser damage resistance. It was suspected that new limiting defects rather than the nano-sized absorbers at coating interfaces initiated LID of NUV HR coatings when the beam size is big. The possible damage mechanisms of NUV HR coatings working at oblique incidence were then discussed. Moreover, for the HR coatings working at the visible region, both nodules and nano-sized absorbers play some part in triggering the LID.

KEYWORDS: High reflection coatings, Defects, Damage mechanisms

10014-9, SESSION 3

Improved manufacturability of high-laser damage threshold ion beam deposited HfO_2/SiO_2 filters

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SPEAKER BIOGRAPHY: Not Available

ABSTRACT TEXT: Manufacturing high laser damage threshold filters with repeatable characteristics and high yield is a key technical challenge. In this presentation we investigate the impact of process parameters and post deposition annealing on the laser damage threshold results and their variability. For this study high laser induced damage threshold (LIDT) values were demonstrated on HfO2/ SiO2 antireflection (AR) coatings deposited on superpolished fused silica substrates using low defect SPECTOR® Ion Beam Sputtering System equipped with load-lock technology. The transmission and reflectance values for the AR coatings were >99.9 and <0.1% respectively. Less than 2 particles/cm2 (≥ 1um) was routinely observed on the deposited filters. LIDT of AR coatings was determined by Quantel USA using a pulsed Nd:YAG (1064 nm) laser using a pulse width of 14.4 ns and a repetition frequency of 20 Hz per ISO11254 procedure.

KEYWORDS: High-laser damage threshold, low defects, hafnium oxide, anti-reflection coatings, ion beam sputtering

10014-10, SESSION 3

Laser-induced damage of F-SiO_2 protected fluoride based AR coating on a subsurface-damage-free CaF2 at 193nm

Jue Wang, Gerald P. Cox, Michael J. D'Lallo, Steven J. Vankerkhove, Jean Francois Oudard, Corning Advanced Optics (United States)

SPEAKER BIOGRAPHY: Dr. Jue Wang is an SPIE senior member and a Principal Scientist at Corning Advanced Optics, Jue specializes in surfaces and coatings from deep ultraviolet to long wave infrared enabling Laser Optics, Precision Optics, Aerospace/Defense Optics and Biomedical Optics businesses. He authors and co-authors over 100 publications.

ABSTRACT TEXT: A laser-induced damage test was performed on an F-SiO2 protected fluoride-based AR coating on an subsurface-damage-free (SSD-free) CaF2 window with an ArF laser operating at 20 ns. Post damage analysis was conducted on the beam entrance and exit surfaces. Early damage initiation sites were detected on the entrance surface at a fluence of 3.5 J/cm2. Delamination was observed on the exit surface with a fluence of 6.25 J/cm2 on the entrance surface. The damage was compared to that of F-doped SiO2 protected SSD-free CaF2, along with uncoated CaF2 with and without SSD. Possible root causes of these damages were discussed.

KEYWORDS: Laser-induced damage, ArF excimer laser, Fluoride AR coating, CaF2 crystal, Subsurface damage, F-SiO2 film, Protective coating

10014-11, SESSION 4

Corrosion-resistant AR coating of high-energy alkali laser components using refractory materials

Zsolt Marton, Harish B. Bhandari, Radiation Monitoring Devices, Inc. (United States); **Dennis Sigler,** EMF Corp. (United States); **Vivek V. Nagarkar,** Radiation Monitoring Devices, Inc. (United States)

SPEAKER BIOGRAPHY: Zsolt Marton received a Doctorate degree in Materials Science and Engineering from University of Pennsylvania, Philadelphia, PA. He has extensive experience in instrumentation, functional thin film processing by electron beam evaporation. Recently his main activities have been focusing on growing structured thin film scintillators for X-ray and γ radiation detection purposes as well as designing novel coatings for diverse applications such as medical imaging and laser damage protection. Before joining the radiation monitoring and imaging fields, he had dedicated 10 years of his scientific career to the synthesis, magnetic and structural characterization of functional oxide thin films, polymer-metal composites, and ferroelectric/ferromagnetic heterostructures. Zsolt is currently a senior scientist at Radiation Monitoring Devices, Inc in Watertown, MA.

ABSTRACT TEXT: Diode-pumped alkali lasers (DPAL) are the most promising laser systems for achieving good beam quality and high output power, simultaneously. Realization of high-performance DPALs will require the development of laser gain cells with durable windows, lenses and advancements in optical coatings. Besides the specific optical response, the windows also have to withstand a combination of the harsh environments of high temperatures, high energy densities and corrosive effects of rubidium-alkali acting as the laser gain medium. Currently, the gain cell windows suffer from severe and rapid deterioration owing to the corrosive and high temperature effects of Rb vapor on the exposed optics.

The primary reason that the highly transparent sapphire windows corrode in an alkali environment is that it has a marginally dense corundum structure, which is a hexagonal lattice (α-Al2O3, R3c). In a corrosive Rb(v) atmosphere, the crystal reacts with the alkali ions, which leads to rapidly diffusing rubidium into the structure resulting in a new type of crystal configuration, so-called "β-alumina". This phase is not only crystallographically different from the host, but also exhibits a much larger ionic conductivity that promotes further alkali diffusion. The continued diffusion ultimately corrodes the entire wafer.

To address this issue, novel coatings for windows have been developed that simultaneously provide the barrier protection against Rb chemical reaction, as well as maintain the high laser transmissivity of coated components to minimize quenching. The protection layer of our proposal is based on a refractory material. It has a densely packed cubic structure, which serves as a non-permeable protection against the corrosive ions, and its refractory nature maintains the crystal properties even under very high temperatures. This substance is proven to be an excellent coating material capable of providing the necessary corrosion resistance in harsh environments.

Incorporating this compound, multi-layer index-matching anti-reflective (AR) coatings were designed and fabricated by electron beam evaporation technique to ensure maximum transmission and minimum reflectance at the D1 and D2 wavelengths of rubidium, at which a high-power DPAL functions. 8% per surface reflectance has experimentally been lowered by an order of magnitude using coatings, and an additional order of magnitude decrease is projected through theoretical calculations. Furthermore, this thin film structure also evidenced to be resistant to high laser power densities of 10 kW/cm2 and as high as 300°C operating temperatures in rubidium environment. A study of combined exposure to hot rubidium vapor and high energy density laser was carried out. Optical microscopy and spectrophotometry demonstrated no evidence of window degradation. The design has been shown to be robust and high-yielding in practice, has proven to be thermally stable and resistant to laser-induced damage. Our comprehensive AR design indicates a greater than 10% increase in laser output.

KEYWORDS: Laser components coatings, corrosion resistant coating, thermal barrier coatings, Diode pumped alkali laser

10014-12, SESSION 4

Suppressing multilayer coatings defomation by substrate pit suture

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SPEAKER BIOGRAPHY: Not Available

ABSTRACT TEXT: The laser-resistance of high-reflective (HR) coatings for high power laser systems depends greatly on the substrate surface quality. In the pursuit for 1064-nm high laser resistance dielectric coatings, a group of $HfO2/SiO2$ high reflectors with and without suture layer were prepared on pre-arranged fused silica substrate with femtosecond laser pits. Surface morphologies and laser-induce damage resistance was investigated for sample with/without suture layer. The results indicated considerable stability in nanosecond 1064-nm laser-induced damage threshold (LIDT) for sample with suture layer by decrease the electronic field (e-field) enhancement and eliminate the internal crack. By effectively reducing the deformational level using suture layer, the e-beam HR coatings, whose laser induced damage resistance was not influenced by the substrate pit, was prepared.

KEYWORDS: Laser damage, Delectric coatings, Laser material interaction, Plasma ion assisted deposition, Coating stress control

10014-13, SESSION 4

Electronic quantization in dielectric nanolaminates

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SPEAKER BIOGRAPHY: 11/2012 degree M.Sc. in physics at Leibniz Universität Hannover; Since 2012 scientific staff at Laser Zentrum Hannover e.V.; Since 2012 PhD student at Leibniz Universität Hannover. Main research activity: Manufacturing of dielectric components for ultrashort pulse laser applications applying Ion Beam Sputtering

ABSTRACT TEXT: The current laser technology and its applications are driven by a continuous improvement which imposes strong demands on the required high end optical components. Especially, steadily growing power capabilities of dielectric optics are crucial and can be optimized by the choice of the layer material as well as by the corresponding design. Taking into account ion beam sputtering (IBS) and the well-known available binary oxides the maximum power handling capability is reached. For a further improvement new materials are needed. One possibility is taking advantage of ion beam co-sputter technique, whereby the ion beam is focused at a well-defined position of a zone target of two different materials to adjust the composition of both materials, respectively. On this basis new materials can be sputtered with new electrical and optical properties. This achievement leads to an improvement of the performance of optical components for ultra short laser pulse applications by using dielectric composites.

However, a second potential for creating new material properties is the use of the binary oxides itself. By reducing the physical thickness of the high refractive index material in the few nm range of a classical high low stack the electron confinement can be changed. Such materials can be considered as dielectric quantized nanolaminates.

The present contribution is focused on the manufacturing and characterization of dielectric quantized nanolaminates applying IBS. Different Hafnium and Silicon oxide coating stacks are manufactured by varying layer thickness of the high refractive index material (low gap material) down to 0.5 nm and keeping constant the thickness of the low refractive index barriers. By comparing the resulting shift of the optical gap to the finite quantum well theory, a method is presented to determine the electronic confinement parameters of the material. On the basis of the results, the samples are investigated by 1 on 1 LIDT measurements according to ISO21254 at a central wavelength of 1030 nm and pulse duration of 850 fs. Furthermore, the results are compared to irradiated ternary composites made of the same materials. Finally a classical and a quantized partial reflector at 1030 nm is presented and the irradiation tests are presented. The experiments are linked to theoretical studies of both, the electronic confinement and the resulting damage threshold. The experiments confirm the theoretical prediction.

KEYWORDS: Ion Beam Sputtering, Nanolaminat, Optical gap, New materials, 1 on 1 LIDT measurements

10014-14, SESSION 4

Few-cycle pulse laser-induced damage of thin films in air and vacuum ambience

Kyle R. P. Kafka, Noah Talisa, Drake R. Austin, Kevin Werner, The Ohio State Univ. (United States); **Gabriel Tempea, Catalin Neacsu,** Spectra-Physics (Austria); **Enam A. Chowdhury,** The Ohio State Univ. (United States)

SPEAKER BIOGRAPHY: Kyle Kafka is a Ph.D. student at the Femtosecond Solid Dynamics Laboratory (Chowdhury group), Department of Physics, The Ohio State University. His research topic includes intense field light matter interaction, laser-induced periodic surface structures, laser damage of materials.

Introduction: Laser-induced damage of thin-film coatings has been studied for decades, but damage behavior with few-cycle laser pulses is relatively uncharacterized thus far. While laser-induced damage threshold (LIDT) measurements typically report threshold fluences, the short temporal width of few-cycle pulses (FCP) implies an extremely high intensity for a given fluence, and may lead to lowering of LIDT due to electric field- or intensity-dependent effects such as ionization. These effects are likely to be further accentuated in the case of thin film coatings, where interference effects lead to regions of enhanced electric field (and therefore local intensity). For multi-pulse damage, the experimental ambience plays a significant role [1], but for FCPs the role is not well-characterized. In this work, we present a systematic study comparing multi-pulse damage in air versus vacuum ambience for various thin-film coatings, where the role of air ambience is found to have a strong influence on the laser-induced damage morphology.

Experimental setup: Few-cycle pulses with nominal central wavelength ~750 nm are generated with a hollow-core fiber and chirped mirror compressor setup (Kaleidoscope, Spectra Physics), pumped by 0.5 mJ pulses from a home-built 3 mJ/pulse, 35 fs Ti:Sapphire laser operating at 500 Hz. The pulse width (< 6 fs) was measured with a home-built dispersionless scanning autocorrelator in situ inside the vacuum chamber. The dispersion was fine-tuned with a fused silica wedge pair, and the beam was subsequently transported using ultralow-dispersion, dielectrically-enhanced silver mirrors. Energy on target was varied with an achromatic air-spaced $\lambda/2$ waveplate and an uncoated wedge aligned to Brewster angle. The laser focus was characterized in situ by image relaying onto a camera for fluence calibration. Test sites were irradiated at 45°-P angle of incidence with 1000 pulses at a given fluence and in air or medium vacuum (<1 mbar) ambience. Targets included commercially-available ultra-broadband optics such as dielectrically-enhanced silver mirrors, beamsplitters, and dielectric mirrors, as well as custom samples of single-layer TiO_2 on fused silica (?/4 and ?/2 optical thicknesses). Damage morphologies were studied with optical-, atomic force- and scanning electron-microscopy.

Results: Damage morphology showed stark contrast between test sites created in air ambience versus those in vacuum ambience, suggesting that there are two competing damage mechanisms for thin films. The morphology of damage in air tends to be dominated by laser-induced periodic surface structures (LIPSS) oriented parallel to laser polarization, whereas in vacuum these structures are greatly suppressed or absent. The effect of the ambient air appears to be most pronounced in samples with high reflectivity, and in fact for highly-transmissive coatings the influence of air is minimized, though resulting LIPSS are rotated by 90°. Two formalisms for LIPSS generation, based on surface-scattered wave and surface plasmon polaritons to explain the role of ambience will be discussed.

Acknowledgement: This work was supported by the Air Force Office of Scientific Research, USA under grant # AFOSR-FA9550-12-1-0454, and FA9550-16-1-0069.

