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LASER DAMAGE

XLIX ANNUAL SYMPOSIUM ON OPTICAL MATERIALS FOR HIGH-POWER LASERS

TECHNICAL
ABSTRACT BOOK

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Millennium Harvest House Hotel
Boulder, Colorado, USA

Conference
24–27 September 2017

SPIE. LASER DAMAGE

XLIX ANNUAL SYMPOSIUM
ON OPTICAL MATERIALS
FOR HIGH-POWER LASERS

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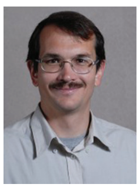

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Sunday • 24 September

TUTORIAL AND DISCUSSION

Femtosecond Laser Damage: Past, Present, and Future

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

Workshop Chair: **Enam A. Chowdhury**
The Ohio State Univ. (USA)

Over the past two decades, the field of femtosecond laser damage have made strides not only in expanding our understanding of a fundamental non-perturbative light matter interaction, but also in building next generation ultra-intense lasers and application of femtosecond laser materials processing. Experimental and theoretical development in this exciting and rapidly expanding field will be discussed.

Welcome and Social Mixer

7:00 to 8:30 pm • Location: Millennium Hotel Gardens

Join your colleagues for light refreshments and mingling.

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

Monday • 25 September

Poster Overviews-Monday

9:50 to 10:20 am

Posters authors are asked to give a 2-minute/2-slide overview of their poster in the order that they appear in the Monday poster sessions.

Poster Viewing and Refreshment Breaks-Monday

10:20 to 11:10 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.

Open House and Reception

6:30 to 8:00 pm

Come, relax, and join your colleagues at Alpine Research Optics (ARO) for an enjoyable evening of refreshments and pleasant conversation.

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Tuesday • 26 September

Poster Overviews-Tuesday

9:50 to 10:20 am

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

Poster Viewing and Refreshment Breaks-Tuesday

10:20 to 11:10 am and 3:40 to 4:30 pm

Conference attendees are ed 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

6:30 to 8:00 pm

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Reception at NCAR
1850 Table Mesa Dr., Boulder, CO

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

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TRIBUTE TO

Prof. Mireille Commandré

This summer the worldwide laser-damage community suffered an irrecoverable loss: Prof. Mireille Commandré passed away on July 11, 2017. Mireille was a full professor with Ecole Centrale Marseille (France) and a leader of research team ILM (Laser Matter Interactions) at Fresnel Institute (Marseille, France). She worked in the field of laser-induced damage of optical materials since the beginning of her research career in 1980s. Since 2010, she served as a member of International Program Committee of Laser-Damage Symposium. Since 2003, she also served as a member of the Program Committee of another worldwide recognized international conference – Advances in Optical Thin Films. The Co-chairs of Laser Damage Symposium, members of International Program Committee of Laser Damage Symposium, and entire laser-damage community highly recognize and appreciate the outstanding contribution of Mireille to success of this conference and to the overall progress of research in the fields related to laser damage and optical materials for high-power lasers.

SUNDAY 24 September	MONDAY 25 September	TUESDAY 26 September	WEDNESDAY 27 September
SPIE LASER DAMAGE 2017			
REGISTRATION MATERIAL PICK-UP, 5:30 pm 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 AND DISCUSSION **Femtosecond Laser Damage: Past, Present, and Future,** 6:00 to 7:00 pm	**Poster Placement,** 7:40 to 8:00 am	**Poster Placement,** 7:40 to 8:00 am	
Welcome and Social Mixer 7:00 to 8:30 pm *Registration Material Pick-up continues until 8:30 pm*	**Opening Remarks and 2016 Award Presentations** 8:00 to 8:30 am **Alexander Glass** Best Oral Presentation and **Arthur Guenther** Best Poster Presentation	**SESSION 5** **Mini-Symposium I: Frontiers of Ultrafast Science Sources, Basic Effects, and Mechanisms of Ultrafast Laser-matter Interactions,** 8:00 to 9:50 am	**SESSION 9** **Thin Films II,** 8:00 to 10:00 am
	**SESSION 1** **Surfaces, Mirrors, and Contamination I,** 8:30 to 9:50 am		**Refreshment Break,** 10:00 to 10:30 am
	Monday Poster Overview, 9:50 to 10:20 am	**Tuesday Poster Overview,** 9:50 to 10:20 am	**SESSION 10** **Thin Films III,** 10:30 am to 12:50 pm
	Poster Viewing and Refreshment Break, 10:20 to 11:10 am	**Poster Viewing and Refreshment Break,** 10:20 to 11:10 am	
	SESSION 2 **Surfaces, Mirrors, and Contamination II,** 11:10 am to 12:50 pm	**SESSION 6** **Mini-Symposium II: Frontiers of Ultrafast Science Sources, Basic Effects, and Mechanisms of Ultrafast Laser-matter Interactions,** 11:10 am to 12:40 pm	
	Lunch Break 12:50 to 2:00 pm	**Lunch Break** 12:40 to 2:00 pm	**Lunch Break** 12:50 to 2:00 pm
	SESSION 3 **Fundamental Mechanisms I,** 2:00 to 3:40 pm	**SESSION 7** **Mini-Symposium III: Frontiers of Ultrafast Science Sources, Basic Effects, and Mechanisms of Ultrafast Laser-matter Interactions,** 2:00 to 3:40 pm	**SESSION 11** **Materials and Measurements I,** 2:00 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 **Fundamental Mechanisms II,** 4:30 to 6:10 pm	**SESSION 8** **Thin Films I,** 4:30 to 5:50 pm	**SESSION 12** **Materials and Measurements II,** 4:30 to 6:10 pm
	Closing Remarks, 6:10 to 6:20 pm	**Closing Remarks,** 5:50 to 6:00 pm	**Closing Remarks,** 6:10 to 6:20 pm
	OPEN HOUSE AND RECEPTION, 6:30 to 8:00 pm	**WINE AND CHEESE TASTING RECEPTION,** 6:30 to 8:00 pm	

10447-1, SESSION 1

Particle damage sources and their mitigation on high energy laser systems *(Keynote Presentation)*

Christopher W. Carr, Jeffrey D. Bude, Philip E. Miller, Thomas Parham, Pam K. Whitman, Marcus V. Monticelli, Rajesh N. Raman, David A. Cross, Brian Welday, Frank Ravizza, Tayyab I. Suratwala, James Davis, Matthew J. Fischer, Ruth A. Hawley, Henry Lee, Manyalibo J. Matthews, Mary A. Norton, Michael C. Nostrand, Diana Vanblarcom, Stanley C. Sommer, Lawrence Livermore National Lab. (United States)

SPEAKER BIOGRAPHY: Not Available

ABSTRACT TEXT: High energy laser systems are ultimately limited by laser-induced damage to their critical components. This is especially true of damage to critical fused silica optics which grows rapidly with exposure to additional laser pulses. Much progress has been made in eliminating damage precursors in the as-processed fused silica optics (the Advanced Mitigation Process, AMP3), and very high damage resistance has been demonstrated in laboratory studies. However, the full potential of these improvements has not yet been realized in actual laser systems. In this work, we explore the importance of potential damage sources, in particular, particle contamination, for fused silica optics fielded in a high-performance laser environment, the National Ignition Facility (NIF) laser system. We demonstrate that the most dangerous sources of particle contamination in a system-level environment are laser-driven particle sources. For the specific case of the NIF laser, we have identified the two important particle sources which account for almost all the damage observed during full laser operation and present mitigations for these particle sources. Finally, with the elimination of these laser-driven particle sources, we demonstrate essentially damage free operation of AMP3 fused silica for ten large optics (a total of 12,000 cm2 of beam area) for shots from 8.6 J/cm2 to 9.5 J/cm2 with 351nm light (3 ns Gaussian pulse shapes). Potentially many other high pulsed energy laser systems have similar particle sources, and given the insight provided by this study, their identification and elimination should be possible. The mitigations proposed here are currently being employed for all large UV silica optics on the National Ignition Facility.

Lawrence Livermore National Laboratory is operated by Lawrence Livermore National Security, LLC, for the U.S. Department of Energy, National Nuclear Security Administration under Contract DE-AC52-07NA27344. (LLNL-ABS-729557)

[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

10447-2, SESSION 1

Contamination, debris, and shrapnel generation arising from large area laser target interactions

James E. Andrew, AWE plc (United Kingdom)

SPEAKER BIOGRAPHY: Jim Andrew is a principal scientist in the Radiation Science Group, AWE plc.

ABSTRACT TEXT: Typically plasma physics targets are of millimetre or sub millimetre dimensions and use an irradiance of ~10^16 W/cm2 in nanosecond ["long"] pulses or ~10^21 W/cm2 for "short" [~500fs] pulse lengths. These conditions lead to target and target mount materials being raised in temperatures that cause changes from the solid state into liquid, gaseous and plasma conditions. Matter from the altered states are then subsequently ejected from the originally solid target location and are spread around in space with a variety of masses and velocities and form layers or regions of contamination, some of which may be deposited on sensitive laser or X ray optical surfaces.

A small proportion of laser usage at the Orion facility is occupied by experiments that involve using centimetre size beams on similar sized targets in a vacuum environment. This smaller class of experiments typically use <400 J pulses over 20 mm diameter spots in 1-5 ns pulses. These targets can be planar or cylindrical in geometry and may be made of metals, glasses or polymers and combinations thereof. We describe the issues of debris and shrapnel generation from such targets and methods to mitigate their effects in an ongoing series of work. The relatively low energy loadings are insufficient to change the target phase from solid to liquid but does produce an impulse in the irradiated targets that then lead to cracking, decomposition or fragmentation. Consideration needs to be given to both achieving the objectives of experiments and any consequent effects on permanent or temporary installed optics and instrumentation used in the facility target chamber. We have used glass witness plates for post shot analysis of target fragment plumes and post campaign surveys of target chamber surfaces to evaluate constrained and unconstrained fielding of the targets. Methods to minimise contamination have also been evaluated.

KEYWORDS: aluminium; borosilicate; contamination; debris; glass; metal; polymer; shrapnel

10447-3, SESSION 1

Research on the cleanliness control technologies for high-power laser facility

Xiaodong Yuan, Wanguo Zheng, Xinxiang Miao, Haibing Lv, China Academy of Engineering Physics (China)

SPEAKER BIOGRAPHY: WORK EXPERIENCE: 2006-Present: Professor, Department Director, Laser Fusion Research Center, Be in charge of the assembly and maintenance of SG-III laser facility. 2000-2006: Associate Professor, Laser Fusion Research Center, Be in charge of XG-II and Silex-I laser facility. 1998-2000: Associate Professor, Institute of Nuclear Physics and Chemistry, Be in charge of XG-II laser facility. 1987-1998: Engineer, Institute of Nuclear Physics and Chemistry, worked on the XG-II laser facility. EDUCATION: 1987, Bachelor in Laser Technology, University of National Defense Science and Technology, China 1998, Master of Science in Optical Engineering, Sichuan University, China 2009, Doctor of Philosophy in Optical Engineering, Tsinghua University, China ADEMIC ACHIEVEMENTS Fellow of the Society of Optical Engineering Member of the Technique Committee of Cleanrooms and Associated Controlled Environments, SAC/TC319 and ISO TC 209

ABSTRACT TEXT: The output capability of the high power laser facility used for Inertial Confinement Fusion (ICF) research is required extremely high. To verify the output properties of the high power laser, a Techniques Integrated Line (TIL) has been built. The output energy is more than 20kJ. The damage induced by contaminants became the main factor to limit the output capability when the energy is more than 15kJ. To control the surface cleanliness of the optics, a guideline including four aspects: “closed-loop cleanliness, dynamic implementation, priority control and grading protection” was proposed. Separate control systems for optics, mechanical components and operating environment of TIL laser facility were built up. Results showed that the contamination on surfaces of optics was successfully minimized.

Firstly, the components of the contaminants in TIL were analyzed. The damage thresholds related on sizes of particles and depths of organs were tested. A red line which means the allowed existed contaminants and a green line which means the initial cleanliness control requirements have been determined. After that, a satisfied operating environment within the TIL laser facility was obtained by means of grading cleanliness control: ISO 8 for experimental zone; ISO 5 for optics assembly building; ISO 3 and ISO 5 for the internal of the facility depending on the running flux. Measures including “enclosed space, positive pressure, isolation and FFU purging” were employed.

Secondly, the optical-mechanical components and modules were cleaned and detected strictly before assembling. The cleanliness at high flux section was ISO SCP 5 for surfaces of mechanical components and ISO SCP 4 for surfaces of optics. An integrated clean-detection system was built and the corresponding cleaning and detecting technologies were developed.

Finally, the aerosol contaminants formed during the running process were successfully eliminated by stray light controlling and gas purging methods. The cleanliness of the internal environment can be recovered back to ISO 5 after running for 5 min.

The TIL laser facility has been built and pilot run for 5 years. The Max. output energy was 21kJ. The cleanliness of the optics can excellently satisfy the requirement of high flux running.

KEYWORDS: high power laser facility; surface cleanliness; laser damage; closed-loop cleanliness; dynamic implementation; environment cleanliness control; red line; green line

10447-55, SESSION PS1

Monolithic antireflection grating on fused silica beam sampling grating for high power laser system

Ying Liu, Huoyao Chen, Univ. of Science and Technology of China (China)

SPEAKER BIOGRAPHY: Ying Liu received her PhD degree from Changchun Institute of Optics and Fine Mechanism, Chinese Academy of Sciences. She is an associate professor of National Synchrotron Radiation Laboratory, University of Science and Technology of China. Her research focuses upon the realization diffractive optical elements for high power laser system and synchrotron radiation based on holographic lithography and ion beam etching. Her recent research involves the development of near field holographic lithography with phase masks, the optical application of ion beam induced self-organized nanostructures, large aperture diffraction grating and fused silica treatment for high laser induced damage threshold.

ABSTRACT TEXT: As an off-axis focusing lens at the wavelength of 351 nm, a fused silica beam sampling grating (BSG) plays a key role as one of final optical assembly in high power laser systems. To suppress the interface reflection, not only antireflective (AR) coatings, but also monolithic subwavelength AR structures on fused silica surface have been utilized on BSG. Compared with AR coatings, monolithic AR structures are relatively stable and reusable after cleaning. Hence, as AR structures for BSG, monolithic antireflection structures attract more and more interests. On one hand, random AR structures have achieved great potential in high threshold and super hydrophobic properties. On the other hand, an additional plasma etching facility is needed to generate random AR structures by self-mask intentionally induced by plasma etching. In addition, defect-free random AR structures are still big challenge for the aperture up to 400 mm×400 mm, which is a common size of BSG in high power laser systems. Presently, meter-size gratings have been realized by holographic lithography combined with ion beam etching (HL-IBE). HL-IBE demonstrates great potential in fabricating of micro- and nano- periodic patterns with large aperture. Since a BSG with the aperture of 400 mm is fabricated by holographic lithography (HL) combined with chemical or dry etching, it is still attractive to develop an integrated fabrication process, i. e. to realize the patterning of BSG and its AR structures into a sequential HL-IBE process.

We aim at realizing monolithic fused silica AR gratings embedded in the structured side of BSGs with the aperture of ~400 mm using an integrated HL-IBE. Our first result on such gratings will be presented. AR gratings with 4500 lines/mm, working at 351 nm and conical incidence, for BSGs with the aperture of 100 mm have been performed. With the proposed AR grating, the 0th transmission of BSGs has been increased by ~2.7%. The transmission of such AR gratings will be further enhanced by optimizing groove profile. Moreover, the wavelength-band and size of such AR gratings will be improved.

Acknowledgement

The work is funded by the National Major Project of China and the Key Science and Technology Program of Anhui Province, China (Grant No. 131015195).

KEYWORDS: fused silica; antireflection grating; periodic antireflection surfaces; beam sampling grating; UV; laser damage resistance

10447-56, SESSION PS1

Elucidation of laser resist removal phenomenon without causing laser damage

Takayuki Yamashiro, Kousuke Nuno, Yuji Umeda, Yusuke Funamoto, Tomosumi Kamimura, Osaka Institute of Technology (Japan); **Ryosuke Nakamura,** Osaka Univ. (Japan); **Takashi Nishiyama, Hideo Horibe,** Osaka City Univ. (Japan); **Hiroyuki Kuramae,** Osaka Institute of Technology (Japan)

SPEAKER BIOGRAPHY: Not Available

ABSTRACT TEXT: Removal of resist by laser irradiation has been investigated instead of the chemical method. Usually, when a laser beam was irradiated to the resist in the normal atmosphere, the resist slightly is stripped due to local thermal expansion by the absorbed energy of the laser beam to the Si wafer surface, but laser damage occurs to the Si wafer surface simultaneously. However, an advanced laser resist stripping method was successfully developed without causing laser damage to the Si wafer. The laser irradiation in the water can improve the resist stripping effect when compared with that of the normal atmosphere irradiation. Still, the mechanism of the removal efficiency improvement is not known regarding the laser irradiation in the water.