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KEYWORDS: laser-induced damage, thin film, few-cycle pulse, femtosecond, laser-induced periodic surface structures, LIPSS

10014-15, SESSION 4

Broadband low-dispersion femtosecond mirror thin film damage competition

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SPEAKER BIOGRAPHY: Raluca Negres has been a Staff Scientist at Lawrence Livermore National Laboratory (LLNL) since 2007. Her research interests include laser-matter interactions and optical materials characterization, time-resolved imaging, ultrafast laser systems and statistical modeling.

ABSTRACT TEXT: Broadband low dispersion mirrors are fluence-limiting components in short pulse lasers. For this study, the mirrors must meet a minimum reflection of 99.5% at 45 degrees incidence angle for P-polarized light with a Group Delay Dispersion (GDD) of <+/- 100 fs^2 over a spectral range of 773 nm +/- 50 nm. The participants select the coating materials, design, and deposition method. This is a continuation of last year's picosecond laser damage competition where all coating samples received have been damage tested with 150-ps pulses, however only a subset of the population was found to meet the GDD requirements. The latter set and new sample submissions that meet all specifications will be damage tested using the raster scan method with a 40-fs pulse length laser system operating at 500 Hz on a single testing facility to enable not only direct comparison among the participants, but also the performance contrast of current broadband high reflector technology between pre-compression and post-compression stages of high power Chirped Pulse Amplification (CPA) laser systems. Details of the deposition processes, cleaning method, coating materials, and layer count are shared.

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

KEYWORDS: broadband low dispersion mirrors, femtosecond laser technology, laser induced damage

10014-16, SESSION 5

Metrology of fused silica *(Keynote Presentation)*

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SPEAKER BIOGRAPHY: - 2011: PhD in Laser and Plasma Physics (Topic: laser particle acceleration) at Technical University Darmstadt, Germany

- since 2012 at Heraeus Quarzglas, Optics Division.

- Responsibilities: worldwide technical Support for science applications mostly: high energy high power lasers, space, accelerators ...as well as laser material processing

ABSTRACT TEXT: In over 100 years of quartz glass fabrication, the applications and the optical requirements for this type of optical material have significantly changed. In the early 20th century the development of spectroscopy led to the need for a purer glass with higher transmittance in the UV. Fused silica as material of choice from natural resources as pegmatite sand or quartz crystal fulfilled here in addition the necessity of thermal stability to over 1000°C. All these requirements led to the development of the first methods for measuring quartz glass: transmission, thermal and mechanical stability. The development of UV flash lamps in the 1960's required the shift of band edge further into the UV - synthetic synthetic fused silica was created. The measurement method of transmission had to be developed in more detail. In addition, this called for a higher resolution in the measurement of trace impurities in quartz glass. With the Apollo missions (retro reflectors) it was essential to understand radiation resistance, and therefore several measurement methods have been developed. Sensitive optical applications demanding precise resolution of homogeneity, stress birefringence, striae and bubbles/inclusions. Optical microlithography (excimer laser) in the 1990's added UV bulk absorption and scatter. The fiber optic technology drove the measurement methods of attenuation, absorption and refractive index profile determination.

Different applications directed the quartz glass development towards new products, technologies or methods of measurement: doping to control the band edge, drying for manufacturing low OH materials or hydrogen enrichment for UV resistance just as 3 major examples. The boundaries of the original measurement methods have been achieved, refined and optimized to applications e.g. fusion laser projects and laser material processing. The presence shows us that the laser energy and intensities continue to rise in the future. Measurement methods such as ring-down cavities and Hartmann-Shack sensors for absorption measurement or calibration cross-referencing of laser damage threshold measurements are becoming increasingly important to establish a common understanding of damage resistance.

This presentation will provide an overview of the development of measuring methods of quartz glass, discuss their limits and accuracy and point out the parameters which are of high relevance for today's laser applications.

KEYWORDS: fused silica, optical properties, radiation hardness, bulk absorption, UV and IR applications, development of metrology, laser material, fused quartz

10014-17, SESSION 5

A double blind study of commercially available CaF_2 absorption, laser-induced damage threshold, and lifetimes at 193nm using an ArF excimer laser

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SPEAKER BIOGRAPHY: As graduate of Montana State Universities physics program, Jason Yager has worked in the photonics industry for 20 years. With experience as a Laser Engineer, Operations Manager for Quantel, Sr. Engineering Manager and Product Line Manager for Newport Corp. and most recently the General Manager for Laser Damage Testing Service at Quantel Laser.

ABSTRACT TEXT: High power ultra-violet wavelengths are the current technology of choice for many challenging applications today including semiconductor photolithography, mass spectroscopy, and LASIK eye surgery. The longevity of these ultra-violet sources is limited by laser induced damage of optical components which can appear after a period of months or years. This study will focus on a widely used deep UV substrate, calcium fluoride (CaF_2). In a double blind study, commercially available samples submitted by leading manufacturers from around the world will be characterized at 193nm using an ArF excimer laser. The initial absorption will be characterized by laser induced deflection (LID) technique (Sandwich concept) and measurements of the LIDT will be calculated using ISO 21254. Corresponding lifetime measurements will then be performed. We will report on the relationship between the initial absorption, LIDT measurements, and actual measured material lifetimes, as well as demonstrating the current performance of UV grade CaF_2 available on the market. If a correlation can be observed, the absorption and / or LIDT measurements may provide insight in predicting CaF_2 lifetimes in the UV.

KEYWORDS: Laser Induced Damage Threshold, Absoption, CaF_2, Lifetime, ArF Excimer, 193 nm

10014-18, SESSION 5

Nanosecond laser-induced damage of transparent conducting ITO film at 1064nm

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SPEAKER BIOGRAPHY: Jae-Hyuck Yoo received his Ph.D. in mechanical engineering, studying the laser based material processing and characterization techniques in UC Berkeley. He joined the Lawrence Livermore National Laboratory in 2015 and investigates transparent conductive film with high laser damage performance, laser chemical vapor deposition of ultra-hard materials, and selective material transformation for high performance optoelectric applications.

ABSTRACT TEXT: Transparent conducting films with superior laser damage performance have drawn intense interests toward optoelectronic applications under high laser energy density environment. In order to make optoelectronic applications with high laser damage performance, fundamental understanding of damage mechanism of conducting films is crucial. In this study, we performed laser damage experiments of tin doped indium oxide film (ITO) using nanosecond (ns) pulse lasers (1064 nm) and investigated damage mechanism. First, single pulse damage tests were performed and the resulting damage sites were examined with a confocal laser (658 nm) scanning microscope, providing high resolution surface morphology information in conjunction with depth profile, where common features of thermal degradation such as cracking, melting, evaporation, and plasma induced re-deposition were observed. The single pulse (9.5 ns) laser ablation threshold of the ITO film (~100 nm, ~10 Ω/?) was estimated as 4.3 J/cm2 based on the damaged area vs log fluence analysis. Although wide bandgap (4 eV) ITO film was optically transparent in visible range, the laser energy (1064 nm, 1.03 eV) was absorbed by free carriers introduced by degenerate doping, resulting in the heating induced damages.

Furthermore, multi-pulse laser damage is more relevant and important for real device operation and therefore multi-pulse laser damage tests on the same ITO film (~100 nm, ~10 Ω/?) were carried out. At the laser fluence of 2.0 J/cm2 that was lower than the single laser damage threshold, damage was observed after 100 shots. The multi-pulse laser damage sites revealed the morphology that could be developed by repeated melting/evaporation events and the damage size was expanded by each pulse based on SEM images. In other words, the area where the temperature was higher than the melting temperature of the ITO film was expended upon pulses even at the same laser fluence, suggesting that laser pulse induced film modification, or so called laser incubation effect. Although obvious damage (based on microscope inspection) was not detected up to 10 shots at the same laser fluence (2.0 J/cm2), it was likely that the film surface was continuously modified by the laser pulses and obvious damage formation was finally initiated. Interestingly, noticeable surface modification just before obvious damage development was captured at certain damage conditions. The laser-induced modification region was shown as less reflective (or darker) than pristine region in microscope images. Based on Drude model, the less reflection in visible range could be attributed to free carrier increase or/and effective mass decrease. Since the effective mass is mostly determined by band structure, the darkening could be mostly caused by the free carrier concentration increase due to the laser-induced modification. Since the free carrier concentration increase led to higher absorption coefficient at 1064 nm wavelength, the multipulse laser damage process occurred in a way of a positive feedback loop.

Interestingly, the ITO film was not damaged at 1.5 J/cm2 even after 1000 shots. For another ITO film (~200 nm, ~160 Ω/?), the single laser pulse (5 ns) damage threshold was 6.5 J/cm2 and no damage was observed at 1.6 J/cm2 even after 10,000 shots. Therefore, there was safe fluence range that does not trigger the positive feedback damage process. However, ITO film's properties under the safe fluence range have not been studied. Therefore, in-situ monitored electrical and optical property of ITO film under the safe fluence range was investigated. This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

KEYWORDS: damage, ITO, laser, nanosecond

10014-19, SESSION 5

Study of defects in bulk potassium dihydrogen phosphate by a three-dimensional laser scattering imaging technique

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SPEAKER BIOGRAPHY: Not Available

ABSTRACT TEXT: Potassium dihydrogen phosphate (KDP) is commonly used for frequency conversion and optical switching applications in many high-power laser systems. Such applications require high damage threshold of KDP crystals. Damage behavior of KDP has been investigated for many years, and results show that intrinsic or extrinsic defects are responsible for highly localized absorption in KDP materials, and in turn cause the damage.

A three dimensional laser scattering imaging technique is used for studying defects in bulk potassium dihydrogen phosphate. The system has a spatial resolution of about 10 micron each dimension, and is demonstrated to be an efficient tool for defect testing for bulk materials. For example it takes less than one hour to imaging a bulk of materials at the size 100mm x 100mm x 10mm. The results are compared to a three dimensional photo-thermal imaging technique. The feasibility of this technique for optical materials with unpolished surfaces is also presented.

KEYWORDS: potassium dihydrogen phosphate, three dimensional, laser scattering imaging

10014-64, SESSION PS3

Influence of the size and concentration of precursor on laser damage performance in KDP crystal

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SPEAKER BIOGRAPHY: Not Available

ABSTRACT TEXT: Laser-induced bulk damage in potassium dihydrogen phosphate (KDP) and its deuterated analog (DKDP) crystals for nanosecond pulses is caused by light-absorbing precursor defects, which are formed during crystal growth. However, current chemical analysis and spectroscopy techniques fail to identify the nature of the responsible precursor defects because of their "invisible" concentration and/or size. In this study, the aim was to explore a novel method for understanding laser–matter interactions with regard to physical parameters, such as size and concentration, affecting the ability of damage precursors to initiate damage. Laser-induced damage performance at 1064 nm of KDP crystals grown using filters of different pore sizes was investigated. By reducing the pore size of filters in continuous filtration growth, laser damage resistance was improved. Furthermore, a model based on a Gaussian distribution of precursor thresholds and heat transfer was developed to obtain a concentration and/or size distribution of the precursor defects. The results revealed that smaller size and/or lower concentration of precursor defects could lead to better damage resistance.

KEYWORDS: precursors, KDP crystals, laser damage, size

10014-65, SESSION PS3

Laser-induced damage threshold characterization of high-bandgap dielectrics with few-cycle femtosecond laser pulses

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SPEAKER BIOGRAPHY: Not Available

ABSTRACT TEXT: Introduction: The interaction with laser pulses that are only a few optical cycles in duration are of great interest in the field of laser damage, since the laser excitation of electrons can no longer be modelled using pulses with slowly varying amplitudes. Although the first few cycle pulse (FCP) LIDT experiment was performed nearly two decades ago[1], significant gaps in fundamental understanding of laser-solid interaction in this regime remain[2][3][4]. A common technique for indirectly probing the interaction experimentally is to measure the laser fluence for which damage begins to occur, the LIDT fluence. A complementary technique to more directly probe the interaction is a pump-probe reflectivity measurement, which provides information about that state of the target solid during the interaction. In this work, a preliminary characterization of the light-solid interaction with FCP's (E_photon ~ 1.65 eV) and high bandgap dielectrics (E_gap ~ 4-13.6 eV) at LIDT using these two techniques is presented and compared to similar measurements made with longer many-cycle pulses. LIDT physics in this regime is very important for future ultra-intense laser system development like multi-PW few cycle systems at ELI-ALPS, or the Petawatt Field Synthesizer.

Experimental Setup: Threshold fluence measurements of single shot LIDT experiments were performed in vacuum (~1 mbar) with p-polarized pulses at 45 degree angle of incidence for sapphire (Al2O3), LiF, CaF2, MgF2, and LiNbO3 for two pulse durations, 5 fs (FCP) and 33 fs. The FCP's are generated by shortening 33 fs pulses via spectral broadening with an Argon gas-filled hollow core fiber followed by dispersion correction with a chirped mirror compressor setup, and have a central wavelength of ~750 nm. Pulses are focused to a 1/e^2 diameter of 30 um, and pulse fluence is varied between 0-10 J/cm^2 by using a waveplate followed by a reflection from a prism at Brewster angle. The pump-probe reflectivity setup uses all reflective optics to minimize dispersion, including a mask and a prism reflection to separate a weak FCP probe from a strong FCP pump. The reflected probe pulse diverges from the pump and is collected on a photodiode.

Results: For the threshold fluence measurements, damage sites were studied using Wyco NT9100 optical depth profiler. Several damage morphologies were observed near threshold, including what appears to be material expansion and cooling just before ablation, as well as ablation crater formation for higher fluences. Measured LIDT fluences for FCP's are lower for all dielectrics than theoretical fluences calculated from a Keldysh photoionization model[5].

Acknowledgement: This work was supported by the Air Force Office of Scientific Research, USA under grant # AFOSR-FA9550-12-1-0454, and FA9550-16-1-0069.

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KEYWORDS: Laser induced damage threshold, ultra-short, few cycle pulse, pump probe, high bandgap dielectric, femtosecond, Keldysh, LIDT

10014-66, SESSION PS3

Initial kinetics of defect-initiated nanosecond-pulse laser damage and ablation

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SPEAKER BIOGRAPHY: Not Available

ABSTRACT TEXT: The STEREO-LID (Spatio-TEmporally REsolved Laser-Induced Damage) method provides the damage threshold fluence (intensity) during a single nanosecond (ns) excitation pulse. It is especially useful for characterizing the threshold of damage initiated locally around performance-limiting defects in thin films and optical surfaces. STEREO-LID works by identifying the initiation of damage in both time by monitoring the transmission/scatter of the excitation pulse and space by imaging the scattered light with an in situ microscope.

Following damage initiation at a local defect there is a drop in transmission of the entire (focused) beam, indicating that the film transforms from transparent to opaque. We have studied this process in HfO2 films of different thicknesses as a function of focused spot size and peak fluence of a laser pulse with 8.5 ns duration and wavelength of 1064 nm. The morphology of the resultant craters suggests that the modification of the material grows from the damage initiation point and is limited to the film itself and not the substrate. Treating the modified region as an expanding opaque disk, we have successfully modeled the transmission results. The expansion rate of the opaque region depends on the local intensity. This result is corroborated by the asymmetric shape of the craters, which grow preferentially from their initiation point towards the highest intensity at the beam center.

Expansion rates as high as 20 microns per second were observed for local intensities near 100 GW/cm2. A thermal diffusion model cannot explain this expansion rate. We present a physical model based on a laser-driven shock wave that expands away from the damage initiation point and increases the absorptivity of the film.

KEYWORDS: laser-induced damage, laser driven shockwave, defects, absorption

10014-67, SESSION PS3

Finite difference time-domain method for simulation of damage initiation in thin film coatings

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SPEAKER BIOGRAPHY: Linas Smalakys holds a master's degree in Physics from Vilnius University (expected as of September 2016) and has been active in the field of laser induced damage since 2012. Main scientific interests include simulation of laser induced damage for ultrashort pulses as well as statistical analysis of laser induced damage in nanosecond regime.

ABSTRACT TEXT: Time-resolved digital holography (TRDH) is a versatile tool, well suited for studying ultrafast phenomena in solids. It enables to obtain the spatiotemporal information of excited material with sub-pump pulse temporal resolution, including the spatial imaging features offered by holographic microscopy. In the context of laser induced damage studies it also provides insights into the dynamics of the femtosecond damage initiation and subsequent ablation processes.

However, understanding of experimental TRDH data in dielectric thin films is a non-trivial task due to the lack of appropriate theoretical models and computer codes allowing correct interpretation of underlying phenomena. Semi analytical methods are often used as an approximation for the interference field within coatings, however this approach cannot be directly applied for pulse widths which are comparable to the thickness of the coating as well as for highly dynamical systems. Therefore a model based on finite difference time domain (FDTD) method was developed to circumvent these issues. It incorporates a complete Keldysh theory to account for multiphoton and tunnel ionizations and uses multiple rate equations (MRE) for linear absorption by conduction band electrons.

The abovementioned model was used to simultaneously analyze both changes in phase and amplitude of probe pulses of TRDH experiments. It provided valuable insight into damage initiation in various dielectric materials commonly used for optical interference thin film coatings.

KEYWORDS: time-resolved digital holography, finite-difference time-domain, multiple rate equations, thin films

10014-78, SESSION PS3

Fine investigations to highlight first stages of fatigue effect in silica

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SPEAKER BIOGRAPHY: Not Available

ABSTRACT TEXT: A decreased of LIDT is often observed under multiple laser irradiations. This decrease, well known as “fatigue effect” in the material, is a critical parameter for laser sources with high repetition rates and with a need of long-term life, as in spatial applications. In previous studies, we have highlighted that the origins of this “fatigue effect” could be attributed to two main causes. The first one is caused to a statistic effect of the multiple irradiations by increasing the probability to exhibit a damage precursor in the material. The second one is clearly due to modifications in the material induced by the subsequent shots. Moreover, results obtained in silica in UV range highlight a long incubation time of the induced modification in the material regarding the shot frequency.

In order to study the mechanism involved in the case of material modification in S:1 mode, it appears interesting to undertake a non-destructive approach in order to observe the first stages of material changes just before breakdown.

In the present work, more devoted to the case of silica samples under nanosecond, UV irradiation, we discuss on the different possibilities to highlight the earliest material changes. Fine modifications of the nonlinear optical properties are followed using to Z-scan measurements. The detection of possible linear index changes, is performed with a phase imaging technique. Due to its high sensitivity, this technique is a very powerful tool to optimize the LIDT determination. Furthermore, in-situ local fluorescence measurements allow the detection of laser-induced “defects”.

KEYWORDS: Not Available

10014-68, SESSION PS4

Study of the picosecond laser damage in-based thin-film coatings in vacuum

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SPEAKER BIOGRAPHY: Mr. Alexei Kozlov graduated from Leningrad Institute of Fine Mechanics and Optics in 1991, where he received his BS and MS degrees in Optics. He has over 25 years of experience in high-power solid-state lasers, including chirped pulse amplification technique, optical phase conjugation and ultra-short optical pulse diagnostics. Since 2002 he has been at Laboratory for Laser Energetics, University of Rochester, where his research interests are in the area of short-pulse laser damage testing.

ABSTRACT TEXT: The laser damage thresholds of various HfO2/SiO2-based thin film coatings, including multilayer dielectric (MLD) gratings and high reflectors of different designs, prepared by E-beam and Plasma Ion Assisted Deposition (PIAD) methods, were investigated in vacuum, dry nitrogen, and after air-vacuum cycling. Single and multiple-pulse damage thresholds and their pulse-length scaling in the range of 0.6 – 100 ps were measured using a vacuum damage test station operated at 1053nm. The E-beam deposited high reflectors showed higher damage thresholds with square-root pulse-length scaling, as compared to PIAD coatings, which typically show slower power scaling. The former coatings appeared to be not affected by air/vacuum cycling, contrary to PIAD mirrors and MLD gratings. The relation between 1-on-1 and N-on-1 damage thresholds was found dependent on coating design and deposition methods.

KEYWORDS: picosecond pulses, thin films, laser damage in vacuum

10014-69, SESSION PS4

Improved LIDT values for dielectric dispersive compensating mirrors applying ternary composites

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SPEAKER BIOGRAPHY: 11/2012 degree M.Sc. in physics at Leibniz Universität Hannover;

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Since 2012 PhD student at Leibniz Universität Hannover. Main research activity: Manufacturing of dielectric components for ultra short pulse laser applications applying Ion Beam Sputtering

ABSTRACT TEXT: During the last years, dielectric dispersive compensating mirrors (CM's) gained rapidly of importance in order to fulfil the strong demands requested by ultra-short pulse laser (USP) applications. A variety of CM's from the visible (VIS) to the near infra-red spectral range (NIR) are commercially available nowadays. Such mirror systems require design thicknesses of several micron meters (μm). The complex design structure of CMs leads to an increase of the electrical field intensity compared to a dielectric QWOT mirror. Both, the increase in layer thickness and the higher internal field strength cause a reduction of the laser induced damage threshold (LIDT). Applying Ion Beam co-sputter technique it is possible to deposit ternary dielectric composites. Further on, it is well known that an increased silica content in the high refractive index material leads to an improved power handling capability. Especially the layers near the surface of a CM are characterized by an increased electrical field strength. The replacement of the sensitive parts of the layer stack by ternary composites can be used for the stabilization of the stack.

In these modifications it has to be respected, that small deviations in the refractive index and layer thickness lead to a total failure of the required group delay dispersion (GDD).

The present contribution is addressed to an improved method to fabricate dielectric dispersive compensating mirrors with an increased LIDT. Layers affected by high electric field intensities are exchanged by ternary composites with higher silica content according to the refractive index steps down (RISED) concept. Taking advantage of a novel in-situ phase monitor system, it is possible to control such sensitive layers more precisely.

The study is initiated by LIDT tests of single layer ternary composites of tantalum and silicon oxide revealing best suited mixtures for increased power handling capabilities of CM's.

The results are used for a design synthesis, to achieve optimum reflection and GDD values. Afterwards the two most suitable designs are manufactured applying an Ion Beam Sputtering (IBS) process. Both have similar target specifications whereby one design is using ternary composites and the other one is distinguished by a conventional high low stack. The first layers of the stack are switched applying in-situ broad band monitoring in conjunction with a forward re-optimization algorithm, which also manipulates the layers remaining for deposition at each switching event. To accomplish the demanded GDD-spectra, the last layers are controlled by novel in-situ white light interferometer operating in the infrared spectral range. Finally the CMs are measured in the USP LIDT in a 10.000 on1 procedure according to ISO 21254 applying pulse duration of 130 fs at a central wavelength of 775 nm.

KEYWORDS: chirped mirrors, ternary composites, RISED concept, LIDT, in-situ GDD monitor

10014-70, SESSION PS4

Preparation of the free-standing silica aerogel thin films and film gratings

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SPEAKER BIOGRAPHY: Not Available

ABSTRACT TEXT: Free-standing nanoporous silica thin films were fabricated by layer-by-layer deposition method or peeling-off method, combining with PAMS (poly-α-methyl styrene)-degradation technique. For the layer-by-layer deposition method, hydrophobic silica gel film was deposited on the PAMS side of PAMS/betaine/glass multilayer substrate, and the SiO2/PAMS bilayer film was separated from the glass by dissolving betaine layer. After that, free-standing nanoporous silica film was prepared by degrading PAMS. For the peeling-off method, silica gel film was deposited on PAMS-coated silicon wafer, dried via supercritical CO2 after being aged for enough time, peeled off from silicon wafer and transferred onto copper grids. Then the free standing aerogel thin film was obtained by eliminating PAMS layer via annealing. The nanoporous free-standing thin film prepared by the first method had no noticeable cracks over hundreds of microns. The PAMS effectively protected the SiO2 films from damage during the dissolving and transfer processes. The refractive index and the porosity of the film is 1.20 and 57% respectively. The formation quality of the film synthesized by the second method was greatly depended on the relative viscosity of the silica sol and the optimal viscosity was ranged from 2 to 7 cP. For the samples with the bulk density of 100 mg/cm3, the thickness of the film could be adjusted from 50 to 500 nm. The roughness is about 20 nm in the area of 600 μm × 600 μm. Finally, the two methods were applied to fabricate free-standing film gratings, using the photosensitive gel film and optical lithography technique.

KEYWORDS: free-standing film, silica, nanoporous, film grating, poly-α-methyl styrene

10014-71, SESSION PS4

ALD Al_2O_3 coating properties for high power laser

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SPEAKER BIOGRAPHY: has worked as optical engineerer for more than 5 years, is presently furthering his education in Lab for Nanoand Quanten- Engineering supervised by Prof. Detlev Ristau. His main interest is optical coating haracterization, coating design, and application.

ABSTRACT TEXT: Atomic Layer deposition (ALD) has been widely studied in Micro-electronics over past decades. ALD also grows coating with precise thickness, highest surface conformity, structural uniformity, and nodular-free structure, which are properties desired in high power laser coatings. These characteristics are facilitated by the comparably low growth rate of the film, which presently stands as economic disadvantage for commercial use. This work is presented in the context of gaining reliable data to characterize the technical potential and economical options of ALD for optical applications, specifically in the laser field.

The deposition process was studied to produce uniform, stable and economic Al_2O_3 single layers. The layer properties concerned in high power laser industry were studied and compared with commonly used Ion Beam Sputtering (IBS) single layers Ta2O5, Al_2O_3 and SiO2, respectively. Al_2O_3 layers grown by ALD exhibit a stable growth rate, high band gap energy and tensile stress. Also, a low absorption at the wavelength of 1064 nm and high LIDT was verified. In addition, ALD Al_2O_3 films were deposited on top of IBS Ta2O5 to produce Anti-reflective coatings. This experiment confirmed the highly precise thickness control of ALD. The absorption and LIDT was observed to be limited by Ta2O5 or the defects at layer interface introduced during cleaning. These properties indicate the high versatility of ALD Al_2O_3 films for applications in high power coatings.

KEYWORDS: ALD Al_2O_3, Laser absorption, LIDT, Band gap

10014-72, SESSION PS4

What are the impacts of the planarization process on thin film properties?

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SPEAKER BIOGRAPHY: Travis Day acquired his B.S. in Engineering Physics at the University of Northern Colorado and is currently progressing toward a M.S. in Electrical Engineering at the Colorado State University in Fort Collins. His graduate research assistantship and thesis work is focused on high energy laser development, ion beam sputtering deposition and growth of thin films, and characterization of complex light-matter interactions that lead to catastrophic damage of thin film optical coatings.

ABSTRACT TEXT: Lawrence Livermore National Laboratory and Colorado State University have co-developed a planarization smoothing process of nodular defects [1-3]. This process consists of depositing a few tens of nanometers of SiO2 and etching using the assist source half of the layer grown. The process is repeated several times until the desired thickness of the SiO2 layer is achieved [1]. The angular dependent ion etching coupled with unidirectional deposition has been shown to reduce substrate defect cross sectional area by 90% [2]. The smoothing of substrate defects using this protocol have resulted in improvements exceeding 20× of the laser damage resistance of mirror coatings tested at 1053 nm with 10 ns pulses [2,3].