In this study, we have investigated the resist removal phenomenon by using a finite element (FE) method. A two-dimensional (2-D) micro-FE model was constructed based on the boundary surface between the Si wafer, resist and water during laser radiation. To strip the resist from the Si wafer, vertical effect (x-axis) is required to the resist and the Si wafer boundary surface. In the normal atmosphere, any effective stress did not occur along the x-axis direction in the resist. In contrast, for the laser irradiation in the water, large compressive stress was confirmed along the x-axis direction in the resist. This compressive stress in the resist is thought to improve the resist removal efficiency.

KEYWORDS: resist stripping; laser damage; finite element (FE) method; compressive stress

10447-57, SESSION PS1

Development of optimal mitigation contours and their machining flow by micro-milling to improve the laser damage resistance of KDP crystal

Jian Cheng, Mingjun Chen, Wenjing Ma, Hao Yang, Qi Liu, Harbin Institute of Technology (China); **Chenhui An, Zhichao Liu,** China Academy of Engineering Physics (China)

SPEAKER BIOGRAPHY: Not Available

ABSTRACT TEXT: Laser-induced damage on optical surfaces and its dramatic growth behavior under subsequent laser irradiations have been the main concern that limits the output energy promotion of high-energy laser systems. The increased heat absorption and light intensification incurred by the initial damage site are the primary sources, leading to the subsequent damage growth. In this context, a strategy of replacing the initial damage site with a pre-designed laser-benign mitigation structure was proposed to mitigate its growth and correspondingly extend the lifetime of optics. For KDP crystals serving as optoelectronic switch and frequency converter, though micro-machining has been proposed as the most promising method to mitigate the surface damage growth, the optimal mitigation geometries have been not determined yet. Moreover, owing to the weak mechanical property of KDP crystals (low fracture toughness), it is still a challenge to steadily and efficiently fabricate mitigation contours with high quality surfaces.

In this work, the optimal mitigation contours and their machining flow by micro-milling have been developed to fabricate the high-quality repaired surfaces on KDP crystals. The laser propagation properties through typical mitigation contours (e.g., Gaussian, spherical, conical and ellipsoidal) were analyzed and compared to determine the optimal mitigation contours for achieving minimum light intensification. Based on Computer Aided Manufacturing (CAM) technology, a specific machining flow combining cavity milling (rough machining) and spiral milling (fine machining) was develop to repair the initial damage on KDP crystal with high efficiency and surface quality. The effect of processing parameters (e.g., spindle and feed speeds, tool path interval and tool tracks) on the repaired surface quality was investigated. Laser damage test was performed on the fabricated mitigation pit using a pulsed ns-laser at 355nm wavelength to verify the effectiveness of optimized mitigation contours and machining flow in improving the laser damage resistance. The results of this study provide theoretical and experimental guidance to the recycling of large aperture KDP/DKDP crystal optics used in large laser systems.

KEYWORDS: KDP crystal; surface damage growth; laser damage resistance; optics recycling; micro-milling repairing

10447-59, SESSION PS1

Optimum inductively coupled plasma etching of fused silica to remove subsurface damage layer

Xiaolong Jiang, Ying Liu, Univ. of Science and Technology of China (China)

SPEAKER BIOGRAPHY: Dr. Xiaolong Jiang, has completed his PhD (Ph.D.-engineering) at the age of 26 years from University of Science and Technology of China. He is now a research assistant at Research Center of laser Fusion, China Academy of Engineering Physics. Currently, His researches focus on the laser induced damage of fused silica optics.

ABSTRACT TEXT: Currently, optical surface finish in fused silica is usually obtained by abrasive-based polishing methods. During these processes, however, damage is created in the subsurface of optics due to the physical force involved at the microscopic scale. In high peak power laser system, SSD is believed to serve as a laser damage precursor when exposed to high power laser. Therefore, obtaining of SSD-free fused silica substrate has been a goal for the optical fabrication industry for many years. Methods to remove SSD layer, such as magnetorheological finishing (MRF) and HF based wet etching, have been intensely studied. However, all these methods have shortcomings. MRF, for example, has very complex finishing procedure and would introduce metal contaminations which will also initialize laser damage. And HF wet etching will result in serious surface roughening due to isotropic etching of SSD. Therefore, exploring new and better technique is still necessary.

As a novel optical manufacturing technology, plasma processing was recently proposed to remove the SSD layer of fused silica. It is based on chemical reaction between silicon-based material atom and reactive fluorine radicals generated by the plasma, then the volatile reaction products are generated to remove the material, which avoids further damage to the processed surface. Jin et al. investigated the removal of SSD layer with CF4/Ar atmospheric pressure plasma processing [5]. But at such high pressure, etching was more isotropic than anisotropic, causing the lateral etching of SSD and serious surface roughening.

In this work, we introduce an optimum inductively coupled plasma etching technique which successfully removes the subsurface damage (SSD) layer of fused silica without causing plasma induced surface roughening (PISR) or lateral etching of SSD. As one of the commonest PISR initiators, metal contamination from reactor chamber is avoided by employing a simple isolation device. Based on this device, a unique low-density pitting damage is discovered and subsequently eliminated by optimizing the etching parameters. Meanwhile etching anisotropy also improves a lot, thus preventing the lateral etching of SSD. Using this proposed technique, SSD layer of fused silica is successfully removed with a surface roughness of 0.23 nm.

KEYWORDS: Fused silica; Subsurface damage; Laser damage; Inductively coupled plasma etching; Plasma induced surface roughening

10447-60, SESSION PS2

System for investigation of laser induced damage dynamics of optical materials for high energy lasers: a brief overview

Baoan Liu, Chang Liu, Xin Ju, Univ. of Science and Technology Beijing (China); **Chengyu Zhu, Zhiwei Lv,** Harbin Institute of Technology (China)

SPEAKER BIOGRAPHY: Not Available

ABSTRACT TEXT: The construction of large high energy laser systems on the world such as NIF, LMJ, or SG series facilities, requires thousands of optical materials with large aperture. A significant limitation on the operating fluence of high peak power lasers is the laser induced damage of these optical components. The events of damage initiation and damage growth are two extremely important aspects included in laser induced damage process. To understand the damage initiation process, the laser-matter interact should be characterized with high time-spatial resolution. The material response during nanosecond laser induced damage could be comprehensively analyzed by obtaining the evolution of transient damage morphology, chemical nature of the ejected particles, spectroscopy signal of the photoexcited species and transient absorption, etc.

In this work, we build an online laser damage station for researching laser induced damage dynamics by using pump-probe experimental technique. The station is based on Hundred Joule Solid Laser in Harbin Institute of Technology which can provide 3? laser with high beam quality and high stability as pump laser. The final output is 50J/3?/3ns laser with beam diameter of 60 mm. The peripherals including image acquiring system, time resolved shadow microscopy system, time resolved Raman and fluorescence spectroscopy, time resolved mass spectroscopy. The Raman scattering signal and fluorescence signal arising from the pump and probe beams crossing area is spectrally analyzed using an imaging spectroscopy arrangement. The time-resolved of data can be up to 1ns. The processes involved in the whole laser damage process, especially span up to about 100ms delay from onset of initial damage, could be accurately characterized on the basis of these data. The detailed description of the laser damage station and some preliminary experiments will be shown in the presentation. In addition, we also expect that the laser damage station could be serviced as an open experimental facility for researchers over the worldwide.

KEYWORDS: Laser induced damage; Time resolved shadow microscopy; Time resolved Raman and fluorescence spectroscopy; Laser damage dynamics; Material modification

10447-62, SESSION PS2

Bulk absorption properties of LBO crystals

Christian Muehlig, Leibniz-Institut für Photonische Technologien e.V. (Germany)

SPEAKER BIOGRAPHY: Not Available

ABSTRACT TEXT: We present the results of comprehensive bulk absorption studies on numerous LBO crystals at 1070nm, 532nm and 355nm using the sandwich-LID measurement concept. One aim of the studies is answering the question whether there is a correlation between bulk absorption coefficients at the different applied wavelengths. Further, intensity dependent absorption measurements at 355nm are performed to investigate the nonlinear absorption in the LBO crystals. From the results it is verified, that at least to a certain extent the nonlinear absorption is related to impurities or defects, i.e. to sequential three photon absorption in addition to a potential intrinsic 3-photon absorption process.

KEYWORDS: Absorption; Photo-thermal technique; LBO; Nonlinear optical materials; Instrumentation, measurements and metrology

10447-63, SESSION PS2

Optical defects absorption produced in fused silica during laser-induced damage

Chunyan Yan, Xin Ju, Univ. of Science and Technology Beijing (China)

SPEAKER BIOGRAPHY: Not Available

ABSTRACT TEXT: Fused silica irradiated with 6.8-ns 355-nm laser pulses is studied by a combination of photothermal(PT) and Raman scattering spectroscopies. Results show that, for laser fluences above the laser-induced breakdown threshold, in all the cases studied, irradiation results in the formation of four laser-induced defect-related Raman bands centered on 1363, 1557, 1609 and 2330cm-1. Bands centered on 1363, 1557 and 2330cm-1 are attributed to Si=O, interstitial O2 and Si-H stretching bond. However, defects giving rise to a broad band at 1609 cm-1 are unknown. For all the laser-modified samples studied, photothermal spectroscopy reveals a dramatic increase in the intensity of cracks, associated with the formation of non-bridging oxygen hole center and interstitial O2, respectively. This indicates laser-induced material fracture. Based on these results, we discuss physical processes occurring during the catastrophic laser-induced material breakdown, leading to the formation of non-bridging oxygen hole center and interstitial O2 and material fracture.

KEYWORDS: fused silica; Raman scattering spectroscopies; photothermal; laser damage

10447-64, SESSION PS2

Influence of sintering aids for optical properties in Nd^{3+}:YAG ceramics

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SPEAKER BIOGRAPHY: Not Available

ABSTRACT TEXT: Most of the transparent Nd3+:YAG ceramics have been produced by using SiO2 , other oxides or fluorides as sintering aids. Nd:YAG ceramics doped with a small amount of SiO2 as sintering aids achieved highly efficient laser oscillation. Generally, ceramics are insulator materials, but they can be changed into semi-conductive materials by modifying the sintering atmosphere and sintering aids, etc. Semi-conductive property is mainly attributed to point defect structure (donor or acceptor), and it may affect the laser performance and optical properties of the materials. In this work, we prepared p-type, n-type and neutral Nd:YAG ceramic laser materials with or without adding impurities and then investigated their effect on optical properties.

YAG material is a complex oxide composed of Y3+, Al3+, and O2-. When cations other than +3 valency or anions other than -2 valency are added, YAG can be changed into a semi-conductive oxide such as p-type or n-type. For this purpose, we selected cations with a valency of +2 or +4 which does not include f electrons, and prepared transparent Nd:YAG ceramics including either of these cations, those including both of these cations (forming neutral type by charge compensation), and pure transparent Nd:YAG ceramics without adding any sintering aids. All samples reached theoretical transmittance value in laser oscillation wavelength regions, and optical loss was estimated to be as low as 0.1%/cm. P-type Nd:YAG ceramics have absorptions near the absorption edge compared to the pure one (without additives). A slight lowering of the oscillation efficiency was also confirmed in p-type materials. When each of the prepared materials was irradiated with UV light (266 and 355nm), only the p-type material showed a significant coloration due to the solarisation effect. It is very important for the improvement of ceramic laser quality.

KEYWORDS: Nd3+:YAG ceramics; optical properties; sintering aids; semi-conductive materials; impurities; point defect structure; ceramic laser materials; the solarisation effect

10447-65, SESSION PS2

An optimized strategy for the measurement of the defect distribution near threshold

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SPEAKER BIOGRAPHY: Dr. Arenberg has been with Northrop Grumman since 1989 having begun his career with Hughes Aircraft Company in 1982. His work experience includes optical, space and laser systems. Dr. Arenberg has worked on such astronomical programs as the Chandra X-ray Observatory, James Webb Space Telescope and helped develop the New Worlds Observer concept for the imaging of extra-solar planets. He has worked on several major high-energy and tactical laser systems, laser component engineering and metrology issues. He is a delegate to the both the OEOSC and ISO sub-committees charged with writing standards for laser and electro-optic systems and components and is a member of SPIE, American Astronomical Society and AIAA. Dr. Arenberg holds a BS in physics and an MS and PhD in engineering, all from the University of California, Los Angeles. He is the author of many conference presentations and publications, and holds a dozen European and U.S. Patents in a wide variety of areas of technology

ABSTRACT TEXT: The defect distribution, f(ϕ), determines the damage behavior of an optic. The STEREO-LID method [1] of making spatially and temporally resolved damage observations makes it possible to retrieve the sample f(ϕ) [2]. In this paper, we investigate the development of an optimized strategy to characterize the low fluence tail of f(ϕ) under the constraint of a limited test area (or number of test sites). The accurate determination of the low fluence tail of f(ϕ) is a problem of great practical interest defining the optic's behavior near the damage threshold. First, Monte-Carlo simulations are used to identify the test parameters (incident fluence F0 and spot size w) optimum for retrieving the desired range of f(ϕ) for a variety of model defect distributions. Then strategies for identifying the optimum test parameters when the defect distribution is unknown will be examined. The expected performance of the optimized process will be discussed.

1. Y. Xu, L. A. Emmert, and a. W. Rudolph, "Spatio-TEmporally REsolved Optical Laser Induced Damage (STEREO LID) technique for material characterization," Opt. Express 23, pp. 21607-21614 (2015).

2. Y. Xu, L. A. Emmert, and a. W. Rudolph, "Determination of defect densities from spatiotemporally resolved optical-laser induced damage measurements," Appl. Opt. 54, pp. 6813-6819 (2015).

KEYWORDS: STEREO-LID; defect distribution; threshold

10447-66, SESSION PS2

A method for the determination of the defect density distribution from standard damage frequency measurements

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SPEAKER BIOGRAPHY: Dr. Arenberg has been with Northrop Grumman since 1989 having begun his career with Hughes Aircraft Company in 1982. His work experience includes optical, space and laser systems. Dr. Arenberg has worked on such astronomical programs as the Chandra X-ray Observatory, James Webb Space Telescope and helped develop the New Worlds Observer concept for the imaging of extra-solar planets. He has worked on several major high-energy and tactical laser systems, laser component engineering and metrology issues. He is a delegate to the both the OEOSC and ISO sub-committees charged with writing standards for laser and electro-optic systems and components and is a member of SPIE, American Astronomical Society and AIAA. Dr. Arenberg holds a BS in physics and an MS and PhD in engineering, all from the University of California, Los Angeles. He is the author of many conference presentations and publications, and holds a dozen European and U.S. Patents in a wide variety of areas of technology

ABSTRACT TEXT: This paper presents a method to make an estimation of the low fluence edge of the defect distribution, f(?), from data collected from ISO 21254 standard damage frequency measurements. The cumulative probability of damage is formulated and the defect distribution is formulated as an expansion of an orthonormal set. This formulation allows the explicit isolation of the terms pertaining to the defect distribution and the intensity distribution. When the intensity distribution is specified, the resulting system is a polynomial in nature. Solutions for the systems relevant for Gaussian and flat top beams are presented with an initial tolerance analysis. The paper concludes with some experimental examples of the method.

KEYWORDS: Defect distribution; ISO 21254; threshold behavior

10447-67, SESSION PS2

An empirical investigation of the laser survivability curve: VIII-Summary

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SPEAKER BIOGRAPHY: Dr. Arenberg has been with Northrop Grumman since 1989 having begun his career with Hughes Aircraft Company in 1982. His work experience includes optical, space and laser systems. Dr. Arenberg has worked on such astronomical programs as the Chandra X-ray Observatory, James Webb Space Telescope and helped develop the New Worlds Observer concept for the imaging of extra-solar planets. He has worked on several major high-energy and tactical laser systems, laser component engineering and metrology issues. He is a delegate to the both the OEOSC and ISO sub-committees charged with writing standards for laser and electro-optic systems and components and is a member of SPIE, American Astronomical Society and AIAA. Dr. Arenberg holds a BS in physics and an MS and PhD in engineering, all from the University of California, Los Angeles. He is the author of many conference presentations and publications, and holds a dozen European and U.S. Patents in a wide variety of areas of technology

ABSTRACT TEXT: In this year's poster we summarize the highlights of the results uncovered over the last years our on-going empirical investigation. In particular, we review the scaling that was found to work well in the nanosecond regime pulsewidths for many test conditions. We also review the data that indicates this same scaling process does not apply at femtosecond pulsewidths. This result indicates that there is no single scaling process than can universally applied making the development of a single standard for the measurement of optic survivability complicated. We summarize the results of this investigation with a particular goal of making recommendations to those involved in the periodic review of ISO 21254.