In this work we investigate the structural and optical modifications of ~350 nm thick SiO2 layer deposited by ion beam sputtering using the planarization/smoothing process just described. A control sample consisting of an unplanarized SiO2 layer of the same thickness was also grown. Initial results of surface roughness from white light interferometer measurements show a small reduction in roughness of the planarized SiO2 layer with respect to the control sample. Initial absorption loss results show an increase of a factor of 2 with respect to the control sample. Investigations of film morphology by electron beam microscopy show the SiO2 planarized layers are amorphous with no signs of crystallization. Experiments to assess the laser damage performance of planarized SiO2 are under way. The results of these studies will enable us to assess the potential of the planarization process during the growth of the multiple SiO2 layers in interference coatings for near infrared high power lasers, and improve their laser damage resistance.

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KEYWORDS: Planarization, Ion beam assist, Ion beam sputtering, laser induced damage, optical properties

10014-73, SESSION PS4

Optimization of electric field distribution for improved optical resistance in chirped mirror

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Linas Smalakys, Gintare Bataviciute, Andrius Melninkaitis, Vilnius Univ. (Lithuania)

SPEAKER BIOGRAPHY: Simas Melnikas is a master's student in Vilnius University. He received his bachelor's degree in physics from Vilnius University in 2014. He works at Optical Coatings laboratory of the Center for Physical Sciences and Technology (CPST). His research interests include precise dispersive coatings and ion beam sputtering (IBS) technology for optical coatings.

ABSTRACT TEXT: Chirped mirrors, invented several decades ago, have had a great impact in development of novel ultrafast laser systems. Research in the field resulted in various types of dispersive optical coatings allowing different application capabilities, while improvement in advanced design methods and accurate manufacturing permitted fairly wide bandwidth and high group delay dispersion (GDD) values of the coatings.

However, constantly increasing laser power in common applications raise demands for high resistance to ultrafast laser radiation. Chirped mirrors, especially high dispersion mirrors, exhibit complex electric field distribution leading to unclear behavior in high power laser systems. In this work several Gires-Tournois interferometer (GTI) type mirrors as well as different high dispersion chirped mirrors with and without electric field optimization were designed and sputtered with IBS technology for LIDT measurements in femtosecond regime. Precise and detailed analysis of laser-induced damage sites was done and weakest layers of coating structures were determined. In all observed cases only layers of high refractive index material were damaged. Optimization of electric field distribution inside chirped mirror structure allowed to improve resistance to optical damage using the same Ta_2O_5/SiO_2 materials as for all multilayer coatings in this study.

In this work relation between electric field intensity and resistance to laser radiation for dispersive coatings was demonstrated. To further increase LIDT for chirped mirrors values different optical coating design optimization methods and strategies can be implemented as well as Ta_2O_5 material may be substituted by other materials, for example HfO_2.

KEYWORDS: chirped mirrors, ultrafast optics, electric field distribution, laser induced damage threshold, optical coatings

10014-74, SESSION PS4

A study of metal-dielectric mirrors technology with regard to the laser-induced-damage-threshold

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SPEAKER BIOGRAPHY: Václav Škoda received his MS degree in Physics from the Charles University in Prague, Faculty of Mathematics and Physics in 1975, PhD. degree in 1990 from the Czech Technical University in Prague, Faculty of Nuclear Science and Physical Engineering. He has been working as thin film specialist in Crytur Ltd. in Turnov, Czech Republic. He is member of SPIE.

ABSTRACT TEXT: Laser-induced-damage-threshold of broad-band metal-dielectric hybrid mirrors was tested using a laser apparatus working at 1030 nm wavelength with 1-3 ps pulse length at 1 kHz repetition rate and in S-on-1 test mode. The laser beam diameter used for measurements was in range of 0.5 mm and the laser induced damage was detected by scattered light diagnostics and after-test microscopy inspection. The damage threshold was tested at 45 deg incidence and P-polarization. There were manufactured four sets of mirror samples with multilayer system centered at 1030nm using Ta_2O_5/SiO_2 materials on silver metal layer, which was prepared at different conditions. Both BK7 and fused silica substrate materials were used for manufacturing of samples. The samples were coated in high-vacuum chamber by electron-beam deposition process for dielectrics and metal layer was deposited from resistive heated boat; ion-assisted-deposition method was used. A comparison of measured laser damage threshold of samples in dependence on material and quality of substrates, and conditions of silver metal layer preparation was carried out.

KEYWORDS: LIDT, metal-dielectric mirrors, hybrid mirrors, laser mirrors

10014-89, SESSION PS4

Use of Al_2O_3 layers for higher laser damage threshold at 22.5 incidence, S polarization of a 527 nm/1054 nm dichroic coating

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SPEAKER BIOGRAPHY: Not available

ABSTRACT TEXT: We have designed and reported on a dichroic beam combiner coating consisting of HfO2/SiO2 layer pairs to provide high transmission at 527 nm and high reflection at 1054 nm for 22.5o angle of incidence (AOI) in S polarization (Spol). The laser-induced damage threshold (LIDT) of this coating at the use AOI and polarization with nanosecond (ns) pulses at 532 nm is 7 J/cm2, and only marginally adequate for our beam combining application. In this paper, we describe the use of a combination of Al2O3 and HfO2 high index layers for the dichroic coating with the result that its LIDT at 22.5o AOI, Spol with ns pulses at 532 nm is higher, at 10 J/cm2.

KEYWORDS: Not available

10014-20, SESSION 6

Optical absorption spectroscopy with a nano-Kelvin calorimeter

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SPEAKER BIOGRAPHY: Not Available

ABSTRACT TEXT: To study the physical and chemical nature of impurities and native and laser-induced defects in optical films and high quality bulk materials, an ultra-sensitive absorption measurement technique with spectral resolution is desirable. The most sensitive absorption measurement techniques for optical components to date, such as common-path interferometry and laser-induced deflection, have achieved sensitivities of a few ten parts per billion [1-4]. These methods are based on photo-thermal methods and require laser pump sources of a few Watts of average power, which are typically available at selected wavelengths.

We have developed a nano-Kelvin calorimeter operating at 4 K. Cryogenic temperatures have several advantages - (i) the heat capacity of optical materials are lower which leads to a larger temperature change for the same absorbed power and (ii) one can use high resolution thermometers with Superconducting Quantum Interference Device (SQUID) readout to achieve nK sensitivity at very low noise levels. Note that the absorption behavior of materials is temperature dependent, which has to be taken into account interpreting data.

A tunable light source, which emits from 170 nm to 1700 nm with an average spectral power density of 10 μW/nm, serves as excitation source and is fiber-coupled to the calorimeter. The temperature differential of the excited sample and a reference is measured. Miniature heaters controlled via a feedback loop can keep the temperature of critical components constant within 4 μK. Our current temperature sensitivity is on the order of 10 nK, which enables us to detect absorbed powers of a few hundred femtowatt. This translates to absorption measurement sensitives of a few ten parts per billion over the entire tuning range of the excitation source.

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KEYWORDS: nano-Kelvin calorimeter, optical absorption spectroscopy

10014-21, SESSION 6

Spatially resolved measurement of the residual reflectance at the interface between neodymium laser glass and edge cladding glass for large aperture applications

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SPEAKER BIOGRAPHY: Not Available

ABSTRACT TEXT: It presents challenges to perform spatially resolved measurement of the residual reflectance at the interface between neodymium laser glass and edge cladding glass for large aperture applications. First of all, the order of magnitude of the residual reflectance is typically at the order of 10-3 to 10-5, precise measurement of reflectance at such low levels itself is challenging. Secondly, for large aperture optics at meter-size levels, any testing systems would present additional challenges due to the difficulties in handling of the large size optics and the trade-offs between the testing efficiency and the testing cost. Lastly but not the least, the interface is not readily accessible without influences from the absorption and scattering losses of the laser glass, that are at the similar order of magnitude to the residual reflectance.

In this paper it is presented our recent progress in the development of a fiber-based technique that performs automatic measurement of the residual reflectance between neodymium laser glass and edge cladding glass for meter size (~ 460 mm X 820 mm) optics. Our results show that the method has both high sensitivity (down to the level of 10-6) and good precision. It has also millimeter size spatial resolution without serious compromising of the testing efficiency and cost.

KEYWORDS: residual reflectance, neodymium laser glass, edge cladding glass, large aperture, Spatially resolved measurement

10014-22, SESSION 6

Preparing for 3 PW at the Centre for Advanced Laser Applications (CALA) in Munich: Laser damage of optics in vacuum under the microscope

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SPEAKER BIOGRAPHY: Christian Kreuzer was born in 1986 and started to study physics at the LMU München in 2006. He finished his bachelors degree in 2009 and his masters degree in 2011. Since December 2011 he is a Phd student in the group of Prof. Dr. Joerg Schreiber, which is mainly dealing with laser ion acceleration using ultra high power laser systems

ABSTRACT TEXT: The Advanced Titanium:Sapphire Laser (ATLAS) chirped pulse amplification system, our workhorse at the Laboratory of Extreme (LEX) Photonics with peak power of currently 300 TW will be upgraded to 3 PW, that is 60 J in 20 fs, when moving to CALA over the course of 2017. Five experimental areas will be connected to ATLAS via the in-vacuum Laser Beam Delivery (LBD) system. The large aperture mirrors and compressor gratings constitute the main bottlenecks of reducing the size of current Petawatt-class facilities. In this context, we established an in-house setup capable of measuring laser induced damage threshold of optics in vacuum, using the ATLAS300 laser. Its energy can be adjusted over 2 orders of magnitude and monitored for every single laser pulse entering the setup. An off axis parabolic mirror focuses the laser pulses in a chamber evacuated down to 6 x 10^-7 mbar onto the test substrate whos surface is monitored under a vacuum compatible microscope. Therefore, a highly magnified image of the irradiated area after each laser pulse is available for detailed analysis of the surface degradation, possible contamination, and the evolution towards damage. In addition, the reflected beam can be analyzed.

In a first step, we used this setup to analyze damage thresholds of mirror and grating samples of a large variety of companies that participated in our tendering process for mirrors supporting a 280 mm beam diameter.

KEYWORDS: vacuum, Laser, Damage

10014-23, SESSION 6

Laser conditioning mechanism revealed by defect and absorption variation in the bulk and at the surface of KDP/DKDP crystals

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SPEAKER BIOGRAPHY: Dr. Guohang Hu (male) graduated in Optical Engineering at Zhejiang University, China (2006). Received his PhD in Optical Engineering at Shanghai Institute of Optics and Fine Mechanics (SIOM), Chinese Academy of Sciences (2011). Since 2011, Dr. Hu has been working permanently at SIOM, responsible for laser-material interaction mechanism, improvement of laser damage resistance, etc. He obtained second class prize of Chinese military science and technology. Dr. Hu was awarded the title associate professor in 2014. Now he was a master tutor. Dr. Hu was the first author of more 10 papers in peer review journal, of which published in Optics Letters, Optics Express, JOSA B, Chinese Physics Letters etc. The typical recent publications were listed as following.

ABSTRACT TEXT: Previous works proved that laser conditioning process was able to improve laser induced damage thresholds (LIDTs) in the bulk of KDP/DKDP crystals. In this paper, it's demonstrated that laser conditioning was also an effective method to improve LIDTs at their surfaces. The variation of scattering defects and absorption in the bulk of KDP/DKDP crystals during laser pre-exposure was investigated by combining light scattering technique and on-line transmittance measurement technique. Laser-induced disappearance of scattering defects and decrease of absorption revealed the mitigation process of laser damage initiators in the bulk of these crystals. At their surface, most of damage initiators were the invisible defects. Laser conditioning process could mitigate the invisible defects, but it's hard to mitigate the scratches or digs. Therefore, it's admitted that laser conditioning process could help to improve the optical properties of crystal material, but it's hard to improve the properties of optical finishing. Based on these results, laser damage mechanism in the bulk and at the surface was discussed.

KEYWORDS: Laser conditioning process, laser damage, scattering defect, absorption, scratch

10014-24, SESSION 7

Periodic Review of ISO 21254: U.S. National Committee Proposal for Revision

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SPEAKER BIOGRAPHY: Jonathan Arenberg has been with Northrop Grumman Aerospace Systems since 1989 having started his career with Hughes Aircraft Company in 1982. His work experience includes optical, space and laser systems, working on such astronomical programs as the Chandra X-ray Observatory, James Webb Space Telescope and is developing the Starshade concept for the direct imaging of extra-solar planets, which he co-invented. He has worked on major high-energy and tactical laser systems, laser component engineering, metrology and optical inspection issues. Dr. Arenberg is currently the Chief Engineer for the James Webb Space Telescope and Space Science Missions at Northrop Grumman and an SPIE Fellow.

ABSTRACT TEXT: Universal standards of units and measurement are at the very foundation of science, technology and commerce. Work on such standards for the measurement of the onset of laser induced damage has been a theme within this conference since the 1980's. As the understanding of laser-induced damage has evolved over the years, so have the standards for measuring it. The recently approved periodic review of ISO 21254 provides an ideal opportunity to review and suggest the next generation of improvements. This paper introduces and discusses the improvements in ISO 21254 as proposed by OEOSC Task Force 7, the US National group charged with laser damage standard development. This paper will review the issues related to the current standards from a theoretical and implementation basis. The proposed revisions and suggested changes to the organization are introduced and evaluated against the current known issues. The next steps for the standard and how this proposal will be reviewed by the relevant ISO subcommittee will be examined and discussed.

KEYWORDS: laser damage standards, ISO 21254, periodic review, ISO

10014-25, SESSION 7

Comparison of different LIDT testing protocols for PW and multi-PW class high-reflectivity coatings

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SPEAKER BIOGRAPHY: Not Available

ABSTRACT TEXT: Development of state of the art high power laser systems requires accurate information about damage resistance of their critical optical components. Since damage threshold fluence decreases significantly with the pulse length, high power systems based on chirped pulse amplification are usually limited by damage threshold of the components utilized in the final pulse compression and the transport of the compressed beams. Sub-picosecond laser damage is complex non-linear process involving multiple types of light-matter interaction and currently, no theory can reliably predict damage threshold values for various combinations of laser parameters, coating properties, and ambient conditions.

To evaluate damage resistance of high reflectivity coating candidates for distribution of compressed PW and multi-PW pulses within experimental areas of ELI beamlines facility, series of laser damage tests in high vacuum were conducted. In this work, we present threshold values for HR dielectric coatings tested according to different ISO-based protocols, in conditions specific to their operation. For several tested samples, we compare results acquired using S-on-1, R-on-1, and Raster Scan routines and discuss their reproducibility, accuracy and time requirements.

KEYWORDS: laser damage, S-on-1, R-on-1, femtosecond, vacuum, petawatt

10014-26, SESSION 7

Accurate measurement of the onset laser damage threshold

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SPEAKER BIOGRAPHY: Jonathan Arenberg has been with Northrop Grumman Aerospace Systems since 1989 having started his career with Hughes Aircraft Company in 1982. His work experience includes optical, space and laser systems, working on such astronomical programs as the Chandra X-ray Observatory, James Webb Space Telescope and is developing the Starshade concept for the direct imaging of extra-solar planets, which he co-invented. He has worked on major high-energy and tactical laser systems, laser component engineering, metrology and optical inspection issues. Dr. Arenberg is currently the Chief Engineer for the James Webb Space Telescope and Space Science Missions at Northrop Grumman and an SPIE Fellow.

ABSTRACT TEXT: In the proceedings of this conference, many papers have been presented in search of an accurate test procedure to measure the value onset laser damage threshold. The search remains unrequited. This paper examines the fundamental question "is such a measurement possible?" The accurate measurement of the value of the onset threshold depends on stratifying two conditions. First, the weakest site must be present in the test area and that site must be correctly identified by the test procedure. Second is that a valid means of extrapolation to the threshold must exist. This paper examines the ability of a general test procedure to satisfy these postulates. It has been shown that for simple distributions, limited in fluence, the first condition is only rarely met. The current report relaxes the previous assumption and shows more generally how and when the first postulate can be met. The challenge of defining a justifiable method for extrapolation is examined. The paper presents arguments illustrating that these two postulates showing both are not generally true, is concluded that a generally accurate measurement of the value of the onset threshold is not possible. The paper concludes with a question that a standardized test can answer.

KEYWORDS: laser damage threshold, onset threshold measurement, measurement procedure, laser damage standards, ISO 21254, accuracy of laser damage threshold measurement

10014-27, SESSION 7

Laser scattering imaging of surface and sub-surface defects for large-aperture optics

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SPEAKER BIOGRAPHY: Not Available

ABSTRACT TEXT: In recent years,the fast development of optics and laser technologies sets higher standard on the properties of large-aperture optics, such as higher surface quality, lower absorbance, higher laser damage threshold, and so on. Most of these requirements are related to defects on large-aperture optics.

The conventional optical microscopy and electronic microscopy show high resolutions, but their fields of view are quite small, so that it is inconvenient to use them for defects characterization of large-aperture optics.

In this paper, we demonstrate a fast laser scattering imaging technique for defect characterization of large-aperture optics.It has realized a testing sensitivity of 500 nm, and a scanning time less than 10 minutes for optics with a size of 300 mm X 300 mm. Application examples will be presented for fused silica and laser glasses. The results show that this laser scattering technique has great potential of applications in the field of large-aperture optics for high power applications.

KEYWORDS: surface and sub-surface defects, laser scattering imaging, large-aperture optics

10014-28, SESSION 8

Laser-induced damage in three-dimensional photonic crystals

Lei Pan, Dayong Zhang, Yueye Lu, Hongbo Xu, Yao Li, Harbin Institute of Technology (China)

SPEAKER BIOGRAPHY: Not Available

ABSTRACT TEXT: Monodisperse polystyrene microspheres with a diameter of 484 nm are synthesized by emulsifier-free emulsion polymerization, with which a photonic crystals film with a reflection peak at 1064nm is fabricated by vertical deposition. As a contrast, a disordered film is fabricated by same method with polydisperse polystyrene microspheres. The laser induced damage threshold of the photonic crystals film is tested, which is as 2.5 times high as the threshold of disordered polystyrene film. The simulation results show that the electric field is enhanced in the pores of photonic crystals while reduced in the polystyrene microspheres, which decreases the absorption of laser energy of the photonic crystals. As a contrast, the electric field distribution is irregular in disordered polystyrene film. Enhanced electric field area located in both pores and microspheres of disordered film. Hence, the disordered film is with a lower laser induced damage threshold.

KEYWORDS: Photonic crystals, laser induced damage threshold, monodisperse polystyrene microsphere

10014-29, SESSION 8

Plume dynamics from UV pulsed ablation of Al and Ti

William Bauer, Glen P. Perram, Air Force Institute of Technology (United States)

SPEAKER BIOGRAPHY: William A. Bauer received his BS degree from the US Air Force Academy in 2008 and his MS from the Air Force Institute of Technology (AFIT) in 2010. A PhD candidate at AFIT since 2016, his research interests include continuous wave and pulsed laser material interactions with graphite, aluminum and titanium.

ABSTRACT TEXT: Pulsed laser irradiation of aluminum and titanium was performed with varying KrF fluences of up to 5 J/cm2 and varying Ar pressures from vacuum to 1 Torr to characterize the ablated plume. Spatially resolved optical emission spectroscopy was performed and various transitions of Al I, Al II, Ti I, Ti II, Ar I, and Ar II identified. Species concentrations and electronic temperatures were recorded as a function of spatial distance from the target surface along the plume centerline, revealing electronic temperatures of on order 10^4 K. Two dimensional spatial maps of the plume were obtained via a gated ICCD with varying gate widths as low as 2nsec and varying gate delays as low as 20 nsec. Time of flight (TOF) profiles were fit with a modified Maxwellian distribution and most probable velocities of magnitude 106 cm/s calculated. Narrow bandpass filters (± 5 nm) were utilized to record individual species' TOF profiles and results compared. Plume splitting was observed for irradiation of both metals, and in general, the length of observation time of the plume splitting increased with decreasing background pressure. Mass loss experiments were also conducted under vacuum conditions and reported as a function of laser fluence. Basic blast and drag models were applied to data and results discussed.

KEYWORDS: pulsed ablation, imagery time-of-flight, electronic temperatures, aluminum, titanium

10014-30, SESSION 8

Laser-induced damage threshold of optical fibers at ns pulses

Jan Vanda, Mihai-George Muresan, Institute of Physics of the ASCR, v.v.i. (Czech Republic); **Matej Sebek, Vojtech Bilek,** Czech Technical Univ. in Prague (Czech Republic)

SPEAKER BIOGRAPHY: Not Available

ABSTRACT TEXT: Novel compact and powerful pulsed laser system designs attract considerable attention from all areas. It seems that the extensive utilization of such technologies can gain ground of general laser material surface treatments broadly. Beam delivery, however, became a crucial problem in transferring powerful pulsed lasers from laboratories towards applications. Beam lines based on mirrors, commonly used in laboratory environment, are for industrial use too fragile, unreliable and even dangerous for the operating crew in the case of malfunction. The only viable option is to use the optical fiber as a high energy light guide and include it properly into the laser design.

Optical fibers offers stable and safe environment for laser pulses propagation, preventing risks from optics misalignment, beam pointing stability and hazards for operational staff. Using optical fibers may also significantly decrease costs of beam delivery system running and maintenance, particularly in the cases where laser beam guiding in vacuum is needed. Further, fibers allow easy integration into processing heads mountable on robotic arms instead of using just fixed location where the beam in delivered.

Aside of mentioned advantages, also certain problems need to be addressed. As optical fibers were developed primarily for use in telecommunication and data transmission, and later as active media and sensors, there was no general requirement of development for high powers. Need to use special fibers as transmitting media for high energy laser pulses arise quite recently, with rapid evolution of diode pumped solid state systems. Consequently, technologies including effective confining and deconfining of the energy, proper front-face and end-face treatment or optimal fiber refractive index profile are not explored yet.

In discussed particular case, we are going to present comparative study of surface LIDT of standard optical fibers and optical fibers preforms for the case of laser pulses with ns duration at 1030 nm. We introduce different methods of fused silica fibers and fibers preform polishing and compare LIDT of fiber preforms and fibers drawn from such preforms. Results will be used for further development of optical fibers suitable for high energy short laser pulses transmission.

KEYWORDS: LIDT, optical fiber, pulsed laser

10014-31, SESSION 8

Laser damage creates backdoors in quantum cryptography

Shihan Sajeed, Poompong Chaiwongkhot, Univ. of Waterloo (Canada); **Mathieu Gagné,** Ecole Polytechnique de Montréal (Canada); **Jean-Philippe Bourgoin,** Univ. of Waterloo (Canada) and Ecole Polytechnique de Montréal (Canada); **Carter Minshull,** Univ. of Waterloo (Canada); **Matthieu Legré,** id Quantique SA (Switzerland); **Thomas D. Jennewein,** Univ. of Waterloo (Canada); **Raman Kashyap,** Ecole Polytechnique de Montréal (Canada); **Vadim V. Makarov,** Univ. of Waterloo (Canada)

SPEAKER BIOGRAPHY: Shihan Sajeed is currently doing his PHD in institute for Quantum computing, University of waterloo. He finished his B.Sc and M.Sc from University of Dhaka, Bangladesh. He works on the security of quantum communication protocols.

ABSTRACT TEXT: Our society relies on cryptography daily. Currently, mathematical complexity-based methods are used for encryption. Their security is threatened by the development of quantum computer, and by advances in cryptanalysis. The mathematical methods thus need to be replaced. One likely replacement is quantum-physics-based secure communication protocols. For example, quantum key distribution (QKD) allows two remote parties to grow a shared secret key in a manner that is resistant to future quantum computers. QKD has seen an impressive technological progress over the past 20 years, and is commercially available today.

The security of QKD is based on the laws of physics: it is impossible to measure an unknown quantum state without altering it. The QKD protocol guarantees that any attempt of eavesdropping will be detected. However, as for any cryptographic system, QKD security relies on both the QKD protocols and the implementation devices on which this protocol runs. However, implementation devices are not perfect. Their behaviour often deviates from the idealized behavior. This often opens exploitable loopholes that compromise the security. Still, if the imperfections are known, the assumed model can be changed and security proofs can be modified to guarantee security. In summary, practical quantum communication protocols are assumed to be secure, as long as implemented devices are properly characterized and all known side channels are closed.

Does it mean, we have reached an unbreakable secure communication protocol, and ended the struggle of cryptographers versus hackers? Not so fast! Even though there is no limit on how perfectly implemented devices can be characterized, an eavesdropper can still create new deviations on-demand in an installed QKD system by laser damage. We present a proof-of-principle demonstration of this. We utilize laser damage to modify device characteristics to break the security of an installed QKD system [1].

Our experiment involved a free-space QKD system for long distance satellite communication [2]. It has been shown in [2] that the system must include a spatial filter or 'pinhole' for security against certain attacks. We have tested the endurance of the system with the pinhole installed against laser damage. From a distance of 26 m, we shot an 810 nm laser beam, delivering 3.6 W c.w. power at the pinhole. The intensity there was sufficient to melt the material and enlarge the hole diameter from 25 μm to $\approx$ 150 μm. With the enlarged pinhole opening, it was again possible for eavesdropper to compromise the security [1,2]. Thus laser damage completely neutralizes the spatial filter countermeasure.

Attacking quantum key distribution systems is a new application for laser damage. Actively engineering imperfections via laser damage represents perhaps the ultimate possibility to breach security of quantum communication. We are excited to present and discuss this new application with the laser damage community, and foster new cross-disciplinary collaboration.

Note: Preliminary results of this investigation were accepted for talk at this conference in 2014, however we could not present it in 2014 owing to delays with obtaining US visa. We now have new and much stronger results. The presenter now has the visa and will deliver the talk if it is accepted again. The preprint version of this work can be found on: http://arxiv.org/abs/1510.03148

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[2] S. Sajeed, P. Chaiwongkhot, J.-P. Bourgoin, T. Jennewein, N. Lütkenhaus, and V. Makarov, Phys. Rev. A 91, 062301 (2015).

KEYWORDS: laser damage, quantum communication, quantum key distribution, quantum hackin

10014-32, SESSION 9 (PLENARY PRESENTATION)

ELI-beamlines and its ultrahigh intensity beam transport system

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SPEAKER BIOGRAPHY: Not Available

ABSTRACT TEXT: Since Mike Perry's milestone achievement of breaking the petawatt (PW) peak power barrier in 1996 at the Lawrence Livermore National Laboratory, new high-intensity laser facilities around the world have revolutionized both our understanding and use of Plasma Physics. The "ELI-beamlines facility" currently under construction in Dolní B?e?any, close to Prague in the Czech Republic is based on the European ESFRI (European Strategy Forum on Research Infrastructures) process. The project is executed in close partnership with Lawrence Livermore National Laboratory and National Energetics in the US. The international user facility will provide access to laser technology that is beyond the current state-of-the-art. 1 PW at 30 J, 30 fs and at a repetition rate of 10 Hz (HAPLS) and 10 PW at 1.5 kJ in 150 fs at a shot rate of one pulse per minute will allow the generation of high-brightness x-ray sources and particle acceleration at multi PW peak powers and repetition rates up to 10 Hz.

This talk will mainly focus on the technological challenges of the complex high-intensity beam transport system of the compressed 30 fs, 10 Hz HAPLS beam over up to 88 meters, but will also describe the basic technological concepts of the ELI facility and sketch a few basic science and multidisciplinary applications.