KEYWORDS: Defect distribution; ISO 21254; threshold behavior

10447-68, SESSION PS2

Superficial modification of a TI-6AL-4V alloy by laser peening

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SPEAKER BIOGRAPHY: Not Available

ABSTRACT TEXT: This research work was focused on the laser peening surface process in a metallic Ti-6Al-4V biomaterial. The Ti-6Al-4V samples were surface treated at different laser conditions varying parameters such as pulse density and wave length. Laser peening induced effects were evaluated by synchrotron radiation X-ray diffraction (SR-XRD) to determine the residual stress state; scanning electron microscopy (SEM) to assess microstructural changes and thermoelectric testing (TEP) to sense the subtle material variations such as local texture, increased dislocation density, hardening and residual stresses degree.The TEP measurements demonstrate that the non-contact technique is very sensitive to the compressive residual stresses with increasing the severity of the laser treatment parameters , while the TEP contact results are closely related to grain size, cracks, anisotropy, and work hardening.

KEYWORDS: Laser peening; Ti6Al4V; Residual stresses ; Biomaterial

10447-69, SESSION PS2

MELBA: a fully customizable laser for damage experiments

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SPEAKER BIOGRAPHY: Matthieu studied applied physics at the University Paris VI – Pierre et Marie CURIE in France where he graduated with a Bachelor's degree in 2012. After a year of ERASMUS exchange at the University of Manchester he continued his Master's studies in Fusion Sciences at the University Paris VI. In 2014 he defended his Master's thesis on the investigation of laser photo-detachment as a tool to measure the negative ion density in a highly electronegative plasma, aimed to be used for space propulsion;In October 2014 Matthieu joined the LA^{3}NET project in partnership with the CERN Resonance ionization Laser Ion Source (RILIS) team at ISOLDE, the radioactive ion beam facility of CERN. He has been involved in the development of narrow line-width lasers for high-resolution RILIS applications. In Febuary 2016 Matthieu started his PhD at the CEA-CESTA. The aim of his thesis is to study the growth of laser-induced damage Under inertial confinement fusion laser conditions.

ABSTRACT TEXT: A millimetric aperture Nd:glass laser system named MELBA has been designed and constructed at the CEA-CESTA. Its purpose is to investigate the numerous physical phenomena relevant to the study of laser induced damage for the optics of the Mégajoule Laser (LMJ). The beam shape can be user-defined within a spot of diameter up to 7 mm. The maximal average fluence at the tested optical component can be adjusted to values up to 14 J/cm2 at 351 nm at a repetition rate of 1 shot per minute. The pulse shape can also be user-defined within the 1-10 ns range. Finally, the beam is also phase modulated at 2 GHz with a modulation depth that can be set between 1 an 7 rad. All the laser parameters are measured by high precision diagnostics. This facility is currently used to investigate numerous subjects relative to the problematic of laser induced damage. The beam fluence map is matched with the in-situ microscopic observation of the tested sample. The local fluence for each damage site can therefore be measured. Laser damage experiments are followed over a serie of hundred succesive shots. This poster illustrates the capacity of the facility over two experiments: the growth of laser damage sites on fused silica, up to millimetric scales and the effect of the optical component thickness on the beam propagation.

KEYWORDS: large aperture laser; laser-induced damage

10447-70, SESSION PS2

Calibration accuracy of laser calorimetry for common crystal geometries

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SPEAKER BIOGRAPHY: Not Available

ABSTRACT TEXT: The determination of optical absorption according to ISO 11551 is well established in optics industry among other photothermal test methods. Its capability for delivering absolute calibration is the major advantage of the method. But this advantage can be affected by the finite heat conduction of optical materials. The time- and spatial dependent temperature profile in the sample of materials with low heat conductivity necessitates accurate temperature measurement strategies for material-independent and absolutely calibrated measurement results. For thin cylindrical sample shapes the temperature detector position can simply be adopted because of the sample symmetry to deliver properly calibrated measurement results. For thick samples an additional temperature distribution along the heating beam propagation direction must be considered. This distribution is dependent on the sample properties, since radiation can be absorbed by front- or backside coatings or the bulk material. The current version of ISO 11551 does not provide a sophisticated solution for this problem, because the heating scheme of a sample is in general not known. Therefore, a reliable calibration procedure can only be applied to samples of well-known absorption properties of surfaces and bulk material. Utilizing such kind of specifically prepared reference samples in combination with FEA calculations, a general measurement and data evaluation concept on the basis of laser calorimetry is presented, that allows deriving absolutely calibrated absorption measurement results for crystal sample geometries.

KEYWORDS: laser calorimetry; ISO 11551; absorption; metrology; laser crystals; frequency conversion; optical loss; thin films

10447-71, SESSION PS2

Quantitative absorption data from thermally induced wavefront distortion on UV, Vis, and NIR optics

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SPEAKER BIOGRAPHY: Not Available

ABSTRACT TEXT: Absorption-induced thermal effects within optical elements represent a major challenge for many high power laser applications, as the thermal distortion of the transmitted laser beam wavefront can lead to severe deteriorations of the imaging or focusing performance. In re-verse, sensitive monitoring of thermally induced wavefront distortions also establishes a pro-cedure for fast and precise absorption measurement, since the extent of deformation is directly proportional to the absorption loss. In this paper a parallelized photo-thermal absorption measurement system based upon a Hartmann-Shack wavefront sensor with extreme sensitivi-ty is presented, providing quantitative absorptance data of optical materials with sub-ppm resolution. Caused by the temperature dependence of the refractive index as well as thermal expansion, the initially plane wavefront of a probe beam is distorted into a convex or concave lens, depending on sign and magnitude of index change and expansion. Wavefront defor-mations as low as 50pm (rms) can be registered, allowing for a rapid assessment of material quality. Absolute calibration of the absorption data is achieved by comparison with a thermal calculation. The method accomplishes not only to measure absorptances of plane optical ele-ments, but also wavefront deformations and focal shifts in lenses as well as in complex optical systems, such as e.g. F-Theta objectives used in industrial high power laser applications. Along with a description of the technique we present results from absorption measurements on coated and uncoated optics at various laser wavelengths ranging from deep UV to near IR.

KEYWORDS: Not Available

10447-88, SESSION PS2

Giant tuning of infrared plasmonics on layered Graphene-based metal nanotrench

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SPEAKER BIOGRAPHY: Not Available

ABSTRACT TEXT: Graphene has recently emerged as a possible platform for integrated optoelectronics and hybrid photonic devices because of its unique characteristics. The optical properties of graphene can be dynamically controlled by Fermi energies and have been used to alter the plasmonics in noble metal nanostructures. Here, we purpose a substitute solution to conventional metal-based plasmonics by exploiting the deep wavelength confinement and tunability of graphene plasmonics. This hybrid plasmonic system composed of rectangle nanotrench gold film covered by graphene dielectric monolayer was theoretically investigated. It is shown that the electromagnetic polaritons in metal grating couple strongly with the plasmonics resonances in graphene thick layer. As a result, the coupling leads to drastically enhanced tuning properties of graphene sheet plasmonics. We found that the plasmonics response in ultra thick multilayer graphene sheets can be unprecedentedly tuned at infrared regime by modifying carrier density. The findings of this work may facilitate the design of optoelectronic devices and metamaterials structures based on hybrid nanostructures especially at IR wavelengths.

KEYWORDS: graphene plasmons; plasmonics; Fermi energy; graphene tunabilities; nanotrench

10447-89, SESSION PS2

Visual defects diffraction in high power lasers: impact on downstream optics prediction

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SPEAKER BIOGRAPHY: Florian Tournemenne graduated last year from the ENSERB engineering school. He is actually a PhD student at "Le commisariat à l'énérgie atomique", Le Barp France. His main interest is the impact of "visual" defects on the propagation of a high power laser beam.

ABSTRACT TEXT: The Laser MégaJoule (LMJ) is a French high power laser that requires thousands of large optical components. For all those optics, scratches, digs and other defects are severely specified. Indeed, diffraction of the laser beam by such defects can lead to dangerous "hot spots" on downstream optics. Our present work models near-field diffraction of simple phase/amplitude objects. With the help of a near-field measurement setup, we make quantitative comparison between simulated and measured near-fields of reference objects (such as circular phase steps for instance). This leads to a better understanding of which parameters are important and how they impact the diffracted field. In this paper, we apply this knowledge to what we call "mitigated" defects. We have a procedure that enables to "mitigate" laser induced damages with the help of a CO_2 laser by digging a conic hole that replace the damage. We demonstrate here which parameters of the hole shape are critical for downstream hot spots formation.

KEYWORDS: visual defects; phase defects; metrology; diffraction; propagation; near field; intermediate field

10447-4, SESSION 2

CW laser damage testing of RAR nano-textured fused silica and YAG

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SPEAKER BIOGRAPHY: Douglas S. Hobbs is active in the design and development of optically functional microstructures for applications ranging from high power lasers to solar cells, imaging sensors, and displays. Doug serves as President of TelAztec, a research and development company he co-founded in 2000 that is currently transitioning into a commercial supplier of nano-textured optics.

ABSTRACT TEXT: Within kW-class laser systems, improvement of the power handling, transmitted beam quality, and long-term reliability of optical interfaces, has been limited by the inconsistent performance, absorption, and low damage resistance of thin-film coatings. For anti-reflection (AR) requirements, nanometer-scale surface relief structures etched into the optic material, can replace coatings to yield a robust, non-scattering, non-absorbing, high laser damage resistant interface. In this study, we compare the surface absorption, optical performance, and continuous-wave (CW) laser damage resistance, of Random AR (RAR) nano-textured fused silica and YAG windows, to laser-optimized thin film AR coated windows. Three cycles of CW damage tests were completed at The Penn State University Electro-Optics Center (PSEOC) using a 1070nm wavelength fiber laser with a maximum 16KW output, where the test protocol was evolved from single point exposures with intensity up to 3MW/cm2, to large area, long duration, scanning beam exposures with intensity up to 15MW/cm2. Ten RAR nano-textured fused silica laser windows survived without damage for all 3 test cycles up to the maximum intensity. Thermal videos recorded for each exposure scan, showed a stable low surface temperature that is consistent with the lack of surface absorption confirmed by prior photo-thermal interference scans. In contrast, the majority of thin-film AR coated windows failed at various and unpredictable levels as low as 2MW/cm2, with some coated sample temperatures operating at over 200C before spiking over 300C at the point of failure. For the third CW test cycle, a set of laser-quality polished, un-doped, single crystal YAG windows were included. The CW damage threshold for the RAR nano-textured YAG windows was found to be more than four times higher than the thin-film AR coated YAG, and surprisingly, three times higher than as-polished YAG windows with no AR treatment.

KEYWORDS: Nano-Textures; Antireflection; AR; Motheye; CW Laser Damage Resistance; high power lasers; Random AR; YAG AR Treatment

10447-5, SESSION 2

Laser damage of optical windows with random antireflective surface structures on both interfaces

Christopher R. Wilson, Matthew G. Potter, The Univ. of North Carolina at Charlotte (United States); **Lynda E. Busse, Jasbinder S. Sanghera,** U.S. Naval Research Lab. (United States); **Ishwar D. Aggarwal,** Sotera Defense Solutions, Inc. (United States); **Menelaos K. Poutous,** The Univ. of North Carolina at Charlotte (United States)

SPEAKER BIOGRAPHY: Christopher Wilson is a Post-Doctoral Fellow of the Optical Structured Surface laboratory in the department of Physics and Optical Science at the University of North Carolina at Charlotte. His main research interests include the fabrication, characterization, and damage testing of random anti-reflective surface structures on high energy laser optics.

ABSTRACT TEXT: High average-power, nanosecond-duration, laser pulses induce damage on uncoated optics, due in part to an enhanced localized field at the exit surface of the components. Similarly, anti-reflection (AR) thin-film coated optics have similar field enhancement regions, due to multiple boundaries, and experience laser induced damage on both entry and exit interfaces. Sub-wavelength anti-reflection randomly structured surfaces (rARSS) have been shown to have a higher laser-induced damage threshold than traditional AR coatings.

Previously published work detailed laser-induced damage on rARSS on a single surface of optical quality, planar, fused silica substrates; optimized for maximum transmission (99.5%) at 1064 nm. This study explores the introduction of rARSS to both sides of the substrate. Laser-induced damage was systematically created and measured at contiguous locations along the substrate, using 1064 nm wavelength, 6-10 ns duration pulses. Laser output was focused to increase incident intensity at the initial interface. Incident fluence was directly controlled by Q-switching the laser to create fluence values at, and above, damage thresholds for both entry and exit sides.

It was determined that double-sided rARSS substrates have a higher damage threshold than thin-film AR coatings, while they have a lower damage threshold than entrance-only and exit-only sided rARSS (previous study), as well as, lower damage threshold than plain, optical quality, uncoated, fused silica. Damage on the exit-side of the substrate was ballistic in nature, showing surface cracks and outward-oriented debris craters. Contrastingly, damage on the entry-side of the substrate was thermally-induced local-densification of random structures with a latent footprint.

KEYWORDS: Laser Damage; Anti-Reflective Surface Structures; Laser Damage Threshold; Fused Silica; Anti Reflection; Q-Switch; High Power; rARSS

10447-6, SESSION 2

Three-dimensional profile of laser-induced surface damage pit of fused silica and its evolution during wet chemical etching

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SPEAKER BIOGRAPHY: I am currently a research assistant in the Research Center of Laser Fusion. I earned my B.S. from the University of Science and Technology of China (USTC) in 2010 and received my Ph.D. in Solid Mechanics from USTC in 2015. My research interest is focused on the science and technology improving the surface quality, as well as enhancing the laser damage resistance, of fused silica.

ABSTRACT TEXT: Large-scale high power/energy laser facility is a basis for the research of inertial confinement fusion. In the facility, fused silica plays an irreplaceable role but simultaneously vulnerable during the routine operation of the facility. When subjected into extremely high-power pulse ultraviolet laser irradiation, fused silica likely gets surface damage pit. The damage pit makes fused silica more vulnerable and much dangerous to subsequent laser shot. To mitigate the laser-induced surface damage pit, one can give a hydrofluoric-acid-based wet chemical etching or a carbon dioxide laser treatment. In respect to laser treatment, the etching is more efficient to treat large-sized damage pit, changes little on the size of the pit, and has no residual stress after treating. But in this time, the three-dimensional (3D) profile of laser damage pit and how it evolves during wet chemical etching are still not clear. Aiming to address this issue, in this work, 3D surface profile of damage pit is measured and its evolution during etching is experimentally traced. It is seen that the surface damage pit will be passivated during etching and this is promising to enhance the laser damage resistance of fused silica. In the meantime, the 3D model of the damage pit is numerically built and finite difference time domain (FDTD) method is developed to simulate its evolution along with the etching. It shows that the result of simulation agrees well with that of experimental test, indicating the FDTD method is valid to reveal the evolving mechanism of surface damage pit during wet chemical etching.

KEYWORDS: Fused silica; laser-induced damage; 3D profile; wet chemical etching; finite-difference time-domain simulation

10447-7, SESSION 2

Growth of laser-induced damage on the exit surface of fused silica optics with a millimetric laser beam

Matthieu Veinhard, Commissariat à l'Énergie Atomique (France) and Institut Fresnel (France); **Odile Bonville, Roger Courchinoux, Romain Parreault, Laurent Lamaignère,** Commissariat à l'Énergie Atomique (France); **Jean-Yves Natoli,** Institut Fresnel (France)

SPEAKER BIOGRAPHY: Matthieu studied applied physics at the University Paris VI – Pierre et Marie CURIE in France where he graduated with a Bachelor's degree in 2012. After a year of ERASMUS exchange at the University of Manchester he continued his Master's studies in Fusion Sciences at the University Paris VI. In 2014 he defended his Master's thesis on the investigation of laser photo-detachment as a tool to measure the negative ion density in a highly electronegative plasma, aimed to be used for space propulsion. In October 2014 Matthieu joined the LA^3NET project in partnership with the CERN Resonance ionization Laser Ion Source (RILIS) team at ISOLDE, the radioactive ion beam facility of CERN. He has been involved in the development of narrow line-width lasers for high resolution RILIS applications. In Febuary 2016 Matthieu started his PhD at the CEA-CESTA. The aim of his thesis is to study the growth of laser induced damage Under inertial confinement fusion laser conditions.

ABSTRACT TEXT: Laser induced damage growth is the main phenomenon that prevents high energy laser facilities to work at their peak power output. The growth behaviour of laser initiated damage sites have herein been studied with a millimetric laser beam, in both lateral and longitudinal directions, for pulse durations of 5 and 1.5 ns. It appears that the previously

reported exponential behaviour (for pulse durations above 2 ns) and linear behaviour (for pulse durations below 2 ns) are correct for damage sizes within micrometric scales. However, once the damage reaches millimetric scales, it has been observed that the growth saturates for a few shots until the expansion of radial cracks. The use of fractal analysis on the images of the damage longitudinal structure has shown that these shifts in growth behaviour seems to be correlated with changes in the damage morphology. This analysis has also shown that the damage morphology seems to be laser pulse duration-dependant.

KEYWORDS: Laser damage growth; longitudinal observation; Fractal analysis

10447-8, SESSION 2

Damage performance under 351nm, nanosecond pulses of magnetorheological finishing-polished fused-silica samples using different polishing compounds and postprocessing methods

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SPEAKER BIOGRAPHY: Not Available

ABSTRACT TEXT: The laser-induced damage threshold (LIDT) in the nanosecond (ns) pulse duration regime is limited by the presence of absorbing defects. However, the potency and density of damage-initiating defects is a function of both the polishing process and subsequent cleaning. Chemical processing and laser conditioning are two methods that have been shown to improve the damage performance of materials. Chemical processing etches the defect-rich layer near the surface. On the other hand, laser conditioning is localized, non-catastrophic modification of the absorbing defects to a state of reduced absorption that is stable under further irradiation.

Magnetorheological finishing (MRF) employs a specialized polishing slurry, where the removal function is generated by the interaction of a magnetic field with an iron-based magnetorheological fluid containing additional abrasive particles. Because the polishing tool is fluid-based, it conforms to the shape of the surface being polished and provides a deterministic approach to improve both part shape and surface quality. The resulting surface quality and material removal rate is dependent on the fluid properties (composition and viscosity) as well as other process parameters. It is recognized that MRF produces surfaces with minimum subsurface damage. However, contaminants on the surface after polishing and conventional cleaning reuce the LIDT.

The aim of this work is to explore pathways to optimize the damage performance of MRF-polished fused silica. We first examined the damage threshold of fused-silica samples processed with various MRF polishing compounds, depending on the type of abrasive material and the post-polishing surface roughness. The capability for effective removal of absorbing species by laser conditioning using a pulse-shaping system with 0.1-ns resolution was also explored using pre-exposure with nanosecond Gaussian pulses and truncated Gaussian pulses at 351 nm. We postulate that temporally shaping the “conditioning” pulses allows the incident absorbed energy to be more confined to the defect area rather than allowing it to expand into the surrounding host material. This confinement of the incident energy can increase the effectiveness of the laser-conditioning process. Chemical etching of the surface was also conducted and the ensuing damage threshold correlated to the etching protocol.

The results presented in this work provide insight into the above-mentioned processes and mechanism and highlight the potential and limitations of each approach.

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KEYWORDS: laser damage; fused silica; magnetorheological finishing; laser conditioning; LIDT

10447-9, SESSION 3

Virtual and real materials for interference coatings *(Keynote Presentation)*

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SPEAKER BIOGRAPHY: Education/Studies: 04/1996 to 01/2001 Study of physics at the Friedich Schiller University of Jena, 01/2001 Graduated in Physics. Since 04/2001 Laserzentrum Hannover e.V. Scientific employee in the department of laser components; 02/2012 Dissertation: Destruction behavior and applications of oxidic mixtures in the ultra-short pulse range; Since 2012 Head of the group advanced photonic materials

ABSTRACT TEXT: Virtual materials gain in importance for the analyses of coating processes. This novel development mirrors the trend to the application of computerization of complex physical problems. These materials are produced in virtual coaters which includes the properties of real coating machines. On the basis of a multiple scale model the structural, electronic and optical properties are discussed for different virtual oxides and the results are linked to measured values from the real coating machines.

KEYWORDS: Virtual material; virtual coater ; multiple scale modelling ; coating simulation

10447-10, SESSION 3

Laser-induced modifications in fused silica up to damage initiation caused by multiple UV nanosecond pulses

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SPEAKER BIOGRAPHY: Alexandre Beaudier obtained his MSc degree in Optics and Signal Processing in 2014 at the University of Aix-Marseille, France, and his engineering degree at the Ecole Centrale Marseille, France in 2014. He is currently 3rd year PhD student in the Light Matter Interaction group at the Fresnel Institute in Marseille France.

ABSTRACT TEXT: Fatigue effects in fused silica have been largely studied in the past years, as this phenomenon is directly linked to the lifetime of high power photonic materials. Indeed, in the UV regime, we observe a decrease of the LIDT when the number of laser shots increases and this has been attributed to laser-induced material modifications. Under 266 nm laser irradiation, with nanosecond pulses of constant fluence, we observed that the photoluminescence is modified until damage occurs. High-OH fused silicas like Suprasil®, "UV fused silica" or Herasil® show NBOHC (Non-Bridging Oxygen Hole Center) luminescence at 664 nm (1.87 eV) whereas low-OH fused silica like Infrasil shows ODC (Oxygen-Deficient Center) luminescence at 404 nm (3.07 eV). We found that the laser-induced density of NBOHCs increased until bulk damage occurred while the ODC's density decreased. We propose a new representation of the experimental S-on-1 breakdown data which allows predicting the occurrence of material breakdown consuming fewer sample surface and saving time compared to the classic representation Nd (Number of shots before damage) versus F (Fluence). The link between LIF and the modifications leading to breakdown is however modified if a break is used during the irradiation. We also study the evolution of linear index modifications thanks to in situ phase imaging techniques and transmission or absorption evolution versus laser shots until damage. Surface and bulk damage morphology are also shortly described.

KEYWORDS: Laser damage; S-on-1 experiments; nanosecond UV laser; laser-induced defects; laser-induced fluorescence; phase imaging techniques

10447-11, SESSION 3

Enhancement of light intensity related to distribution of defects in the final optics assembly

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SPEAKER BIOGRAPHY: Not Available

ABSTRACT TEXT: Laser induced damage in the final optics assembly is one of the bottleneck problems in high power laser systems for the inertial confinement fusion. Defects on the optical elements can cause optical intensity intensification and therefore damage the optical elements in the downstream. However, only single defect is considered for most cases. In this paper, physical models are established to study enhancement of light intensity related to distribution of defects in the final optics assembly. Results show that, when the distance of two localized defects reduces to a certain distance, there will be a stronger light intensity intensification duo to the interference effect. What's more , it will be much more serious when the nonlinear effect is taken into consideration. Meanwhile, the interaction of two kinds of different defects are also studied, i.e., the periodic defect and the localized defect. The optical field will be enhanced to a certain extent at the overlapped area. Thus, we can see that single defect may not cause optical damage. But when there are more than one defect with a certain distribution, light field may be further enhanced ,thus damaging the optical element. .As a conclusion, the distribution of defects also needs strict constraints. The results could give some references to the mitigation of damage caused by defects in the final optics assembly.

KEYWORDS: optical intensity intensification; laser damage; defect distribution; final optics assembly

10447-12, SESSION 3

Simulation of internal stress waves generated by laser-induced damage in multilayer dielectric gratings

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SPEAKER BIOGRAPHY: Not Available

ABSTRACT TEXT: Multilayer dielectric (MLD) gratings for pulse compression of ultrafast lasers system are a critical component for achieving high peak intensities. MLD structures are composed of alternating high and low optical refractive index layers to generate the required reflection efficiency with each layer having a predefined thickness. The manufacture of MLD gratings requires a uniform photoresist coating and very precise generation of the holographic pattern that defines the grating parameters, including pillar height and shape, duty cycle, and sole width. As a result of the intensive fabrication processing, which involves etching of organic materials, the damage thresholds of current generation grating structures remain well below values anticipated by the corresponding damage threshold of the underlying MLD structure. While improving the damage-initiation threshold of grating structures remains an active area of research, the mechanical properties of the gratings might be an equally critical issue in determining the extent of modified material following laser-induced damage. Laser-energy deposition on a surface can cause heating, material ejection from the surface, and propagation of a shock wave. The ensuing material modifications can affect the response of the structure to subsequent laser irradiation (such as the damage-growth properties).

In this work we investigate stress-wave propagation within grating structures generated by short time duration pressure pulses, simulating the generation of stress waves by a laser-induced surface damage event. Finite element simulations were used to investigate the potential of these internal stress waves to cause additional damage within MLD grating structures. Stress intensification occurs at surfaces, interfaces, or geometric discontinuities, leading to cohesive or adhesive potential failure. High tensile stresses produced within the grating pillars and at layer interfaces were identified. Dynamic stresses in the pillars were highest and therefore may be most likely to accelerate crack propagation in the pillars. High stresses at layer interfaces were identified for their potential to cause delamination between dielectric layers. Because the waves spread as they propagate, the highest interface stresses usually occur at the top interface.

Elastic wave simulations were obtained for structures of different materials, layer thicknesses, and pillar duty cycles. The thickness of the top layer(s) strongly affects the amplitudes of the reflected waves and the peak stresses due to constructive interference. The effect of the location and time duration of the applied pressure pulse on the stress wave fields and peak pillar and interface stresses were also investigated. Our analysis may be adapted to account for either bulk or nanoindentation-based layer mechanical properties (such as the elastic modulus, and therefore acoustic impedance) of the individual layers. Contributions by tensile stresses (leading to fracture) or shear stresses (leading to plastic or viscous deformation) will also be compared.

This material is based upon work supported by the Department of Energy National Nuclear Security Administration under Award Number DE-NA0001944, the University of Rochester, and the New York State Energy Research and Development Authority. The support of DOE does not constitute an endorsement by DOE of the views expressed in this article.

KEYWORDS: laser-induced damage; multilayer dielectric gratings; internal stress waves

10447-13, SESSION 4

Material fatigue damage under large number of laser or FELpulses

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SPEAKER BIOGRAPHY: Not Available

ABSTRACT TEXT: The high-repetition-rate hard X-ray FELs Euro XFEL and LCLS-II will enable a broad range of high-resolution, coherent 'pump probe' experiments over a large photon energy range. On top of the extreme high peak power of the FEL, the average power of this high-repetition-rate FEL reaches several hundred watts. This combination of extreme high peak power and high average power becomes very challenging for the X-ray optics to preserve the FEL beam quality, for the safe operation of the components for the X-ray beam transportation, and also for the integration of the experimental sample.

With the LCLS-II high-repetition-rate FEL, the number of pulses on the optics over ten years reaches 20 trillion. The thermal fatigue, damage and lifetime of the optics, beam transport components under such large number of FEL pulses are important issues that should be addressed. In this paper, we propose combining theoretical modeling, experimental tests with laser beams and the LCLS-I FEL beam to develop a thermal fatigue model to predict the lifetime of the X-ray optics, and beam transport components. The materials to be investigated are silicon, Boron Carbide (B4C), copper, and diamond which are widely used for X-ray optics, and photon beam stopper. Previous studies indicate that the material damage threshold depends on many parameters, including; the material, photon beam energy and intensity, angle of grazing incidence, the number of pulses, and the beam pulse duration. There are significant publications on ablation threshold with a limited number of photon beam pulses. However, for the optics, the definition of the damage should be the significant (for instance, 50%) reduction of reflectivity, which is premonitory of damage, and much more stringent than the ablation threshold.

We propose to use an infrared laser beam model for the majority of the damage threshold tests. The parameters of the laser beam will be chosen such that the laser beam power absorption mechanism is comparable with the X-ray FEL beam.

The outcome of this project will be a fatigue damage model predicting the lifetime of the key components used for high-repetition-rate hard X-ray FELs and also sample material under large number of laser pulses. This will be a major tool useful for SLAC, LCLS but also for the whole FEL community and potentially to semiconductor industry.

KEYWORDS: X-ray optics; Large number of pulse; Thermal fatigue; Damage; Reduction of reflectivity; Laser and/or FEL; Silicon

10447-14, SESSION 4

Wavelength dependence of the mid-IR ablation threshold of ZnSe

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SPEAKER BIOGRAPHY: Drake Austin is a Ph.D. student at the Femtosecond Solid Dynamics Laboratory (Chowdhury group), Department of Physics, The Ohio State University. His research topic includes high-intensity ultrafast laser interactions with non-metal crystals, laser-induced periodic surface structure formation, and mid-IR laser damage of materials.

ABSTRACT TEXT: Introduction: The fundamental interactions between ultrashort laser pulses and non-metal crystals have been studied for more than two decades, but such studies have been largely limited to visible and near-infrared wavelengths. With the recent availability of femtosecond lasers at mid-infrared wavelengths as well as the discovery of high-order harmonics in non-metal crystals [1], there is an increasing need for understanding such interactions in the mid-infrared regime. With lower photon energies and higher ponderomotive energies in this regime, the interaction may differ significantly from the near-infrared regime. In this work, we measured the ablation threshold of ZnSe across multiple mid-infrared wavelengths and compared it to various theoretical models, identifying key physical mechanisms in the process.

Experimental methods: The 1 cm x 1 cm sample was a <100> single-crystal ZnSe wafer, oriented with the <110> direction 45 degrees relative to the laser polarization. Experiments were carried out at wavelengths of 0.78, 2.0, 2.4, 3.0, and 3.6 um using four separate laser systems including three optical parametric amplifiers. Single 90 fs pulses of both s- and p-polarized light were focused onto the sample at a 45 degree angle of incidence. A collection of at least ten laser shots were taken at each energy selected using waveplate-polarizer combination. Damage sites were examined under a scanning electron microscope, an interferometric depth profiler, and an atomic force microscope to determine whether ablation had occurred, defined as the detectable removal of material. From these images, the ablation threshold was determined by the intensity at which ablation ceased.

Results: The measured ablation threshold was observed to increase with increasing wavelength for both s- and p-polarized light, with s-polarized light exhibiting a greater threshold. In order to explain the experimental data, the Keldysh model of photoionization [2] was used to calculate the conduction band electron density by the end of the pulse, with bond-breaking occuring at ~10% ionization [3]. With the standard Keldysh model, the predicted trend does not agree with the experimental data. Contributions from multiple valence bands were included as a modification to this model. In addition, the greater ponderomotive energy at longer wavelengths was considered by using a model of free-carrier absorption by Vinogradov [4]. The resulting trend is a marked improvement over the standard Keldysh approach, agreeing well with the experimental data.

Acknowledgements: This material is based upon work supported by the Air Force Office of Scientific Research (AFOSR), USA under award no. FA9550-12-1-0454, FA9550-12-1-0047, and FA9550-16-1-0069. The DiMauro group acknowledges support from MIR MURI award FA9550-16-1-0013. C. I. Blaga acknowledges support from AFOSR YIP, award FA9550-15-1-0203.

References:

[1] S. Ghimire et. al. Nat. Phys., Vol. 7, No. 2, 138 (2011)

[2] L.V. Keldysh. Sov. Phys. JETP, Vol. 20, No. 5, 1307 (1965)

[3] P. Stampfli et. al. Phys. Rev. B, 42, 7163 (1990)

[4] An. V. Vinogradov. Sov. Phys. JETP, Vol. 41, No. 3, 540 (1975)

KEYWORDS: laser ablation; mid-infrared; femtosecond; photoionization; semiconductor; crystal band structure; fundamental mechanisms of laser damage

10447-15, SESSION 4

The transient dynamics of femtosecond laser-induced ripples on fused silica

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SPEAKER BIOGRAPHY: Not Available

ABSTRACT TEXT: Femtosecond laser with ultra-short pulse duration (1 fs=10-15s) and ultra-high peak power exhibits important applications in the field of laser micro-and nanofabrications. As important as it is, the femtosecond laser induced periodic ripples structures can find potential applications in nanostructured devices such as nanosensors, light-modulators and surfaced functional coatings. The energy transfer processes for femtosecond laser induced ripples occur from photon to electron, then from electron to phonon for a wide range of materials, in which the electron excitation dynamics can play an important role in affecting the nonlinear photoionization, energy transfer and material damage. In this paper, we explore the transient dynamics mechanism of laser interferencing with surface plasmon polaritons(SPPs) for explaining the formation of the femtosecond laser induced periodic nano-ripples on fused silica. The non-linear ionization for supporting SPPs is taken into account for analysis of the ripples dynamics. The electron dynamics model is proposed to descripe the ripples formation and for adjusting the ripples period via tuning femtosecond laser excitation. The relationship bewteen the ripple periods and femtosecond laser pulses parameters are well predicted based on the proposed dynamics model. This study provide theoretical basis for the fundamental understanding of the transient formation mechanism of femtosecond laser induced periodic nano-ripples and precisely controlling the ripples periods.

KEYWORDS: Femtosecond laser; Ripples; Laser parameters; Surface plasmon polaritons

10447-16, SESSION 4

First principles simulation of the dynamics of transient warm dense matter during the formation of ultrashort laser pulse induced damage using the particle-in-cell method

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SPEAKER BIOGRAPHY: Not Available

ABSTRACT TEXT: Fundamental treatments of laser damage are challenging in part due to the need to resolve dynamics spanning over six orders of magnitude in time from the femtosecond to the nanosecond scale and over a significant spatial extent, typically many microns. A particularly vexing problem is the presence of the warm dense matter (WDM) state in the region of eventual damage. WDM is a state between a solid and ideal plasma, not amenable to many of the approximations often employed. The significance of WDM is very broad with research in this area leading to a better understanding of its behavior in laser ablation, planetary formation, and stellar evolution. Due to the novelty of the phase space in which it lies, it is not well described by standard liquid and solid equations of state or pair potentials, especially since the ions and electrons that comprise WDM are generally not in equilibrium. Moreover, the standard molecular dynamics approach to modeling the mechanics of WDM is restricted in size due to computational constraints. We have developed a simulation approach based on the particle-in-cell (PIC) method capable of modeling the formation of warm dense matter on a mesoscopic scale while utilizing two temperature interionic potentials [1]. Traditional 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 is a hybrid of PIC and molecular dynamics in that it implements a PIC pair potential model (PPPM) for PIC codes allowing ab initio treatment of an experimentally realizable target represented by a large system of particles coupled via a temperature and density dependent inter-particle force. Implementing the PPPM formalism with the PIC code LSP [2], we demonstrate the accuracy of our simulation method by showing that it produces crater morphologies in quantitative agreement with precision experiments without the use of tunable parameters and then show the dynamics of warm dense matter formation produced by an ultrashort laser pulse.