KEYWORDS: Not Available

10014-33, SESSION 9 (PLENARY PRESENTATION)

Laser performance of the SG-III Laser Facility

Wanguo Zheng, China Academy of Engineering Physics (China) and Shanghai Jiao Tong Univ. (China); **Xiaofeng Wei,** China Academy of Engineering Physics (China); **Qihua Zhu,** China Academy of Engineering Physics (China) and Shanghai Jiao Tong Univ. (China); **Feng Jing,** China Academy of Engineering Physics (China); **Dongxia Hu, Jingqin Su,** China Academy of Engineering Physics (China) and Shanghai Jiao Tong Univ. (China); **Kuixing Zheng, Xiaodong Yuan, Hai Zhou, Wanjun Dai, Fang Wang, Wei Zhou, Dangpeng Xu, Xudong Xie, Bin Feng, Zhi-tao Peng, Liangfu Guo, Yuanbin Chen, Xiong-jun Zhang, Donghui Lin, Zhao Dang, Lanqin Liu, Yong Xiang,** China Academy of Engineering Physics (China); **Xuewei Deng,** China Academy of Engineering Physics (China) and Shanghai Jiao Tong Univ. (China)

SPEAKER BIOGRAPHY: Not Available

ABSTRACT TEXT: The SG-III laser facility, which is now the largest laser driver for inertial confinement fusion research in China, finished its engineering construction in 2015. The whole laser facility can deliver 180kJ energy and 60TW power ultraviolet laser onto target, with power balance better than 10%.

The engineering construction of the SG-III laser facility started in 2007, lasting nearly 8 years, and met its goal of generating 180kJ/3ns/351nm laser energy in 2015. The whole laser facility was designed and collectively integrated by Laser Fusion Research Center in China Academy of Engineering Physics. In the past 8 years, this largest laser facility in China has involved nearly 200 institutes, universities and companies as vendor, and several thousands of scientists, engineers, technicians and skilled laborers have worked for it. The 1st shot in SG-III with its full output capability was conducted in 14, Sep., 2015, in which shot the output 351nm ultraviolet laser energy reached 181.3kJ, exceeding its designed point for the first time. This meaningful shot indicated that China had finished the engineering construction of the 100kJ level ICF research platform and the SG-III laser facility established its world second output capability currently.

In this paper, we briefly review the laser system and then introduce the SG-III laser performance in detail. After precise adjustment, the whole laser facility has met all the design requirements, such as the 180kJ energy and 60TW power ultraviolet output capability, 30μm pointing precision, 10ps synchronization level (RMS value), 10% power balance level (RMS value), pulse shaping capability and so on, which form solid foundations for deeper ICF researches in China.

KEYWORDS: Not Available

10014-34, SESSION 9 (PLENARY PRESENTATION)

Overview of the LMJ: PETAL project

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SPEAKER BIOGRAPHY: Not Available

ABSTRACT TEXT: The laser Megajoule (LMJ), developed by the French Commissariat à l'Energie Atomique et aux Energies Alternatives (CEA), will be a cornerstone of the French Simulation Program. The LMJ facility is under construction at CEA CESTA near Bordeaux. It will offer experimental capabilities to study High-Energy Density Physics (HEDP). The PETAL project consists in the addition of a short-pulse (ps) ultra-high-power, high-energy beam (kJ) to the LMJ facility. The status of the LMJ-PETAL project is presented in this paper. The global architecture of this facility is detailed. We focus on both long nanosecond pulse high energy LMJ beams as well as short pulse high intensity picosecond PETAL beam. Current state of the project as well as recent performances are given, with some details on optical performances and laser damage resistance of optical components.

KEYWORDS: laser facility, laser damage

10014-35, SESSION 9 (PLENARY PRESENTATION)

Challenges for robust laser systems of ELI-Beamlines

Daniel Kramer, Bedrich Rus, Pavel Bakule, Jonathan T. Green, Roman Antipenkov, Jiri Thoma, Jack A. Naylon, Pavel Trojek, Stepan Vyhlídka, Michal P. Košelja, Michal Durák, Praveen K. Velpula, Martin Fibrich, Institute of Physics of the ASCR, v.v.i. (Czech Republic)

SPEAKER BIOGRAPHY: Daniel Kramer Joined ELI Beamlines project in 2011 to become the main optical designer of the laser team. He worked previously at CERN, where he was designing optical and radiation detectors for LHC accelerator chain and Cherenkov detectors.

ABSTRACT TEXT: ELI-Beamlines facility is currently constructing its backbone laser systems with state-of-the art technologies in order to provide ultra-high peak power as well as high average power to the service of the experimental user community. Four main lasers are currently in construction to reach this goal while maintaining high versatility to satisfy most experiments and future upgradability.

Architecture and key optical subsystems of the 1kHz L1 and 10Hz L2 OPCPA beamlines, as well as the diagnostic and dispersion management systems of the 10Hz L3 HAPLS and the 10-PW L4 beamlines, will be presented with emphasis to design margins and machine safety.

Experience with in-house built vacuum LIDT station and commissioning of laser subsystems will be outlined as well.

KEYWORDS: ELI, extreme light, ultrafast, HAPLS, laser

10014-36, SESSION 10 (PLENARY PRESENTATION)

Sandia's Z-Backlighter Laser Facility

Patrick K. Rambo, Jens Schwarz, Marius Schollmeier, Matthias Geissel, Ian C. Smith, Mark W. Kimmel, Christopher S. Speas, Jonathon E. Shores, John C. Bellum, Ella S. Field, Damon E. Kletecka, John L. Porter, Sandia National Labs. (United States)

SPEAKER BIOGRAPHY: Not Available

ABSTRACT TEXT: The Z-Backlighter Laser Facility at Sandia National Laboratories was developed to enable high energy density physics experiments in conjunction with the Z-Accelerator at Sandia National Laboratories, with an emphasis on backlighting. Since the first laser system became operational in 2001, the facility has continually evolved to add new capability and new missions. The facility currently has several high energy laser systems including the nanosecond/multi-kilojoule Z-Beamlet Laser (ZBL), the sub-picosecond/kilojoule-class Z-Petawatt (ZPW) Laser, and the smaller nanosecond/100J-class Chaco laser. All of these systems and associated pump lasers within the facility operate at 1064nm or 1054nm as well as the second harmonic at 532nm or 527nm.

When used at the Z-Accelerator, the Z-Backlighter beams propagate through significant amounts of vacuum before delivery to the Z-Accelerator experiment. A lens focuses the beam through a vacuum window and debris shield en route to the Z target experiment. These final optics are subjected to large amounts of shrapnel, debris, and evaporated metals from the experiment, causing the last two optics to be disposable. In addition, the optics that are in the Z-Accelerator building are subject to exposure by vapor from large amounts of oil used for electrical isolation of high voltage components. All of these factors led to the development of the Sandia Large Optics Coating Operation to support the unique high damage threshold optics needs described.

In addition to operating with the Z-Accelerator, the various lasers have multiple local stand-alone target chambers used for high energy density physics experiments, which have included such diverse research areas as shock physics studies, blast wave studies, x-ray source development, and backlighter development. Recently, a magnetic field pulser capable of 10 to 30T fields has been added to two of the laser target chambers within the facility. The use of multiple chambers and lasers allows an ever growing parameter space to be explored with the capability that is distinct from Z.

Beyond target area flexibility, the lasers are in various stages of upgrade. For example, The ZBL system recently added bandwidth to enable an increased energy output of up to 4kJ at 527nm. ZBL has also added a commercial adaptive optics system to improve focal spot quality. ZPW is finalizing the installation of a narrow bandwidth front-end to allow nanosecond 527nm operation in conjunction with ZBL. Finally, ZPW is also undergoing an energy upgrade which will utilize an increased amplification aperture and multilayer dielectric gratings.

KEYWORDS: Nd:Phosphate Glass Laser, Petawatt, Coating, x-ray Backlighting

10014-37, SESSION 10 (PLENARY PRESENTATION)

Overview of large-scale laser at ILE/ Osaka University and future plan

Junji Kawanaka, Osaka Univ. (Japan)

SPEAKER BIOGRAPHY: He recieved Doctor of Science from University of Electro-Communications (UEC) at Tokyo in 1993 about laser cooling and trapping of neutral atoms at Institute of Laser Science (ILS) of UEC. His research was changed, rare-gas excimer laser at Miyazaki University, diode-pumped high power lasers by using cryogenic ytterbium material at Japan Atomic Energy Research Institute (JAERI), huge glass laser for fusion and astrophysics at Osaka University. Recently ultrahigh peak power lasers with both high pulse energy and high repetition rate.

ABSTRACT TEXT: Recent progress and future plan of the large scale laser systems developed at ILE, Osaka university, are introduced. The LFEX laser has been developed as a heating laser of fast ignition in laser fusion. Recently, the LFEX demonstrated more than 2 PW peak power with ~ 2 kJ pulse energy in 1 ps pulse duration. Suppressing pedestal and pre-pulses with our original pulse cleaner, the pulse contrast is 10^(-10) at 170 ps before the main pulse. Proton acceleration using the LFEX laser showed very high energy compared with other huge facility. Combining the LFEX with the kilo joule, nano second Gekko XII laser begins fast ignition experiments. On the other hands, repeatable diode-pumped laser system with Yb:YAG ceramic at 77K has been developed to show 1 J at 100 Hz repetition rate with about 20% optical-optical efficiency. Based on the obtained knowledge, repetable kilo-joule pulse energy system has been conceptually designed. In the talk, other activities will be also shown.

KEYWORDS: high pulse energy laser, fusion laser, ultrahigh peak power laser

10014-38, SESSION 10 (PLENARY PRESENTATION)

Overview of the Orion Laser Facility: update on performance, experimental schedule, and laser operations

Rory Penman, Mark Girling, David Egan, Stephen P. Elsmere, Ewan J. Harvey, David Ianto Hillier, Dianne Hussey, AWE plc (United Kingdom); **Stefan J. F. Parker, Paul A. Treadwell, David N. Winter, Nicholas W. Hopps,** AWE plc (United Kingdom)

SPEAKER BIOGRAPHY: Not Available

ABSTRACT TEXT: The Orion laser facility at AWE in the UK has been operational since April 2013 following three years of integrated commissioning of the laser and target systems, and target shots to validate performance and safety measures. A full description of the facility will be described in terms of laser architecture and performance, target systems and diagnostics capability, including the recent upgrade to increase the frequency doubled energy in one of the short-pulse beams by a factor of two. An overview of the experimental schedule will be presented with particular attention given to external collaboration with the academic community. Some of the operational challenges in terms of evaluating potential target debris and protecting the target chamber optics will be described, along with other optical damage issues that have been experienced, and measures and techniques put in place to mitigate these issues will be described.

KEYWORDS: Not Available

10014-77, SESSION 10 (PLENARY PRESENTATION)

Making a precision measurement at metawatt circulating power levels

Stefan Ballmer, Massachusetts Institute of Technology (United States) and LOGO Science Collaboration (United States)

SPEAKER BIOGRAPHY: Not Available

ABSTRACT TEXT: We have designed and reported on a dichroic beam combiner coating consisting of HfO2/SiO2 layer pairs to provide high transmission at 527 nm and high reflection at 1054 nm for 22.5o angle of incidence (AOI) in S polarization (Spol). The laser-induced damage threshold (LIDT) of this coating at the use AOI and polarization with nanosecond (ns) pulses at 532 nm is 7 J/cm2, and only marginally adequate for our beam combining application. In this paper, we describe the use of a combination of Al2O3 and HfO2 high index layers for the dichroic coating with the result that its LIDT at 22.5° AOI, Spol with ns pulses at 532 nm is higher, at 10 J/cm2.

KEYWORDS: Not Available

10014-39, SESSION 11

Investigation of mechanisms leading to laser damage morphology *(Keynote Presentation)*

Laurent Lamaignère, Maxime Chambonneau, Romain Diaz, Pierre Grua, Roger Courchinoux, Commissariat à l'Énergie Atomique (France); **Jean-Yves Natoli,** Institut Fresnel (France); **Jean-Luc Rullier,** Commissariat à l'Énergie Atomique (France)

SPEAKER BIOGRAPHY: L. Lamaignère studied physics in the University of Bordeaux. After obtaining his PhD at the Centre de Recherches Paul Pascal, he had for two years a post-doctoral position at the CEA-CESTA. He has been working for CEA since 2000 on the laser damage topic in the framework of the Laser Megajoule and the PETAL laser. He is in charge of CEA laser damage metrology, and he supervises thesis dealing with the ns and fs laser damage issues.

ABSTRACT TEXT: The original damage ring pattern at the exit surface of fused silica induced by highly modulated nanosecond infrared laser pulses demonstrates the time dependence of damage morphology. Such a damage structure is used to study the dynamics of the plasma issued from open cracks. This pattern originates from electron avalanche in this plasma, which simultaneously leads to an ionization front displacement in air and a silica ablation process. Experiments have shown that the propagation speed of the detonation wave reaches about 20 km/s and scales as the cube root of the laser intensity, in good agreement with theoretical hydrodynamics modeling.

During this presentation, we present the different phases and the associated mechanisms leading to this peculiar morphology:

• During an incubation phase, a precursor defect provides energy deposit that drives the near surface material into a plasma state.

• Next the silica plasma provides free electrons in the surrounding air, under laser irradiation an electron avalanche is initiated and generates a breakdown wave.

• Then this breakdown wave leads to an expansion of the air plasma. This latter is able to heat strongly the silica surface as well as generate free electrons in its conduction band. Hence, the silica becomes activated along the breakdown wave.

• When the silica has become absorbent, an ablation mechanism of silica occurs, simultaneously with the air plasma expansion, resulting in the formation of the ring patterns in the case of these modulated laser pulses.

These mechanisms are supported by experiments realized in vacuum environment. A model describing the expansion of the heated area by thermal conduction due to plasma free electrons is then presented.