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 the formation of WDM we similarly simulate energy deposition via an ultrashort laser pulse into an aluminum film and model the ensuing ion motion. The simulation dynamics are modeled by two sequential stages: treating the femtosecond-laser interaction using PIC and the nanosecond-target evolution using the PPPM, the latter of which simultaneously models electron diffusion and electron-ion relaxation via the two temperature model (TTM) and models the dynamics of the ions via an appropriate pair potential. The copper pair potential was derived for solid density and near room temperature dynamics while that for aluminum was derived from finite temperature density functional theory. The coefficients used for the TTM are density and temperature dependent and were calculated for the modeling of WDM. For the laser-target interaction, 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.

This material is based upon work supported by the Air Force Office of Scientific Research under award number FA9550-16-1-0069 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.

[2] D. R. Welch, D. V. Rose, M. E. Cuneo, R. B. Campbell, and T. A. Mehlhorn, “Integrated simulation of the generation and transport of proton beams from laser-target interaction,” Phys. Plasmas, vol. 13, no. 6, 2006.

KEYWORDS: laser damage; warm dense matter; particle in cell; ultrashort pulse; simulation; density functional theory

10447-18, SESSION 5

Attosecond x-rays generated with intense, few-cycle MIR lasers

Zenghu Chang, CREOL, The College of Optics and Photonics, Univ. of Central Florida (United States)

SPEAKER BIOGRAPHY: Not Available

ABSTRACT TEXT: No Abstract Available

KEYWORDS: Not Available

10447-19, SESSION 5

Electron dynamics just below the damage threshold and a dream of petahertz electronics

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SPEAKER BIOGRAPHY: Aug. 2016–present: Staff researcher at the Max Planck Institute of Quantum Optics (Garching, Germany). Apr. 2014–Aug. 2016: Postdoctoral researcher at the Center for Nano-Optics (CeNO), Department of Physics and Astronomy, Georgia State University (Atlanta, U.S.A.). Mar. 2011–May 2014: Academic staff member ("Akademischer Rat auf Zeit") at the LMU Munich. Nov. 2006–present: Scientific member and project leader of the Munich Excellence Cluster for Advanced Photonics (MAP, http://www.munich-photonics.de). Feb. 2005–Aug. 2014: Project leader in the Laboratory for Attosecond Physics at the Max Planck Institute of Quantum Optics (Garching, Germany). Oct. 2004–Feb. 2011: Research assistant at the LMU Munich. Jul. 2003–Oct. 2004: Postdoctoral researcher at the TU Wien (Technische Universität Wien, also known as Vienna University of Technology). May 2000–Jul. 2003: Researcher in the Institute of Photonics, TU Wien (Austria).

ABSTRACT TEXT: The ultimate physical speed limits of metrology and signal processing are defined by how fast the electric or optical properties of materials can be manipulated. Direct time-resolved access to the underlying phenomena in bulk systems and insight into their interaction with electromagnetic radiation on extremely short timescales are the keys to clarifying and, possibly, pushing these limits. In this context, nonlinear processes induced by intense few-cycle laser pulses are of particular importance. This presentation reviews our recent theoretical work on exploring strong-field-driven electron dynamics in solids.

In one of the projects, we studied the interplay between intraband electron motion and interband transitions in a direct bandgap semiconductor in the case where the photon energy is close to the bandgap. In our simulations, we observed a new nonlinear resonance that forms in the regime where a laser pulse is sufficiently strong to make charge carriers traverse a significant part of the Brillouin zone [1].

In another project, we focused on the optical Faraday effect, where a circularly polarized optical pulse induces transient chirality in an achiral transparent dielectric. This effect is attractive for time-resolved measurements because it is enabled by non-instantaneity of the nonlinear response and also because it represents relaxation of time-reversal symmetry by all-optical means. According to our numerical modeling, intense few-cycle pulses not only make the optical Faraday effect observable with samples as thin as a few micrometers, but they also present a spectroscopic tool capable of studying chiral dynamics with an attosecond temporal resolution [2]. These dynamics include a nonperturbative transfer of angular momentum between light and matter.

References

[1] M. S. Wismer, S. Yu. Kruchinin, M. Ciappina, M. I. Stockman, V. S. Yakovlev. Strong-field resonant dynamics in semiconductors. Phys. Rev. Lett. 116, 197401 (2016).

[2] M. S. Wismer, M. I. Stockman, V. S. Yakovlev. Ultrafast optical Faraday effect in transparent solids. arXiv:1612.08433 [cond-mat.other].

KEYWORDS: Strong-field phenomena; Rabi flopping; optical Faraday effect; nonperturbative

10447-20, SESSION 5

Self-consistent modeling of laser energy deposition in photo-ionized dielectronics

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SPEAKER BIOGRAPHY: Arnaud Couairon studied at Ecole Normale Supérieure in Paris and obtained his Ph.D. at Ecole Polytechnique, Palaiseau in 1997 He is currently a research director at the CNRS and associate professor at Ecole polytechnique. His main research interests are laser-matter interactions induced by ultrashort laser pulse propagation in gases and solid dielectrics. He developed a virtual numerical laboratory for simulating the nonlinear propagation and filamentation of ultrashort laser pulses in transparent media. He is author of 150 peer-reviewed publications on these topics.

ABSTRACT TEXT: We will present a self-consistent model for ultrashort laser pulse propagation and laser energy deposition in dielectrics based on the coupling of a unidirectional envelope propagation equation with rate equations describing the dynamics of the free carrier density and average electron energy. Laser-matter interaction is described by a quantum-kinetic model for the dielectric response, accounting for photoionization via a new nonperturbative theory obeying selection rules as well as for electron-phonon and electron-impurity scattering via Boltzmann collisional integrals expressed in Kubo-Greenwood terms. Numerical simulation results providing excellent agreement with measured transmission data in fused silica will be discussed.

KEYWORDS: Not Available

10447-21, SESSION 5

Revealing the relative contribution of photo- and impact-ionization in ultrashort pulse laser-induced damage in solid dielectrics

Peter Jürgens, Anton Husakou, Mikhail Ivanov, Marc J. J. Vrakking, Alexandre Mermillod-Blondin, Max-Born-Institut für Nichtlineare Optik und Kurzzeitspektroskopie (Germany)

SPEAKER BIOGRAPHY: Studies in physics at University of Hannover, Masters Degree in 2016 under the supervision of Prof. Dr. Ristau and Dr. Jupe' on theoretical and experimental investigations of nonlinear losses and damage mechanisms in transparent materials. Since October 2016 PhD student at Max-Born-Institute for nonlinear optics and short time spectroscopy in Berlin under supervision of Prof. Dr. Vrakking and Dr. Mermillod-Blondin.

ABSTRACT TEXT: The main primary process responsible for fs laser-induced damage of optical components is dielectric breakdown. Dielectric breakdown corresponds to the sudden onset of laser energy absorption by bound electrons. In the ultrashort pulse regime, dielectric breakdown occurs when the laser electric field is sufficient to promote electrons from the valence to the conduction band through photoionization (PI).

The quasi-free electrons generated by PI may be accelerated by the trailing edge of the incident laser pulse and produce more quasi-free electrons by impact-ionization. The conjugated contributions of PI and impact-ionization result in the formation of an electron-hole plasma with consequences on the material's structural properties which may be irreversible.

Despite extensive research in the past decades, the identification of the relative contribution of these two ionization channels, especially at ultrafast time scales, is still an open challenge.

We will present a strategy to gain better insights into the plasma formation process, which is based on the detection of an optical signal carrying solely the signature of the PI dynamics. PI produces a characteristic stepwise increase of the plasma density at every half-cycle of the excitation field. This sudden variation of the carrier density results in the emission of a light burst containing harmonics of the incident laser field. Detection of time-resolved spectra in a pump-probe arrangement maps the sub-cycle ionization dynamics into the frequency domain.

In this presentation, a numerical procedure to retrieve the plasma density from the spectral information will be proposed. Furthermore, the experimental strategy will be shown and first experimental results, in good agreement with a description based on intra-band high harmonic generation in solids, will be presented.

KEYWORDS: metal resist; nano particle; EUV lithography; sensitization mechanism; reaction mechanism; trade-off relationship; line edge roughness; defect

10447-72, SESSION PS3

Kinetic model of optical damage in transparent crystals under continuous-wave laser irradiation

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SPEAKER BIOGRAPHY: Not Available

ABSTRACT TEXT: High-power continuous-wave (cw) lasers, which average powers are from several watts to kilowatts, are used in many industries, including laser processing, fiber-optic communication, and laser display.

However, laser-induced damage in crystals is still a limiting factor of their application.

LiNbO3 and LiTaO3 are frequently used in second harmonic conversion of cw light from the infrared to the visible regions [1]. Especially, LiNbO3 is widely used and investigated [2]. Optical damage of nonlinear optical crystal is a crucial issue in the high-power laser systems. The damage thresholds are above 300, 10, and 1 GW/cm2 for a 50 fs (laser wavelength λ =400 nm), 7 ps (530 nm), and 40 ns (690 nm) laser pulse, respectively [3,4,5]. On the other hand, the damage or breakdown thresholds for a cw laser remain to be clarified.

Since the 1990s, absorption due to the presence of polarons has been studied in LiNbO3-type crystals [6,7]. We have proposed a light-induced heating by the accumulated polarons because polarons have long decay times [8]. The absorption power density is proportional to the cube of the laser intensity by the use of a simple kinetic model. The light-induced heating becomes important at relatively low intensities of the order of MW/cm2.

In this paper, we investigate the optical damage by the light-induced heating due to polarons and thermal breakdown in LiNbO3-type crystals. In addition to polarons or self-trapped excitons, color centers are created by a radiation. Therefore, we add the population of these excited states in a new model. As a results, it is shown that a creating rate from the self-trapped state to the color center becomes a important parameter on the determination of critical power.

[1] H. Lim, T. Katagai, S. Kurimura, T. Shimizu, K. Noguchi, N. Ohmae, N. Mio, and I. Shoji, Opt. Express 19, 22588 (2011).

[2] L. Arizmendi, phys. stat. sol. (a) 201, 253 (2004).

[3] S. Sasamoto, J. Hirohashi, and S. Ashihara, J. Appl. Phys.105, 083102 (2009).

[4] S. K. Kurtz and J. A. Giordmaine, Phys. Rev. Lett. 22,192 (1969).

[5] T. Kushida, Y. Tanaka, M. Ojima, and Y. Nakazaki, Jpn. J. Appl. Phys. 14, 1097 (1975).

[6] F. Jermann and J. Otten, J. Opt. Soc. Am. B 10, 2085 (1993).

[7] M. Imlau, H. Badorreck, and C. Merschjann, Appl. Phys. Rev. 2, 040606 (2015).

[8] S. Kato, S. Kurimura, H. H. Lim, and N. Mio, Opt. Mater. 40, 10 (2015).

KEYWORDS: EU LiNbO3-type crystals; continuous-wave laser; polarons

10447-73, SESSION PS3

Model for visualizing high-energy laser (HEL) damage

Gail Erten, Raytheon Space and Airborne Systems (United States)

SPEAKER BIOGRAPHY: Dr. Gail Erten has over 25 years of experience in developing modeling and simulation tools for various technology components. She joined Raytheon SAS in 2014 where she is a Senior Engineering Fellow Prior to that she was leading business development and internal R&D at Optical Physics Company. Before that she was co-owner of a small high tech company in Michigan which was acquired in 2005 and is currently part of Qualcomm. She received her PhD in Electrical Engineering from Caltech in 1994

ABSTRACT TEXT: This paper describes and presents results from a model created in MATLAB® to calculate and display the time dependent temperature profile on a target hitspot as it is being engaged by a high energy laser (HEL) beam. The model uses public domain information namely physics equations of heat conduction and phase changes and material properties such as thermal conductivity/diffusivity, latent heat, specific heat, melting and evaporation points as well as user input material type and thickness. The user also provides time varying characteristics of the HEL beam on the hitspot, including beam size and intensity distribution (in Watts per centimeter square). The model calculates the temperature distribution at and around the hitspot and also shows the phase changes of the hitspot with the material first melting and then evaporating. User programmable features (selecting materials and thickness, erosion rates for melting) make the model highly versatile. The objective is to bridge the divide between remaining faithful to theoretical formulations such as the partial differential equations of heat conduction and at the same time serving practical concerns of the model user who needs to rapidly evaluate HEL thermal effects. One possible use of the tool is to assess lethality values of different aimpoints without costly (as well as often dangerous and destructive) experiments.

KEYWORDS: laser damage; laser thermal damage; laser damage visualization; laser thermal damage visualization; high-energy laser

10447-74, SESSION PS3

A practical model of laser induced damage on fused silica: from defect to damage growth

Yi Zheng, Zhichao Liu, Feng Pan, Chengdu Fine Optical Engineering Research Ctr. (China); **Jian Cheng,** Harbin Institute of Technology (China); **Jian Wang, Qiao Xu,** Chengdu Fine Optical Engineering Research Ctr. (China)

SPEAKER BIOGRAPHY: Dr.Yi works in the field of high laser power material for over 10 years. He is familiar with damage mechanism of fused silica

ABSTRACT TEXT: The damage growth on fused silica is a serious problem that greatly threatens the safety of high power laser device. Previous works indicates that rule of fused silica damage growth is affected by many factors, including initial damage size, radiation fluence, wavelength, pulse duration, shot number and so on. A great deal of research has been devoted to reveals the relationship between initial damage and damage growth, and the mechanism of initial damage coupled with defects in fused silica was also widely studied. However, there relationship between defect and damage growth is rare studied. The knowledge of whole process from defect to initial damage, and then to damage growth, is still insufficient. For this reason, we've carried out experiments and developed a statistical model to describe this whole process. By use of this model, the tendency of damage growth and final damage status of a fused silica component could be predicted via nondestructive defect detection. The damage growth model for large aperture components in practical application should only contains a reasonable number of parameters. If setting too many parameters, the whole model will be very complicated and lack of availability for application. Based on this point of view, our study focuses on the growth rule of defect and damage size under different laser irradiation fluence. The experiment was carried out by a Raster-Scan method based on small laser beam. A full-automatic imaging system based on dark field microscopy was built up to accurate measure the size and number of defects and damages. This statistical model is based on numerous experimental data from fused silica component. The results shows that:

1. Irradiation fluence has a important influence on the damage size expansion rate;

2. There exists a linear relationship between the defect area and initial damage area, while the linear fitting parameters are closely related with the irradiation fluence;

3. The damage area increases exponential with the pulse shot, and the growth coefficient is linear with the radiation fluence;

4. Finally, with a given tolerance of damage ratio, it is possible to evaluate the lifetime of the fused silica component from this statistical model.

KEYWORDS: laser induced damage; fused silica; damage growth; dark field imaging

10447-75, SESSION PS3

Single-shot femtosecond mid-infrared laser induced multi-stage damage and ablation of silicon

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SPEAKER BIOGRAPHY: Graduate student/PhD candidate at The Ohio State University in the Department of Physics. Working under Dr. Enam Chowdhury in the Femto-Solid Laboratory

ABSTRACT TEXT: Introduction: Ultrafast mid IR laser interactions have generated great interest in laser field enhancement by plasmon coupling[1], attosecond pulse x-ray generation[2], molecular resonance based detection of pollutants[3] or explosives[4], and high order harmonic generation in bulk crystals[5]. Laser solid interaction in the mid IR regime differs from the UV/vis/near IR due to a shift from multi-photon to tunneling ionization, higher ponderomotive energies, and the initiation of surface wave/plasmon coupling[6][7][8]. These differences may lead to changes in the LID mechanisms, which can be explored experimentally through LID thresholds and morphological studies. Experimental studies of mid IR femtosecond laser damage are almost non-existent[6]. Previous studies by our group did not distinguish between optical breakdown/damage and ablation, such as through observation of the LID depth profile through AFM. In this work, we observed mid-IR femtosecond laser induced damage of silicon occurring in multiple stages, and determined thresholds for each corresponding damage mechanism as a function of wavelength. We then compared these thresholds against various theoretical models.

Experimental Setup: Threshold fluence measurements of single shot LID threshold experiments were performed in air with p-polarized pulses at 31o angle of incidence for Si (100)/<110>. Mid IR pulses from wavelength = 2.7 - 4.5 μm with pulse duration of 200 fs and peak energy of 40 μJ/pulse were obtained from a home built KNbO3/KTA optical parametric amplifier (OPA) pumped by a home built 2 mJ/pulse, 80 fs Ti:Sapphire laser with center wavelength of 780 nm operating at 500 Hz repetition rate. Mid IR pulse duration was obtained using an AGS crystal based mid IR autocorrelator. Mid IR spectra were obtained using an A.P.E. Wavescan USB MIR spectrometer. Wavelengths were varied as 2.75, 3.15, 3.75, and 4.15 um. Pulses are focused using an infinite conjugate, gold coated, 15X/0.28NA HP reflex objective configured for input through the side for maximum energy efficiency. The focal spot was measured for each wavelength and varied between 20 and 25 um FWHM. The fluence was varied between 0.25 and 2 J/cm2 using a mid IR waveplate polarizer combination. The pulse energy of every shot was recorded using a calibrated photodiode.

Results: Curve fits of log(Fluence) vs damage diameter squared plots were used to determine threshold fluences for three different damage regions, which most likely corresponds with melting of underlying Si, removal of native oxide layer, and ablation of Si at the center of damage site. Damage morphology and depth was studied using both SEM and AFM. Experimental LIDT were compared to several theoretical approaches, including those by Gamaly[9] and Keldysh[10]. We found that treating Si as direct vs indirect gap in determining valence to conduction band transitions, and modification of wavelength dependent modified critical density to be crucial in model vs experimental observation comparisons.

Acknowledgement: This work was supported by the Air Force Office of Scientific Research, USA under grant #FA9550-16-1-0069 and MIR MURI Award No. FA9550-16-1-0013.

References:

1. Park et. al. Nature Photonics 5, 677-681 (2011)

2. Tenio Popmintchev et al., Science 336 1287 (2012)

3. A. Schliesser, et al., Opt. Exp. 13, 9029-9038 (2005).

4. Neely et. al., Lasers, Sources, and Related Photonic Devices Technical Digest 2012

5. S. Ghimire, A. D. DiChiara, E. Sistrunk, P. Agostini, L. F. DiMauro, and D. a. Reis, Nat. Phys. 7, 138 (2010).

6. Drake Austin et. al., Proc. SPIE 92370V, Laser-Induced Damage in Optical Materials (2014). doi:10.1117/12.2068205

7. Austin et. al., Opt. Express 23, 19522-19534 (2015)

8. Austin et. al., Journal of Applied Physics 120, 143103 (2016)

9. Gamaly et. al., Physics of Plasmas 9, 949 (2002)

10. L. V. Keldysh, JETP 20, 1307-1314 (1965).

KEYWORDS: Laser induced damage; Mid IR; femtosecond laser; laser ablation; short pulse ; optical parametric amplifier ; Silicon LIDT ; Single-Shot

10447-76, SESSION PS3

Femtosecond pre-breakdown dynamics in dielectric chirped mirror

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SPEAKER BIOGRAPHY: Not Available

ABSTRACT TEXT: The damage of optical materials displays highly deterministic damage performance in the ultrashort pulse regime. Compared with standard stack structure films, CMs have a more complicated structure and electric field distribution, generating a more complex damage mechanism. As far as we know, the damage-related carrier dynamics in CMs have not yet been studied in depth. Most of the studies on CMs have focused on the measurement of laser-induced damage threshold (LIDT). In the present study, the femtosecond pre-breakdown dynamics of SiO2/Nb2O5 chirped mirror induced by the ultrafast laser with the pulse duration of 35 fs, which may help to understand the origin and mechanism of laser damage and to improve the laser damage resistance in dielectric chirped mirror coatings.

In the manuscript, the relative change of the time-resolved reflectance in chirped mirror coating after excitation by femtosecond pulse has been studied by pump-probe spectroscopy. Two different laser-induced reflectivity decrease bands was found in ~780nm and ~795nm, respectively. The carrier dynamics in Nb2O5 layers was interpreted by non-linear process, such as multiphoton ionization, impact ionization, and electronic relaxation. And the change of reflectance decreases with the increase in delay time have been analyzed by three possible mechanisms. The photon absorption of the free electrons in the conduction band is the main explanation of the decrease. The Nb2O5 layers, where layers laser damage occurred firstly, are the most vulnerable parts in chirped mirror. The electronic relaxation time from different bands was measured in the experiment. To explain these relaxation time, a theory including two possible mechanisms was built, that the LIDT of the coatings is affected by the absorption cross-section of the defect state.

ACKNOWLEDGEMENT

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REFERENCES

[1] S. Li Chen, Y. An Zhao, J. Da Shao, et al. Applied Physics Letters 102, 081605 (2013)

KEYWORDS: Not Available

10447-77, SESSION PS3

UV laser damages from the nano- to the femtosecond regime

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SPEAKER BIOGRAPHY: Not Available

ABSTRACT TEXT: Defects in the bulk or coating of optical components can lead to a degradation of their optical performance. Substrate imperfections, particulates, or interface defects can increase scattering losses, absorption, and weaken the mechanical and environmental stability of the optics [1]. In laser damage testing, defects are often observed as the main limitation in the nanosecond regime. Here, high absorption of laser radiation in the defect combined with poor thermal coupling between the defect and the surrounding material lead to a rapid heating of the defect. This results in an evaporation of the material which damages the optical component. The statistical distribution of defects and their individual failure criteria lead to an equally statistically determined laser damage threshold. Moving to shorter pulse durations, however, damage mechanisms have traditionally been observed as deterministic [2]. Theoretical models used to successfully describe damage mechanisms in this pulse regime, have been based on multiphoton and avalanche ionization processes which are determined by the electronic band structure of the irradiated material. Upon reaching a critical electron density in the conduction band via these ionization processes, damage in the material is initiated. Only in recent work [3] the influence of defects on the damage threshold even in the femtosecond regime has been observed, however, only at a single wavelength in the near infrared and for a single pulse duration. In this work, we investigate the impact of defects on the damage threshold at 266 nm for nanosecond to femtosecond pulse durations. At this wavelength, material fatigue induced by the high photon energy and high defect densities, already severely limit the performance of optics in the nanosecond regime. In the femtosecond regime we report for the first time the performance of optical components at these short wavelengths. Third and fourth harmonics radiation of Ti:Sa and Nd:YAG lasers allow a direct comparison of the performance of optical components at femto-, pico- and nanosecond pulse regimes. We combine the raster scanning procedure [4] with In-Situ microscopy and online defect detection, enabling us to identify defects during the measurement and observe their response to radiation. This allows us to establish a direct link between damage and defect and to establish damage relevant defect densities for the different pulse durations.

References

[1] X. Cheng and Z. Wang, "Defect-related properties of optical coatings.," Advanced Optical Technologies, pp. 65-90, 2014.

[2] B. C. Stuart, M. D. Feit, A. M. Rubenchik, B. W. Shore and M. D. Perry, "Laser-Induced Damage in Dielectrics with Nanosecond to Subpicosecond Pulses," Phys. Rev. Lett., pp. 2248-2251, Mar 1995.

[3] L. Gallais, X. Cheng and Z. Wang, "Influence of nodular defects on the laser damage resistance of optical coatings in the femtosecond regime," Optics Letters, pp. 1545-1548, 2014.

[4] M. R. Borden, J. A. Folta, C. J. Stolz, J. R. Taylor, J. E. Wolfe, A. J. Griffin and M. D. Thomas, "Improved method for laser damage testing coated optics," Boulder Damage Symposium XXXVII: Annual Symposium on Optical Materials for High Power Lasers, pp. 59912A-59912A, 2005.

KEYWORDS: Laser Induced Damage; UV; Ultrashort Pulse; Femtosecond; Picosecond; Nanosecond; LIDT

10447-78, SESSION PS3

Beyond the Drude model: the Keldysh-Vinogradov model of ultrafast generation and heating of electron-hole plasma

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SPEAKER BIOGRAPHY: Not Available

ABSTRACT TEXT: Ultrafast laser-induced excitation and heating of electron-hole plasma is the major process of energy deposition in wide-band-gap semiconductors and dielectrics during femtosecond laser-crystal interactions. Those processes include two groups of effects: inter-band electron excitation from a valence to conduction band, and heating of the conduction-band electrons. The inter-band electron transitions can be produced by either the photo-ionization or impact ionization. In a majority of publications, the rate of the photo-ionization is frequently evaluated by the Keldysh formula [1], and ultrafast heating of the conduction-band electrons is simulated with the Drude model. Combination of the Keldysh formula with the Drude model introduces an internal contradiction to the entire model of the ultrafast generation and heating of electron-hole plasma in wide-band-gap crystals. Here we propose to replace the Drude model with the Vinogradov equation [2] and merge it with the multi-band photo-ionization transition model based on the Keldysh formula. Generation of the electron-hole plasma is simulated for ZnSe – a typical wide-band-gap semiconductor. Reported results show that average absorption rate by the conduction electrons predicted by the Drude model differs from the evaluations by the Vinogradov equation by as much as one order of magnitude. Furthermore, the two models predict different energy distributions of the conduction-band electrons: while the Drude model delivers quasi-thermalized distribution, the Vinogradov approach delivers highly non-equilibrium distribution with discrete occupied energy levels. That non-equilibrium energy distribution is qualitatively similar to that delivered by simulations with the Boltzmann equation [3]. We discuss impact of the Keldysh-Vinogradov model on simulations of the ultrafast electron excitations and limitations of applicability of that new model. The reported model supports interpretation and theoretical fitting of the experimental data to be presented at this conference [4].

[1] L.V. Keldysh. Sov. Phys. JETP, Vol. 20, No. 5, 1307 (1965).

[2] An. V. Vinogradov. Sov. Phys. JETP, Vol. 41, No. 3, 540 (1975).

[3] N. Kaiser, B. Rethfeld, et al, Phys. Rev. B (2000).

[4] D. R. Austin, K. R. Kafka, et al, “Wavelength dependence of the mid-IR ablation threshold of ZnSe”, Laser Damage 2017.

KEYWORDS: photoionization; Drude model; Keldysh formula; wide-band-gap crystals; Vinogradov equation

10447-79, SESSION PS4

Structural modifications of hafnia/silica composite coatings deposited by ion assisted coevaporation

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SPEAKER BIOGRAPHY: Not Available

ABSTRACT TEXT: Low absorption, low scatter and high-density HfO2 coatings play an important role in high power laser systems. In order to suppress the crystallization of HfO2 coating fabricated with IAD method, we used double electron-beam coevaporation with ion beam assisting method to fabricate HfO2-SiO2 mixed film from two independent material sources. Crystallization following the different HfO2-SiO2 mixture ratios was investigated. Several prototypes were designed, featuring different HfO2-SiO2 ratios, but with similar physical thickness (530nm). The samples were deposited on fused silica and silicon substrates. X-ray diffraction showed that the degree of crystallization gradually fades away with increasing SiO2 contents. All the prototypes prepared by the IAD method have rather high absorption level compared with Electron Beam (EB) evaporated coatings in this study. In order to control the absorption, thermal annealing in air at progressive temperatures was subsequently performed. It was found that as long as the temperature increase is high enough, the absorption of all samples could decrease to the single digit ppm level as well as the substrate. However, accompanying the increase of annealing temperature, the original amorphous mixed HfO2-SiO2 coating eventually crystallized. Progressively increased SiO2 contents exhibited higher threshold temperatures for crystallization onset. To every HfO2-SiO2 compound coating a proper annealing temperature can be found to balance the absorption and crystallization. Accordingly, it can be expected that HfO2 composites with appropriate SiO2 contents will be able to sustain higher annealing temperatures without crystallization, and likely yielding better optical and mechanical properties for laser damage coatings and advanced coatings application.

KEYWORDS: laser damage; co-evaporation; HfO2-SiO2 mixture coating; crystallization; absorption; annealing

10447-80, SESSION PS4

Few-cycle pulse laser-induced damage of thin films

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SPEAKER BIOGRAPHY: Noah Talisa is a Ph.D. student at the Femtosecond Solid Dynamics Laboratory (Chowdhury group), Department of Physics, The Ohio State University. His research topic includes high-intensity ultrafast laser interactions with non-metal crystals, few-cycle pulse laser-solid interaction dynamics, and laser damage of materials

ABSTRACT TEXT: 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 single-pulse damage in air and vacuum environments on ultra-broadband chirped mirrors, microscopic analysis of damage morphology suggests that several different damage mechanisms occur across a fluence range above the LIDT before ablation is observed [1]: shallow swelling (< 10 nm), tall blistering (~150 nm), and annular blistering where damage is suppressed in the highest intensity region of the laser focal spot. In this work, to better understand the complex mechanisms of multi-layer interaction with FCPs, cross-sectional scanning electron micrographs of chirped mirror damage sites and damage on simpler λ/2 and λ/4 single layer TiO_2 thin films on UVFS substrates are also presented in both single and multi-shot regimes in air and vacuum ambience. With field distributions between the "reflective" (λ/4, R) and the "anti-reflective" (λ/2, AR) layer setup being different, field induced FCP effects become more apparent.

Experimental setup: Few-cycle pulses with nominal central wavelength ~760 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 +/- 1fs) was measured with a home-built dispersionless scanning autocorrelator in situ inside the vacuum chamber. Careful dispersion management using wedge pairs and ultra-low dispersion mirrors is implemented to minimize the pulse duration at the target sample. The laser focus was characterized in situ by image relaying onto a camera for fluence calibration. Test sites were irradiated with single pulses at 45°-P angle of incidence in air or rough vacuum (<1 mbar) ambience. The samples tested were a commercially-available ultra-broadband multilayer chirped mirror (GSM014, Spectra Physics), as well as custom samples of single-layer TiO_2 on fused silica (λ/4 and λ/2 optical thicknesses). Damage morphologies were studied with optical-, atomic force- and scanning electron-microscopy.

Results: The relative roles of the two proposed mechanisms for the annular damage morphology on the chirped mirrors are discussed in light of the cross-sectional SEM analysis. The same analysis is done for the single layer thin film damage sites, and is compared with the multilayer chirped mirror damage morphologies, shedding light on how the number of layers affects the damage. The analysis of multi-pulse damage morphology in air shows that surface scattered wave coupled structures are exhibited on the R-layer, whereas the AR-layer exhibits surface plasmon polariton coupled structures, even though there are no metallic layers.

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.

References:

[1] Kyle R. P. Kafka, Noah Talisa, Gabriel Tempea, Drake R. Austin, Catalin Neacsu, Enam A. Chowdhury; Few-cycle pulse laser-induced damage of thin films in air and vacuum ambience. Proc. SPIE 10014, Laser-Induced Damage in Optical Materials 2016, 100140D (Dec. 6, 2016)

KEYWORDS: thin film; laser induced damage; few cycle pulse; ultrashort; reflective; anti reflective; damage morphology; femtosecond

10447-81, SESSION PS4

High LIDT mirrors for 355nm wavelength based on combined ion beam sputtering and glancing angle deposition technique

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SPEAKER BIOGRAPHY: Giedrius Abromavicius after graduation from Vilnius University has started to work in optical coating company Optida Co Ltd as an engineer, and later as a researcher. After few years he has joined a newly formed Optical Coating Laboratory at Institute of Physics. After more than ten years experience in optical coating development and production environment, he has started PhD studies at Optical Coating Laboratory at National Center of Physical Sciences and Technology, His main research interests are preparation of substrates for high power applications, optical and physical properties of sputtered thin films, research of multilayer systems for use for high power laser pulses for UV

ABSTRACT TEXT: Laser induced damage of optical coatings has been one of the most important research target during many decades Different substrate preparation techniques, coating materials, coating technologies, additional in-situ and ex-situ techiques were used and explored with the aim to increase the resistance of multilayer systems to laser pulses.

In this work, first results are presented while combining ion beam sputtering of the widest bandgap metal oxide materials, their mixtures and further enhancing the structure with glancing angle deposition of SiO2. Different mirror layer design structures are used and their LIDT is explored – „standard“ quarter-wave, E-field optimized and RISED concept design.

KEYWORDS: Laser induced damage; Glancing angle deposition; Ion beam sputtering; Mixtures; RISED design; E-field minimization; 355nm

10447-82, SESSION PS4

A comparison of LIDT behavior of metal-dielectric mirrors in ns and ps pulse regime at 1030nm with regard to the coating technology

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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 and head of coating department 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 in ns and ps pulse length domains 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 prepared several sets of mirrors with multilayer system centered at 1030nm using Ta_2O_5/SiO_2 materials on silver metal layer made at different conditions. Both BK7 and fused silica substrate materials were used for manufacturing of samples. The samples were coated in high-vacuum cryo-pumped chamber by electron-beam deposition process for dielectrics and using resistive heated boat for metal layer; both PVD and ion-assisted-deposition methods were used for metal layer. A comparison of measured LIDT of mirrors in dependence on pulse length, technology of silver metal layer preparation and substrate material was carried out.