Next, the paper deals with the two damage formation phases that are distinguished. The first phase corresponds to the incubation of the laser flux by a subsurface defect until the damage occurrence: an incubation fluence corresponds to this phase. The second is related to the damage expansion that only refers to the energy deposit feeding the activation mechanism up to the end of the pulse: an expansion fluence corresponds to this phase. A striking feature is that the damage diameters are proportional to the fluence of expansion at a given shot fluence. Indirectly, the fluences of incubation by the precursors are then determined.

In fine, laser damage densities measurements for different conditions (environment, surface sample, laser parameters) are analyzed and understood to the light of the knowledge of the incubation fluences.

This work is also due to a refined metrology allowing a better knowledge of the laser pulses. The latest progress linked to metrology will be also presented.

KEYWORDS: damage mechanisms, fused silica, ring pattern, ablation

10014-40, SESSION 11

Morphology and mechanisms of picosecond ablation of metal films on fused silica substrates

Isaac L. Bass, Lawrence Livermore National Lab. (United States)

SPEAKER BIOGRAPHY: Isaac Bass received his bachelor's degree in math and chemistry from the University of California, Berkeley in 1960, and his Ph.D. in physics from Columbia University in 1965. He has taught physics at Sonoma State University, worked in the laser industry, and has been in the Laser Programs at the Lawrence Livermore National Laboratory since 1984. He has worked on mitigation of laser induced damage in optical materials and dielectric reflective coatings for the National Ignition Facility since 2003.

ABSTRACT TEXT: The ablation of thin metal films on fused silica substrates by a picosecond class laser will be reported in an issue of Applied Optics as a method of in-situ characterization of the laser spot under conditions commonly used at the sample plane for laser machining and damage studies. Film thicknesses ranged from ~20 nm to ~60 nm. Depth profiles and SEM images of the ablation sites showed several interesting features distinct from those typically observed for ablation in bulk metals. Very sharp thresholds were observed for both partial and complete ablation of the films. Partial film ablation was largely independent of laser fluence. Clear evidence of material displacement was seen at the boundary for complete film ablation. These features were common to a number of different metal films including Inconel on commercial neutral density filters, gold, stainless steel, aluminum, and tungsten. We will present data showing the morphology of the ablation sites on these films as well as models of the possible physical mechanisms producing the unique features observed.

KEYWORDS: picosecond, ablation, metal films

10014-41, SESSION 11

First principles simulation of void and crater formation using the particle-in-cell method

Alex Russell, Douglass W. Schumacher, Kyle R. P. Kafka, Enam A. Chowdhury, The Ohio State Univ. (United States)

SPEAKER BIOGRAPHY: Not Available

ABSTRACT TEXT: Void formation resulting from ultrashort pulse lasers is encountered in a variety of materials when the incident pulse fluence is just below the ablation threshold. These density gaps not only have applications in integrated optics and data storage but are also of fundamental interest in damage formation research. While voids are found both experimentally and via molecular dynamics (MD) simulations, there are limitations to the resulting analysis. Their subsurface nature hampers a time resolved measurement of their formation during experiment and MD simulations are often size-limited due to computational requirements. We have recently developed a new simulation approach based on the particle-in-cell (PIC) method that is complementary to existing approaches [1]. PIC formalism is ideal for treating the intense laser-matter interaction and the evolution of plasmas at a fundamental level but lacks any of the particle-particle interactions that act to bind a material together to form a solid. Our simulation framework implements a Lennard-Jones pair potential model (LJPPM) for PIC codes allowing ab initio treatment of an experimentally realizable target represented by a large system of particles coupled via an attractive inter-particle force. Implementing the LJPPM formalism with the PIC code LSP [2], we show that for fluences exceeding the laser damage threshold, our simulation method produces crater morphologies in quantitative agreement with precision experiments, while for heating patterns corresponding to lower fluences is capable of producing void formation, both without any parameter tuning.

The comparison between simulation and experiment consists of the experimental generation of craters on single crystalline copper via a single ultrashort pulse and craters generated under equivalent simulation parameters. To analyze void formation we investigate room temperature copper with various energy deposition profiles below the ablation threshold. The simulation dynamics are modeled by three sequential stages: treating the femtosecond-laser interaction using PIC; the picosecond-thermalization using the two temperature model; and the nanosecond-target evolution using PIC with LJPPM. It is critical that the laser interaction model uses realistic particle collision rates and can treat non-thermal particle distributions to accurately represent the time-varying skin depth and absorption rate. We describe a new approach that facilitates this based on the binary-collision algorithm. Electron-ion collision rates were determined via the Lee-More-Desjarlais model and electron-electron collision rates were determined via a polynomial spline interpolating between the well understood cold metal and plasma regimes. Finally, we show the results of simulations in 2D3V and 3D and discuss the comparison. 2D3V simulations use a 2D spatial grid but still employ 3-component vectors for fields, currents, and momenta. This effectively treats the laser focus as a line focus.

This material is based upon work supported by the Air Force Office of Scientific Research under award numbers FA9550-16-1-0069 and FA9550-12-1-0454 and computing time from the Ohio Supercomputer Center.

[1] R. A. Mitchell, D. Schumacher, and E. A. Chowdhury, “Using particle-in-cell simulations to model femtosecond pulse laser damage,” in Proc. SPIE 9237, Laser-Induced Damage in Optical Materials: 2014, 2014, p. 92370X.

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KEYWORDS: Void Formation, Copper, Simulation, Ultrashort, Pair Potential, Crater, Benchmarks

10014-42, SESSION 11

Electrostatic effects following irradiation of fused silica surfaces with nanosecond laser pulses

Stavros G. Demos, Univ. of Rochester (United States); **Christopher W. Carr, David A. Cross,** Lawrence Livermore National Lab. (United States)

SPEAKER BIOGRAPHY: Not Available

ABSTRACT TEXT: It is well known that electrostatic attraction in cleanroom manufacturing increases contamination of critical product and equipment surfaces, causing defects and increasing maintenance costs. It is also well established that laser irradiation (at below laser induced damage conditions) causes ejection of electrons and ions from the surface of dielectric materials. This may be suggestive that laser irradiation can cause electrostatic charging of the exposed surfaces. Within the operating environment of ICF class laser systems, electrostatic charging of the optical elements during irradiation compounded with the potential ejection of electrostatically charged particles from laser induced damage sites could generate such conditions that static charges can facilitate secondary contamination of the optical elements and a cascade degradation of the performance of the system. Such charges generated on nominally dielectric materials will be very stable taking many hours to days to dissipate.

The objective of this work was to explore the existence and magnitude of electrostatic effects generated as a result of irradiation of fused silica parts with nanosecond laser pulses. Experiments were performed using the output of a tabletop laser system as well as a large aperture (about 1 cm diameter) laser system using fluences above and below the damage threshold of the samples. In addition, collector samples were positioned on the path of the ejected particles during damage initiation (and growth) of tested samples in order to characterize the electrostatic charge state of the ejected particle and the intercepting substrate.

The preliminary results suggest that laser irradiation alone (below damage threshold) induces electrostatic charging of the substrate. Furthermore, the results suggest that at least a subset of ejected particles (produced during laser-induced damage) are negatively charged. Complex electrostatic charging patterns were also observed, involving both, negative and positive charges within the same optic as well as changing patterns with increasing number of exposure pulses. Such effects may be attributed to the mobility of charges within the generated plasma as well as the dynamics of plume expansion. The measured laser-induced electrostatics charge range between tens to hundreds of Volts and can be positive or negative, depending on excitation conditions and induced modification (damage) of the samples. The potential impact of these electrostatic charging effects on the secondary contamination of the optics in the operational environment of ICF class laser system has not been investigated. However, measurements have shown that metallic or dielectric particles on the order of 10 μm in diameter can be transported between surfaces of dielectrics using only electrostatic forces.

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KEYWORDS: Not Available

10014-43, SESSION 11

Time-resolved microscopy studies of laser damage dynamics at 0.5-1ps, 1030nm

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SPEAKER BIOGRAPHY: Not Available

ABSTRACT TEXT: In order to gain knowledge on the physical processes that occur during laser damage events, it is necessary to observe and analyze in-situ and in real time the laser material interactions and the response of the material to the excitation. For this purpose there exists a large variety of pump / probe techniques that are based on the monitoring on the change of properties of a probe beam (reflection, transmission, phase shift, etc) passing in an area where a pump beam induces the excitation. Implementing such techniques in a microscope configuration is also possible to obtain information on the excited zone with high spatial resolution which is particularly useful for laser damage studies in case of defect-initiated processes.

The system that we have developed is based on an optical microscope with high magnification that is used to observe the sample in the area of pump beam excitation (1030nm, 0.5-3ps). A probe beam is used as the illumination source in the microscope, operating in transmission mode. This probe beam comes either from second harmonic generation of the pump beam and a delay line is used to adjust timing between pump and probe (0 to 1ns), or either from another laser source with electronic synchronization (>1ns). It is therefore possible to cover the whole sequence of damage events: from energy deposition during the pulse excitation to material fracturation or removal. Additionally a wavefront sensor can be used to obtain time-resolved amplitude and phase images of the laser material interactions. With this system, it is possible to obtain a complete picture of the material optical properties at a given time, ie the real and complex parts of the refractive index with spatial resolution.

We will detail and discuss in our contribution different results that were obtained with this system: quantitative measurement of the Kerr effect in fused silica, dynamics of free electron generation and relaxation in an Nb_2O_5, HfO_2 and SiO_2 single layers, damage initiation and shock wave generation by defects, fatigue effects in optical coatings and gratings, and damage growth in multilayer optical coatings.

KEYWORDS: pump probe experiments, time-resolved microscopy, phase microscopy, laser damage, optical coatings

10014-44, SESSION 11

The effect of ns laser conditioning on the fs laser-induced damage in optical films

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SPEAKER BIOGRAPHY: Not Available

ABSTRACT TEXT: The nanosecond laser conditioning has been confirmed as an effective method for improving the LIDT of the optical coatings [1-4], which is due to the desorption of contaminants [2] or the elimination of the defects and absorbers in subsurface [3] to avoid the occurrence of catastrophic damage. However, in our previous work [4], we found the femtosecond LIDT of Ta_2O_5/SiO_2 high reflectors were decreased after nanosecond laser conditioning. In the present work, the effect of nanosecond laser conditioning on the femtosecond laser-induced damage of optical films was studied systematically. Series of thin films (Al_2O_3, HfO_2, SiO_2 films, Al_2O_3/SiO_2 UV high reflectors) after nanosecond laser conditioning by Raster-scanning have been investigated theoretically and experimentally. After nanosecond laser conditioning, the femtosecond damage of samples are less deterministic than before, which has a wider range of fluence interval with damage probability between 0% and 100%. The LIDT of all the investigated film after laser conditioning is lower than the one before conditioning slightly. In order to expound the damage mechanism, a theoretical model including MPI, AI, and the mid-gap defect state is built to simulate the evolution process of the electron density in the conduction band. The decrease of LIDTs of samples is elucidated reasonably by the seed electron contribution from the electronic defect state in the band gap to conduction band, which could enhance the initial seed electron density in the conduction band for MPI and AI processes and accelerate the final breakdown. If the nanosecond laser conditioning induces mid-gap electronic defects inside the films, it will promote the evolution process of femtosecond laser damage by increasing the initial seed electron in the ionization process. Hence, LIDT will be decreased in the femtosecond range.

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KEYWORDS: laser induced damage, nanosecond laser conditioning, optical film, femtosecond laser

10014-45, SESSION 12

Effect of deuterated levels and impurities on laser-induced damage in DKDP crystals

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SPEAKER BIOGRAPHY: Baoan Liu obtained his doctoral degree in materials science from State Key Laboratory of Crystal Materials, Shandong University. Now he works in University of Science and Technology Beijing. His research interests focus on mechanism of laser induced damage in KDP/DKDP crystals, defect structure, microstructural evolution.

ABSTRACT TEXT: Laser induced damage of optics has a very complex process, which decided by both laser parameters and properties of material. Although the relationship between the properties of material and laser damage has not been cleared yet, the study on the properties of material and the physical parameters of optical element is important for forecasting possibility of laser induced damage. In present work, a series of DKDP crystals with different deuteration levels and 80%DKDP crystals grown with different KH_2PO_4 raw materials by two growth methods were prepared. The mechanical, thermal, electrical and optical property of DKDP crystal were measured and analyzed with its structure for investigating the effect of material on laser damage of DKDP crystal for THG. Moreover, the defects related to laser induced damage in DKDP crystal were investigated by using Positron Annihilation Spectroscopy and Electron Paramagnetic Resonance. Tri-axial strain and stress in DKDP single crystals were studied by neutron diffraction. The behavior of laser damage with specified laser parameter was investigated to provide references for users.

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KEYWORDS: DKDP crystal, Laser induced damage, Damage behavior, Defect, Neutron diffraction

10014-46, SESSION 12

First-principles calculations for initial electronic excitations in dielectrics induced by intense femtosecond laser pulses

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SPEAKER BIOGRAPHY: Shunsuke Sato received PhD in Physics from Graduate School of Pure and Applied Sciences, University of Tsukuba, Japan in 2016. His research concentrates on first-principles calculations for interactions of intense ultra-short laser pulses with dielectrics.