KEYWORDS: LIDT; laser mirrors; metal-dielectric mirrors

10447-83, SESSION PS4

Measurement of nonlinear refractive index in optical thin films

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SPEAKER BIOGRAPHY: 22.03.2017-(expected) 21.03.2022 Gottfried Wilhelm Leibniz Universität Hannover; PHD student physics under supervision of Prof. Dr. Detlev Ristau; Since 03/2017 scientific employee at the Laser Zentrum Hannover e.V.; 10/2014-02/2017 Gottfried Wilhelm Leibniz Universität Hannover ; Master of Science physics (Grade 1.1); 10/2011-11/2014 Gottfried Wilhelm Leibniz Universität Hannover; Bachelor of Science physics (Grade 1.1)

ABSTRACT TEXT: The technological evolution of laser sources and laser application is more and more addressed to highest power applications. With respect to the development of the laser sources and beam propagation systems the optical components are exposed to increasingly high power densities. This well known fact led to detailed research of laser damage mechanisms and damage behaviour of dielectric thin films. Much less attention in the research is addressed to the nonlinear changes in dielectric materials which are caused by the Kerr-effect and the plasma generation below the critical density for dielectric damaging. Actually, only a small number of applications have to respect the changes of the index of refraction. Nevertheless, the task gains in importance following state of the art developments of high energy laser systems with few-cycle pulses. The non-linear refractive indices of dielectric thin films are investigated, insufficiently. Therefore, a novel measurement procedure was developed to characterize the nonlinear optical behaviour of dielectric thin films. Based on the z-scan method, an interferometric set-up was engineered and optimized. Utilizing a Mach-Zehnder configuration, the wavefront deformation caused by the optical Kerr-effect is monitored. Fitting this deformation to a theoretical approach basing on a beam propagation model the nonlinear refractive index is obtained. Contrary to the indirect approaches using the self-phase modulation for example, the presented method directly measures the Kerr induced self-focussing. The procedure can be applied to measure the non-linear refractive index of both, the substrate material as well as the deposited dielectric layer on top of the substrate. Different influencing physical properties of the samples are discussed in detail and their effect on the measurement accuracy is analysed.

KEYWORDS: nonlinear optics; thin film measurement; thin films; kerr effect; nonlinear refractive index

10447-84, SESSION PS4

Influence of temperature and environment on the laser damage threshold of ion-beam sputtered anti-reflective coatings at 355nm wavelength

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SPEAKER BIOGRAPHY: Roelene Botha obtained her PhD degree in Applied Physics at the Laboratory for Physics of Interfaces and Thin Films (LPICM) at Ecole Polytechnique, Palaiseau (France) in 2008. After working in various roles in industry, she joined the institute PWO for Production Metrology, Materials and Optics at the NTB in Buchs, Switzerland in November 2014. Since then, she is a technical project manager at the innovation and research center, RhySearch, responsible for the LIDT and CRD measurement systems and the build-up of the RhySearch optical coating lab.

ABSTRACT TEXT: In this investigation the influence of the local environment on the laser damage threshold of anti-reflective coatings is reported. For this purpose, HfO_2/SiO_2 anti-reflective coatings were deposited on fused silica substrates using an ion-beam sputter system. Laser damage threshold measurements were performed at 355 nm at temperatures ranging from room temperature up to 220 °C and under different atmospheres. The aim of the study is to gain a better understanding of the influence the environmental factors have on the laser damage threshold of optical components used for UV-applications and how to improve their long-term stability.

KEYWORDS: laser damage; ion-beam sputtering; AR coating; environmental effects; HfO_2

10447-85, SESSION PS4

Spectroscopy of the absorption in dielectric optical coatings

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SPEAKER BIOGRAPHY: Not Available

ABSTRACT TEXT: Absorption in the dielectric coatings of optical components can lead to thermal effects in addition to the effects in the bulk materials. The absorption depends both on the layer materials as well as on the coatings process. Usually it is characterized by a single absorption value for the whole dielectric stack derived from high-sensitivity absorption measurements.

In the case of HR coatings, one observes a strong wavelength dependence of the absorption signal when tuning the pump laser outside the HR band, caused by the wavelength-dependent penetration depth of the light field into the layer stack. As a result, one has a depth-varying probe of the absorption properties of the coating. In addition, the enhancement effects lead to improved measurement sensitivity.

This paper evaluates the potential of absorption spectroscopy with tunable sources in combination with the simulation of the coating properties to extract additional information about the absorption properties of the layers in the coating stacks.

KEYWORDS: HR coating; absorption spectroscopy; instrumentation; photo-thermal common-path interferometry; dielectric layers

10447-86, SESSION PS4

Mitigation and removal of laser damaged antireflection coatings from laser damaged KDP optics

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SPEAKER BIOGRAPHY: Not Available

ABSTRACT TEXT: We describe an approach for the recycling of laser-damaged large-aperture potassium dihydrogenphosphate (KDP) crystals used in megajoule-class high-power laser systems. The approach consists of micromachining the surface laser damage sites (mitigation), combined with multiple soaks and ultrasonication steps in a coating solvent to remove, synergistically, both the highly adherent machining debris and the laser-damage-affected antireflection coating. We identify features of the laser-damage-affected coating, such as the “solvent-persistent” coating and the “burned-in” coating, that are difficult to remove by conventional approaches without damaging the surface. We also provide a solution to the erosion problem identified in this work when colloidal coatings are processed during ultrasonication. Finally, we provide a proof of principle of the approach by testing the full process that includes laser damage mitigation of DKDP test parts, coat stripping, reapplication of a new antireflective coat, and a laser damage test demonstrating performance up to at least 12 J?cm2 at UV wavelengths, which is well above current requirements. This approach ultimately provides a potential path to a scalable recycling loop for the management of optics in large, high-power laser systems that can reduce cost and extend lifetime of highly valuable and difficult to grow large DKDP crystals.

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KEYWORDS: Not Available

10447-87, SESSION PS4

Testing the limits of the Stoney Equation for assessing stress in thin films from interferometric wavefront deformation measurements

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SPEAKER BIOGRAPHY: Not Available

ABSTRACT TEXT: Thin-film stresses from the optical coating process, both compressive and tensile, cause a risk to the performance and longevity of the coated optics. Large residual stress can lead to cracking or peeling of the thin film stack. Therefore, non-intrusive, full-field measurements of the radius of curvature (R) and of curvature changes in an optics due to stress is essential. Interferometric techniques are widely used to obtain sample's curvature. Residual stress is calculated from the R via the Stoney equation [1] under certain geometrical conditions.

In this paper we describe a novel interferometric method based on carrier frequency interferometry [2] that is used to measure wavefront deformation of coated optics. We show the interferometer has the capability to determine R in the range of 10 to 2000 m (flat substrate) with a 0.5% accuracy for R<100 m and 2% accuracy for R>500 m. This sensitivity significantly exceeds that of phase shifting interferometry. Analysis of a set of samples in which the thickness of the HfO_2 layer was kept constant and the substrate thickness varied, and a second set in which the layer thickness was changed and the substrate thickness is kept constant were used to determine the validity of the Stoney equation to calculate stress in thin films.

References:

[1] G.G. Stoney, "The Tension of Metallic Films Deposited by Electrolysis," Proc. R. Soc. Lond. A 82, 172 (1909).

[2] E. Jankowska, S. Drobczynski, and C.S. Menoni, "Analysis of surface deformation in thin-film coatings by carrier frequency interferometry," Appl. Opt. 56, C60-C64 (2017).

KEYWORDS: Not Available

10447-90, SESSION PS4

Recent improvements in LIDT of optical components for pulsed and CW applications

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ABSTRACT TEXT: Today, many applications focus on optical components requiring a high laser damage threshold. Especially the development of lasers toward higher and higher output power drives optical components quality to further improved damage threshold values. Several design strategies may be applied to achieve perfect performance. Recently, several investigations were performed on the design wavelength of 1030 nm and an angle of incidence of 44°. IBS and PIAD deposition methods for the material combination HfO_2/SiO_2 were used. Especially the shiftable target position inside the IBS chamber was applied to produce high reflective rugate and mixed design variations. All kind of different designs were tested for LIDT at 560 fs and s-polarization. These results were compared with those high-reflective designs made in a PIAD process. In addition to extensive experiments on pulsed operation, the most suitable cw conditions were studied as well for several designs.

Highest values for LIDT in pulsed operation were found for mixed IBS and PIAD designs with an average of 2 J/cm2 @ 1-on-1 and the best results @ 105-on-1 were rugate designs with more than 1.3 J/cm2. Measurements were performed up to 1.7 J/cm2. A value of 1 MW/cm2 for cw operation was achieved without damage to the sample.

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10447-22, SESSION 6

Atomic and molecular dynamics in mid-infrared fields

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SPEAKER BIOGRAPHY: Not Available

ABSTRACT TEXT: No Abstract Available

KEYWORDS: Not Available

10447-23, SESSION 6

Band-gap excitation dynamics at optical frequencies

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SPEAKER BIOGRAPHY: Not Available

ABSTRACT TEXT: Attosecond soft-X-ray pulses became available as a result of the rapid developments of ultrafast laser technology. After a decade of efforts to optimize their synthesis, attosecond pulses now are a tool for time resolved spectroscopy of electron dynamics in the condensed phase.

I will discuss a set of experiments where attosecond spectroscopy provides us with a time-domain understanding of the complete energy exchange dynamics between a light field and a solid. The experiments study the electron dynamics in the band structure of small- and wide-gap materials and reveal lasting and transient optical excitations across the band gap of semiconductors and dielectrics with sub-femtosecond response time. Band-structure modifications resulting from the optical excitation are observed as well as the separation of the initially purely electronic response of the system to the incident light field form the subsequent onset of lattice dynamics.

KEYWORDS: Not Available

10447-24, SESSION 6

Ultrafast strong-field effects in semiconductors

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SPEAKER BIOGRAPHY: Not Available

ABSTRACT TEXT: No Abstract Available

KEYWORDS: Not Available

10447-25, SESSION 7

First-principles calculations for ultrafast energy transfer from laser to solids

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SPEAKER BIOGRAPHY: Not Available

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 spatial profiles of laser damages and ablations. To obtain fundamental understanding of the laser-induced damage process, a quantitative evaluation of the energy transfer is important. However, theoretical description of the energy transfer is not simple since it involves extremely nonlinear electron dynamics induced by the laser pulse.

We have been developing a first-principles computational approach based on ab-initio time-dependent density functional theory (TDDFT) [1]. In microscopic scale, we describe the electron dynamics induced by the laser electric field by the TDDFT. In mesoscopic scale, we describe the propagation of the laser pulse solving Maxwell equations. Combining two descriptions in a multiscale framework provides a comprehensive description of the nonlinear interaction between intense and ultrashort laser pulses with solids and is capable of evaluating the energy transfer.

We have applied the method to simulate irradiation of a few-cycle laser pulses on SiO_2 surface [2, 3]. 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 causes the laser-induced damage. We simply estimated the laser damage threshold and ablation depth from the energy transfer to electrons, comparing it with melting and cohesive energies of alpha-quartz. The estimated threshold and depth show fair agreement with recent experimental data [2]. We also compare it with the energy transfer evaluated from the shape of the laser pulse that passes through a thin film of fused silica. It has been shown that the onset of the energy transfer in the measurement is reasonably reproduced by our numerical calculation.

Finally, we have recently conducted a large-scale computing attempt, solving three-dimensional Maxwell and three-dimensional time-dependent Kohn-Sham equations simultaneously. In the calculation, we describe interactions of a pulsed light with optical vortex with a flat surface of solids and of a pulsed light with three-dimensional nanostructures such as nano-sphere and nano-pillar. It shows a potential usefulness of the present approach for nano-processings.

[1] K. Yabana, T. Sugiyama, Y. Shinohara, T. Otobe, and G. F. Bertsch, Phys. Rev. B 85, 045134 (2012).

[2] S.A. Sato, K. Yabana, Y. Shinohara, T. Otobe, K.M. Lee, G.F. Bertsch, Phys. Rev. B 92, 205413 (2015).

[3] A. Sommer, E.M. Bothschafter, S.A. Sato, C. Jakubeit, T. Latka, O. Razskazovskaya, H. Fattahi, M. Jobst, W. Schweinberger, V. Shirvanyan, V.S. Yakovlev, R. Kienberger, K. Yabana, N. Karpowicz, M. Schultze, F. Krausz, Nature 534, 86-90 (2016).

KEYWORDS: Not Available

10447-26, SESSION 7

Interferometric frequency-resolved optical gating for probing optical nonlinearities as the verge of multiphoton-induced breakdown

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SPEAKER BIOGRAPHY: Not Available

ABSTRACT TEXT: No Abstract Available

KEYWORDS: Not Available

10447-27, SESSION 7

Time-resolved investigations of laser-dielectric interaction mechanisms

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SPEAKER BIOGRAPHY: Not Available

ABSTRACT TEXT: Laser processing and machining of dielectrics, like for instance silica or sapphire, is a growing field, involving increasingly complex laser temporal and spatial pulse shaping. The situation is intricate due to the feedback between electronic excitation and pulse propagation. Obviously, a detailed knowledge of all elementary processes involved in the interaction is mandatory for optimizing any laser manufacturing process. In particular, the critical step is energy deposition, which must be controlled to achieve precise laser induced modification. In order to improve our understanding of the interaction, we perform various time resolved experiments: time resolved holography and interferometry. Thus we have access to the excited carrier and deposited energy distribution in the solid. Also, we use a double excitation scheme allowing to control both plasma density and temperature, and gives detailed information on the excitation and relaxation mechanisms, which could not be observed so far.

These experimental results show that the appropriate criterion to determine the ablation or damage threshold is not the density of carriers. The latter, measured at breakdown threshold, decreases with increasing pulse duration. We also report a direct observation of laser induced impact ionization/avalanche. This phenomenon is a hypothesis in a huge number of publications, but has never been directly demonstrated. More important, we show that it is not con-nected to the optical breakdown, occurring far above the threshold for damage/ablation. Finally, the most interesting result is that it does not take place in all materials.

In order to interpret these experimental results we have developed a simple model (initially introduced by B. Rethfeld) based on multiple rate equations which takes into account various elementary processes: nonlinear laser excitation through the band gap, carrier heating within the conduction band, impact ionization, as well as time and space evolution of the laser beam intensity. Using this model we are able to successfully explain and quantitatively repro-duce all these experimental data.

KEYWORDS: dielectric; breakdown threshold; pump-probe experiment; ultrashort pulses; impact ionization; avalanche; electronic processes; multiple rate equations

10447-28, SESSION 7

Conversion of direct-gap energy bands of a wide-band-gap crystal into indirect-gap transient bands by ponderomotive potential of Bloch oscillations driven by ultrashort laser pulse

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SPEAKER BIOGRAPHY: Not Available

ABSTRACT TEXT: Various ultrafast high-intensity laser interactions with wide-band-gap crystals involve modification of material properties and responses to laser action. One of major mechanisms of the ultrafast response modification is associated with distortion of original energy bands by electric field of a laser pulse. In wide-gap dielectrics the fastest laser-induced distortions are attributed to coherent laser-driven oscillations of electrons/holes (Bloch oscillations). Energy of those oscillations averaged over a single cycle of laser field (pondermotive potential) adds to initial energy of the electrons and holes to modify the energy bands. Analysis of that mechanism is often based on a specific monochromatic approximation for laser pulses. When coupled to the concept of the Bloch oscillations, that approximation predicts conservation of a direct-gap band structure during entire laser-solid interaction and shift of the bands to higher energy so that the original band gap increases by the pondermotive potential.

We employ a time-dependent non-perturbative model of the energy-band modification by the pondermotive potential of the laser-driven electron-hole oscillations. We consider a Gaussian shape of slow amplitude of the laser pulse and derive analytical relations for time-dependent modification of parabolic conduction and valence bands. We separately introduce the Keldysh parameters for each of the considered energy bands. Evaluation of time-dependent position of the conduction-band bottom and valence-band top points delivers a relation for the mutual shift of the two bands with respect to each other along a quasi-momentum direction parallel to electric field of the laser pulse. The p-shift significantly depends on absolute pulse phase. In particular, $\varpi/2$ absolute phase is favorable for suppression of the transient-band p-shift while zero and ϖ values of the absolute phase are favorable for maximizing the band p-shift. Numerical simulations confirm that the initial direct-gap bands become transient indirect with a significant p-shift of the modified bands along the momentum direction collinear with the electric field. The effect becomes stronger with reduction of pulse width and increase of peak fluence/intensity. Compared to the effective monochromatic band gap, the Gaussian pulse model predicts lower effective band gap at the leading front of a laser pulse and higher effective band gap at the tail of the pulse. This is in full agreement with the general non-perturbative non-monochromatic theory of band-structure modification by slowly-varying laser pulses. This effect distorts the time symmetry of the laser-crystal interactions with respect to the peak point of the laser pulse and can affect multiple processes of energy absorption and deposition during the interactions.