ABSTRACT TEXT: Energy transfer from laser pulses to electrons in the medium, which takes place in the initial stage of laser-induced damage, is a key quantity that determines profiles of laser damages and ablations. To understand fundamental mechanisms of the laser-induced damage process, a quantitative theoretical description of the energy transfer is significant. However, especially for transparent materials, the description of the energy transfer is highly complex because of quantum nature of the electron dynamics and nonlinearity of the light-matter interactions. To overcome these difficulties, we have been developing a theoretical approach [1] combining two theoretical frameworks: One is the time-dependent density functional theory that provides a first-principles description of nonlinear electron dynamics in crystalline induced by an intense laser pulse. The other is the macroscopic Maxwell's equation that describes the propagation of the intense laser pulse in the medium in micrometer scale. Numerical simulations combining these two frameworks provide a comprehensive description of nonlinear interactions between intense and ultrashort laser pulses with dielectrics in the first-principles level.

We have applied the method to simulate irradiation of femtosecond laser pulses on an alpha-quartz surface [2]. From the numerical simulations, we have obtained spatial distributions of the transferred energy from the laser pulses to electrons in the medium in micrometer scale. The transferred energy will trigger subsequent atomic dynamics and finally cause the laser-induced damage. We simply estimated the laser damage threshold and ablation depth from the energy transfer to electrons, comparing the spatial distribution of the energy transfer with melting and cohesive energies of alpha-quartz. The estimated threshold and depth show fair agreement with recent experimental data. We further estimated spatial profiles of craters created by the laser ablation, assuming a spatial profile for the laser pulse. The estimated crater profile well reproduces the experimental one when the laser intensity is slightly above the ablation threshold. In contrast, the theoretical estimation fails to reproduce the measured profile if the intensity is high above the threshold. This fact may indicate the significance of the subsequent atomic dynamics in the laser-ablation phenomena induced by very intense pulses.

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KEYWORDS: laser damage, ultrashort pulse, first-principles calculation, time-dependent density functional theory

10014-47, SESSION 12

Dual wavelength laser damage mechanisms in the ultrashort pulse regime

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SPEAKER BIOGRAPHY: Not Available

ABSTRACT TEXT: The high intensities of ultrashort laser pulses cause strong nonlinear absorption in optical components. These nonlinear absorption processes can be sufficient to generate a critical density of free electrons in the conduction band which initiate non reversible modifications in the material.

In this work we report on the laser induced damage threshold of high reflective coatings for 387.5nm and 775nm. These high reflective coatings are designed and manufactured of stacks of different dielectric materials. Materials used include aluminum oxide, tantalum oxide, niobium oxide and silicon oxide. The coatings were deposited on fused silica substrates via the ion beam sputtering process, which generates dense and amorphous thin films. We expose these coatings to fundamental and second harmonic femtosecond radiation simultaneously. Although these coatings are transparent to the used wavelengths of 387.5nm and 775nm, the high peak intensities drive nonlinear absorption processes which cause the promotion of initially bound electrons to the conduction band. Once in the conduction band, these free electrons gain further energy through the linear absorption of photons and can, given sufficient energy, ionize additional electrons via electron-electron collisions. When a material dependent critical conduction band electron density is reached, irreversible material modification or removal is induced. The laser induced damage threshold testing procedure used in the experiments was derived from S-on-1 threshold measurements described in the Standard ISO 21254 with the addition of a second harmonic pulse. The applied fluence of the second harmonic part of the incoming beam and the temporal delay to the pulses of the fundamental wavelength was fixed for each individual test and then repeated at different fluences and delays. Our experimental results are compared to an expanded Keldysh model which accounts for the additional excitation channels caused by the simultaneous presence of photons at different wavelengths.

KEYWORDS: LIDT, dual wavelength, ultrashort pulse, photoionization

10014-48, SESSION 12

Ultrafast polychromatic ionization of dielectric solids

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SPEAKER BIOGRAPHY: 07/2015 degree M.Sc. in physics at Leibniz Universität Hannover; Since 2012 PhD student at Max-Born-Institut Berlin

ABSTRACT TEXT: The modeling of the damage process can be divided into thermal and electronic processes. Especially, the electronic damage seems to be well understood. The damage threshold is linked to the excitation of valence electrons into the conduction band, and often, the damage is obtained if a critical density of free electrons is reached. For the modeling of the electronic excitation, rate equation models are applied which can vary in the different terms representing the different excitation channels. According to the current state of the art, the photoionization and avalanche ionization induce the major part of the ionization process, and consequently the determination of the LIDT is based on the calculation of the respective terms. For the theoretical description of both, well established models were developed. For the quantitative calculation of the photoionization, the Keldysh theory is used most frequently and for the avalanche processes the Drude theory is often applied. Both, the Drude and the Keldysh theory calculations, depend on the central laser frequency and use a monochromatic approach. For most applications the monochromatic description confirms very well with the experimental findings, but in the range of few cycle pulses the necessary broadening of the laser emission spectrum leads to high uncertainties for the calculation.

In this paper, a novel polychromatic approach is presented including photo- as well as avalanche ionization. The simulation combines different ionization channels in a Monte-Carlo procedure according to the frequency distribution of the spectrum. The resulting influence on the wavelength and material dependency is discussed in detail for various pulse shapes and pulse durations. The main focus of the investigation is placed on the damage threshold as well as the specific characteristics in the wavelength and material dependency. The results are linked to measurement results.

KEYWORDS: avalanche ionization, photoionization, modeling of the damage process

10014-49, SESSION 12

Influence of multiple energy bands on the photoionization of non-metal crystals

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SPEAKER BIOGRAPHY: Dr. V. Gruzdev received PhD in Optics from S. I. Vavilov State Optical Institute in St. Petersburg, Russia in 2000. Since 1992 he works in the field of theoretical studies of the fundamental mechanisms of laser-induced damage. Since 2005 he is with the Department of Mechanical and Aerospace Engineering, University of Missouri, Columbia, MO. Since 2009 he is a co-chair of Laser Damage Symposium.

ABSTRACT TEXT: The majority of laser-induced ionization models consider electronic processes in the highest valence and the lowest conduction bands for transparent solids. This approach is usually justified by assuming that an increase in the gap separating the energy bands involved in laser-driven electron transitions results in an exponential reduction of the rate of the transitions. Here we demonstrate that this assumption is true only in low-intensity multiphoton regime if the energy of laser photons is significantly smaller than the band gap. In general case, several valence and conduction bands can significantly contribute to the rate of inter-band electron transitions attributed to the photoionization and nonlinear absorption. Contribution of each particular energy band strongly depends on laser parameters (wavelength and intensity) and on the details of band structure.

We present a modification of the Keldysh model for the multi-band case achieved by proper employment of several energy bands treated by the usual Keldysh formula for each. The regular two-band approximation is compared to the multiple-band approach with proper band gaps and effective masses obtained from previously published independent measurements. The obtained results demonstrate that, in the multiphoton regime, the major contribution to the photoionization is from the highest valence and the lowest conduction bands. However, in the tunneling regime, contributions of different energy bands are very similar and can be accounted for by multiplying a two-band photoionization rate by a proper factor.

The multi-band effect of electron excitation must influence the value and wavelength scaling of the laser-induced damage threshold (LIDT) for laser pulses with pulse width smaller than 100 fs. Moreover, the discussed effects are expected to be the most evident in the mid-IR wavelength range. In this connection, we present a novel interpretation of experimental data [1] on LIDT measurements in ZnSe and Si for the range 780-3600 nm. While 780 nm is favorable for LID by multiphoton absorption, longer wavelengths are favorable for the tunneling regime of the photoionization that combines contributions of several energy bands. Different bands start contributing significantly to LID at different wavelengths, and this effect explains specific wavelength scaling of LID thresholds in ZnSe.

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KEYWORDS: photoionization, fundamental mechanisms of laser damage, semiconductor crystals, multiphoton ionization, tunneling ionization, crystal band structure

10014-50, SESSION 12

Simulation of heating by optical absorption in nanoparticle dispersions

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SPEAKER BIOGRAPHY: Not Available

ABSTRACT TEXT: With the proliferation of highly confined, nanophotonic waveguides and laser sources with increasing intensity, the effects of laser heating will begin to greatly impact the materials used in optical applications. In order to better understand the mechanism of laser heating, its timescales, and the dispersion of heat into the material, simulations of nanoparticles in various media are presented here.

A generic model to describe a wide variety of nanoparticle shapes and sizes is desirable to describe complex phenomenon. These particles are dispersed into various solids, liquids, or gases depending on the application. To simulate such nanoparticles, as well as the interaction with their host material, the Finite Element Method (FEM) is used. Heat transfer following an absorption event is also described by the parabolic partial differential equation:

rho*C*(dT/dt)- $\bar{\nabla}$ • (k$\bar{\nabla}$T)=F

where rho is the density, C is the specific heat and k is the thermal conductivity of the materials in each finite element. These material parameters relate to F, the heat generated over time, t, to a temperature, T. Transient solutions are generated in response to continuous, pulsed, or modulated laser radiation.

The simplest physical system described by FEM is that of a broadly-absorbing round-shaped nanoparticle dispersed in viscous host fluid or solid. Many experimental and theoretical studies conveniently describe a very similar system: a carbon “black” nanoparticle (CNP) suspended in water. This material is well-known to exhibit nonlinear behavior when a laser pulse carrying 0.7 J/cm2 is incident on the material. The mechanisms are believed to be nonlinear scattering, by the transfer of heat from the absorbing nanoparticle to the dispersing fluid, or carbon sublimation and plasma formation, by the extreme laser heating of the particles. The heat of the CNP is described as:

T(t) = A*integral(0,t,I(t)dt)/V*rho*C

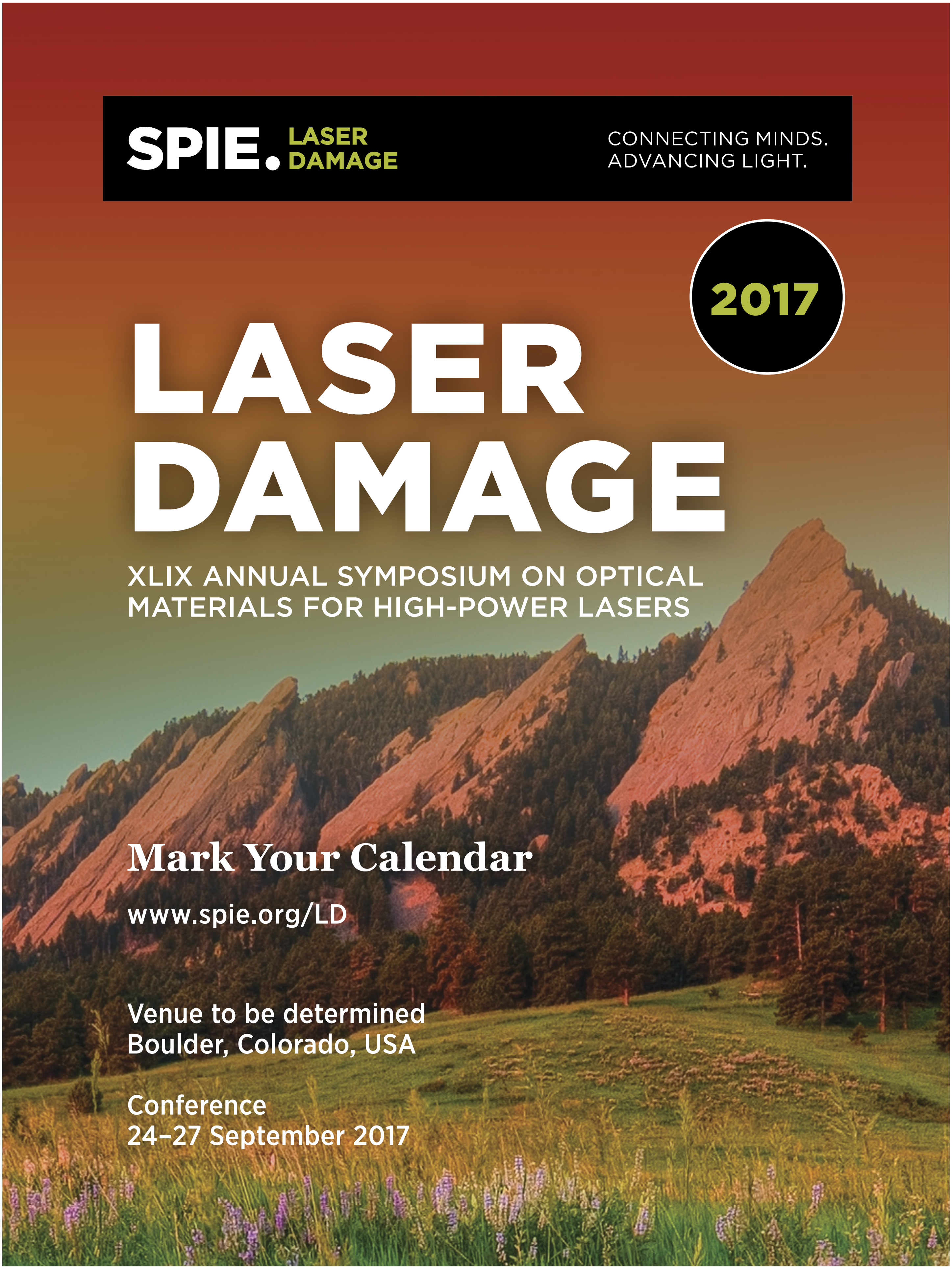
where V is the volume of the particle, I(t) is the intensity of the laser irradiation, and A is the absorption cross-section.

Using FEM methods to solve the PDE for heat transfer we can measure the heating of the nanoparticle as a function of the laser power and also observe the nanoparticle cool by transferring heat to its host material after the irradiation is complete.

For this process the FEM simulations agree with experimental results to show that a pulse of this fluence is capable of heating the solvent elements adjacent to the nanoparticle to their boiling point. This creates nonlinear scattering which is empirically observed as a nonlinear decrease in the transmitted power at this input fluence.

KEYWORDS: Nanoparticles, Finite Element Method, Simulation, Carbon Black

NOTES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