This material is based upon work supported by the Air Force Office of Scientific Research under award number FA9550-15-1-0254.

KEYWORDS: Ultrashort laser pulses; Transient energy bands; Bloch oscillations

10447-29, SESSION 8

Optical damage of high-performance thin film transparent electrodes *(Keynote Presentation)*

Selim Elhadj, Jae-Hyuck Yoo, Andrew Lange, Nan Shen, Raluca A. Negres, Marlon G. Menor, Antonio Correa Barrios, Phil Ramsey, Jeffrey D. Bude, John J. Adams, Lawrence Livermore National Lab. (United States)

SPEAKER BIOGRAPHY: Not Available

ABSTRACT TEXT: Thin film transparent conductive electrodes (TCE) are components of optoelectronic devices. Optimization of transparency and conductivity have been the focus of industry and research in photovoltaics, display panels, energy efficient windows, flexible electronics, and a range of other applications requiring both good conductivity and transparency in the Vis-NIR range. A new requirement for large aperture, high optical damage performance TCE's is emerging to support the design of next generation optoelectronic devices suitable for compact, high rep rate, high power laser systems. These requirements, sometimes-conflicting, necessitate selection of scalable, low defect semiconductor-based materials to go beyond the current optical damage limitations of typical conductive oxide materials widely used in industry. In this study, a range of next generation widegap materials were tested to determine their optical damage mechanisms and lifetime performance. Additionally, we describe ways to engineer ruggedized TCE films that are both less susceptible to absorption and thermally more stable, based on an understanding of the damage mechanisms involved in each type of material. Order of magnitude gains are demonstrated that can help establish a new class of transparent electrode materials for the high-power optoelectronics industry and for lasers for high energy density research.

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KEYWORDS: Not Available

10447-30, SESSION 8

Next-generation all-silica coatings for UV applications

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SPEAKER BIOGRAPHY: Andrius Melninkaitis was born 23 May 1980, in Jurbarkas (Lithuania). Since 2009 he holds a Ph.D. in Physics obtained from Vilnius University. He has specialized in laser-induced damage threshold metrology, time-resolved digital holography, laser-matter interactions and statistical Monte Carlo simulations. He co-authored more than 50 scientific publications in the field of laser damage. Currently, he is Associate Professor at the Department of Quantum Electronics and Research Fellow in Laser Research Center (VULRC) at Vilnius University in Lithuania. Since 2012 he is also co-founder and CEO of Lidaris company – providing laser damage testing metrology services.

ABSTRACT TEXT: The ability to withstand laser-induced damage in UV optical coatings have been explored for several decades. Band-gap and refractive index - a fundamental properties of pure optical materials were found as good predictor variables of optical resistance [1]. Therefore, artificial nano-structures with high porosity were designed and investigated to overcome the laser damage boundaries of standard materials [2]. Conventional Al2O3 and SiO2 multilayers produced by Ion Beam Sputtering (IBS), namely mirrors of 99.5 % reflectivity were used as reference coatings. New generation all-silica mirrors were prepared by GLancing Angle Deposition (GLAD) using electron beam evaporation. High reflectivity was achieved by tailoring the porosity of silica material during the deposition process. Additionally, a hybrid multilayer structure was designed to exploit the advantages of both technologies. Damage performance of experimental coatings in was directly compared and analyzed. GLAD approach resulted in significant improvement of laser damage resistance for all-silica based and hybrid design mirrors. Besides laser damage testing, other characteristics of experimental coatings are analyzed and discussed – reflectance, surface roughness and optical scattering. We believe that reported concept can be expanded to virtually any design of thin film coatings thus opening a new way of next generation highly resistant thin films well suited for high power and UV laser applications.

References:

[1] A. Melninkaitis, T. Tolenis, L. Mažule, J. Mirauskas, V. Sirutkaitis, B. Mangote, X. Fu, M. Zerrad, L. Gallais, M. Commandré, S. Kičas, and R. Drazdys, "Characterization of zirconia– and niobia–silica mixture coatings produced by ion-beam sputtering," Appl. Opt. 50, C188-C196 (2011)

[2] T. Tolenis, L. Grinevičiūtė, R. Buzelis, L. Smalakys, E. Pupka, S. Melnikas, A. Selskis, R. Drazdys, and A. Melninkaitis, "Sculptured anti-reflection coatings for high power lasers," Opt. Mater. Express 7, 1249-1258 (2017)

KEYWORDS: Silica; Nanostructured thin films; Evaporation; Optical coatings; Ion beam sputtering; Laser damage; Mirrors

10447-31, SESSION 8

Optimal coating solution for the total internal reflection surface of zig-zag slab laser amplifier

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SPEAKER BIOGRAPHY: Bruce D. MacLeod is Vice President in charge of micro-structured optics manufacturing at TelAztec. Mr. MacLeod has over 28 years of experience designing and fabricating optical microstructures. Bruce's experience also includes 8 years at Raytheon, 2 years at Lockheed Martin, and 6 years at Holographic Lithography Systems. Mr. MacLeod holds a B.S. degree in Ceramic Engineering from Alfred University. He is co-inventor on three U.S. Patents and has 15 journal publications.

ABSTRACT TEXT: The nano-precursors concentrated near the Nd:YAG crystal-film interface were limiting factor that caused laser-induced damage at the total internal reflection (TIR) surface of zig-zag slab laser. For the traditional thick SiO_2 single layer coating at the TIR surface of Nd:YAG crystal, the strong electric-field (E-field) at crystal-film interface decreased the laser-induce damage threshold (LIDT). To improve the LIDT of TIR surface, a high refractive index material layer was added between the thick SiO_2 layer and Nd:YAG crystal to greatly reduce the E-field at crystal-film interface and raise LIDT of the crystal-film interface. Using usual HfO_2 as the high refractive index material would increase the total absorption and decrease the LIDT in the film because of the high absorption coefficient of HfO_2. Then annealing procedure was used to decrease the absorption of the high refractive index material layer. Using co-evaporated mixed-material of HfO_2 and SiO_2 as the high refractive index material, compared with HfO_2, could avoid the influence of film crystallization after annealing. Finally, an optimal coating with high LIDT and low absorption for TIR surface was obtained, which was composed by an annealed co-evaporated HfO_2/SiO_2 mixed-material layer and a thick SiO_2 layer. It has similar absorption but about 2 times higher LIDT than the traditional SiO_2 single layer. And the laser-induced damage occurred at deep subsurface in the Nd:YAG crystal.

KEYWORDS: thin films; total internal reflection ; laser damage; electric-field; absorption; annealing; crystallization; co-evaporated

10447-32, SESSION 9

Pulsed laser damage resistance of nano-structured high reflectors for 355nm

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SPEAKER BIOGRAPHY: Not Available

ABSTRACT TEXT: Nanometer scale surface relief structures can be configured to enhance or modify the performance of dielectric film stacks, produce high efficiency wavelength selective high reflectors, and potentially increase laser damage resistance. For this study, polarization and wavelength selective nano-structure resonant (NSR) filters were designed and demonstrated as 355nm wavelength laser mirrors. In addition, Random Anti-Reflection (RAR) nanostructures were integrated as cap layers on top of conventional multi-layer thin-film dielectric stack high reflectors also designed for 355nm wavelength lasers. The surface absorption, optical performance and damage resistance of these nano-textured high reflectors was then compared to commercially available thin-film high reflectors through standardized, 5ns pulse, laser induced damage threshold testing at Quantel USA.

KEYWORDS: Nano-Textures; Micro-Structured High Reflectors; Guided Mode Resonant Mirrors; Pulsed LiDT; High Average Power Lasers; Random AR; Surface Structure Resonance; Dielectric Gratings

10447-33, SESSION 9

355-nm, Nanosecond laser mirror thin film damage competition

Raluca A. Negres, Christopher J. Stolz, Lawrence Livermore National Lab. (United States); **Michael D. Thomas, Mark Caputo,** Spica Technologies, Inc. (United States)

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: Multilayer dielectric (MLD) coatings are integral part of the design of high power laser systems and are used in multiple applications including beam combination, beam steering, wavelength separation and diffraction gratings. Currently, such laser systems are often fluence-limited by the MLD coatings due to laser-induced damage. Moreover, future utilization of lasers for applications under more extreme conditions, such as the exposure to high energy in the ultraviolet range, is significantly limited by the performance of available coatings. For this study, we propose to survey state-of-the-art UV high reflectors; mirrors must meet a minimum reflection of 99.5% at 45 degrees incidence angle for P-polarized light at 355 nm. The participants in this effort will select the coating materials, coating design, and deposition method. The samples will be damage tested using the raster scan method with a 5-ns pulse length laser system operating at 10 Hz in a single longitudinal mode. Experiments will be performed at a single testing facility to enable direct comparison among the participants. Details of the deposition processes, cleaning method, coating materials, and layer count will be 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. LLNL-ABS-690975.

KEYWORDS: Thin films; Laser damage resistance; Nanosecond lasers; Ultraviolet

10447-34, SESSION 9

Time resolved digital holography measurements of the nonlinear optical filters

Balys Momgaudis, Vilnius Univ. (Lithuania); **Tatiana V. Amotchkina,** Max-Planck-Institut für Quantenoptik (Germany); **Linas Smalakys,** Vilnius Univ. (Lithuania); **Michael K. Trubetskov,** Max-Planck-Institut für Quantenoptik (Germany); **Andrius Melninkaitis,** Vilnius Univ. (Lithuania); **Ferenc Krausz,** Max-Planck-Institut für Quantenoptik (Germany); **Vladimir Pervak,** Ludwig-Maximilians-Univ. München (Germany)

SPEAKER BIOGRAPHY: Balys Momgaudis received his physics bachelor's degree in 2015 and master's in 2017. At the moment he is pursuing his PhD in the same area of research. His field of study is nonlinear light and mater interaction, time resolved digital holography and laser-induced damage in optical materials. Co-author of best oral paper in SPIE Laser Damage 2015.

ABSTRACT TEXT: Recent progress in the design and production of optical interference coatings allow precise tailoring of the spectral behavior of optical components as well as group-delay dispersion control over broadband spectral ranges. Due to high laser induced damage threshold, the dielectric coatings can be exposed at high intensity laser radiation on the order of 10-1000 GW/cm2. Until now the dielectric multilayer were considered in the linear regime only. At the same time, at the high intensities optical coating can exhibit nonlinear effects. Namely, intensity dependent addition to the refractive index (Kerr effect) causes variation of the reflectance coefficient [1] and consequently reflectance growth.

We designed and produced a special edge filter extremely sensitive to any change in refractive indices, layer thicknesses and angle of incidence [2]. As thin film materials, Nb2O5 and SiO2 were used. The developed nonlinear multilayer coating (NMC) consists of 69 layers and has total physical thickness of 8.7 µm. The filter was deposited on fused silica substrates with thicknesses of 0.2 mm and 6.35 mm by magnetron sputtering at Helios plant from Leybold Optics (Alzenau, Germany). The layer thicknesses were controlled using a well-calibrated time monitoring [3].

In the present work we perform pump-probe measurements with a custom time-resolved digital holography (TRDH) setup developed at Vilnius University [4]. The experiments were performed with 309 fs pump pulses at 1030 nm central wavelength and 28 fs probe pulses at 540 nm central wavelength in different intensity ranges around the laser induced damage threshold (LIDT) fluence value of 0.15 J/cm2. Different processes overlapped in time were found to occur, namely the Kerr effect, free-electron generation and their subsequent trapping.

A numerical model based on finite-difference time-domain (FDTD) method, electron rate equations and Drude theory was used to reproduce the experimental results and investigate both amplitude and phase change of the probe pulses in order to decouple the contribution of the before mentioned physical processes.

References

[1] B. M. Bass, "Handbook of Optics", Vol. IV, McGraw Hill (2010)

[2] E. Fedulova et al., Kerr effect in multilayer dielectric coatings, Opt. Express 24, 21802-21817 (2016)

[3] V. Pervak et al., "1.5-octave chirped mirror for pulse compression down to sub-3 fs," Appl Phys B 87, 5–12 (2007).

[4] N. Šiaulys et al., "Direct holographic imaging of ultrafast laser damage process in thin films," Opt. Lett. 39, 2164-2167 (2014)

KEYWORDS: nonlinear effects in multilayer optical coatings; pump-probe experiments

10447-35, SESSION 9

Characterization of laser induced damage of HR coatings with picosecond pulses

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SPEAKER BIOGRAPHY: Not Available

ABSTRACT TEXT: The laser induced damage in optical components have always been the key point to challenge the development of high peak power/high energy laser systems. Extensive experimental and theoretical studies of laser damage with nanosecond pulses and femtosecond pulses suggest extrinsic mechanisms and intrinsic mechanisms, respectively. However, there are few studies focusing on the laser damage in the transition region of 0.5-100 picosecond pulses in which the laser-matter interactions tend to be quite complicated. Therefore, it is of great importance to study laser induced damage of optical coatings with picosecond pulses.

In this study, laser induced damage of HfO2/SiO2 HR coatings was measured. Two coating stacks with and without protective layer were tested with 1064nm, 35ps S-polarized and P-polarized pulses in different incident angles, all of these different testing conditions correspond to discrepant electric fields intensity in the HR coatings which were simulated by software. Damage morphology and depth information of damage sites were characterized by scanning electron microscope (SEM) and step profiler, respectively. Results of damage tests measured in different testing conditions were compared and the reasons were discussed.

KEYWORDS: HR coatings; laser-induced damage; protective layer; picosecond pulse; Electric field distributions

10447-36, SESSION 9

Picosecond pulse damage mechanism of hafnia-silica high reflectors Investigated by high-resolution microscopy

Alexei A. Kozlov, Semyon Papernov, Stavros G. Demos, James B. Oliver, Amy Rigatti, Brittany N. Hoffman, John C. Lambropoulos, Univ. of Rochester (United States)

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: We report the results on studies of the morphology of the damage sites generated in vacuum on different hafnia/silica-based high reflectors by 1053-nm-wavelength picosecond pulses. The high reflectors of various designs were manufactured by the e-beam deposition method and damage tested using 600-fs, 10-ps, 20-ps, 50-ps, and 100-ps-long pulses at s- and p-polarization in single pulse (one-on-one) and multiple pulse (N-on-one) irradiation regimes. An earlier analysis of the damage sites,1 performed by using Nomarski and scanning electron microscopy (SEM), revealed a change in the damage initiation mechanism from intrinsic at 600 fs pulse length to localized-defect–driven damage at longer pulses. In this work, the damage craters depth measurements under atomic force microscopy showed that the damage is confined within three top layers of the coating stack with the damage onset location governed by an electric-field distribution. In the 600-fs one-on-one irradiation regime, the damage morphology is characterized by homogeneous removal of the material to a depth corresponding to the e-field intensity peak location. For the N-on-1 regime at 600 fs, the damage craters have complex morphology with preferential orientation, transverse to the beam propagation direction. For longer pulses, 10 to 100 ps, precise measurements of the damage onset depth confirmed earlier observations,1 based on the SEM measurements. The damage at 10-ps pulses is linked to localized absorbers inside the first HfO_2 layer, and for 100-ps pulses, an origination of the damage is confined to first silica layer. For intermediate pulse lengths (20 ps and 50 ps) the damage-morphology analysis reveals a complex interplay between two mechanisms, described above.

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References

1. A. A. Kozlov, S. Papernov, J. B. Oliver, A. Rigatti, B. Taylor, B. Charles, and C. Smith, “Study of the Picosecond Laser Damage in HfO_2/SiO_2 –Based Thin-Film Coatings in Vacuum,” Proc. SPIE. 10014, 100141Y (2016).

KEYWORDS: picosecond pulses; thin-film coatings; laser damage in vacuum; atomic force microscopy

10447-37, SESSION 9

Femtosecond laser-induced blister structure in high dispersive mirrors

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SPEAKER BIOGRAPHY: Not Available

ABSTRACT TEXT: The high dispersive mirrors (HDMs) with group delay dispersion (GDD) of minus and plus 1000 fs2 in the wavelength range of 750-850nm were designed and fabricated. These HDM samples were irradiated by a single 800 nm-40 fs laser with spectral width of 35 nm (full-width at half maximum, FWHM), operating at a repetition rate of 1 KHz. The thresholds were about 0.11J/cm2 and 0.22J/cm2 for the -1000fs2 HDM and +1000fs2 HDM, respectively, which were approximately 1/3-1/4 of standard high reflectance coating. A blister structure was observed at a wide fluence range. A pressure-induced-bulging model was proposed and applied to elucidate the primary feature of blister. According to this model, the blister evolution can be explained by partial evaporation of the film and a subsequent internal pressure, driving the bulging of the film upward until the outer layer falling off the inner layers, where the blister feature begins to be destroyed. The relation between blister height and blister radius was modeled. A great agreement between the modeled result and measured result was obtained.

KEYWORDS: high dispersive mirror; laser damage thresholds; blister; pressure-induced-bulging model

10447-38, SESSION 10

Approaches toward optimized laser-induced damage thresholds of chirped mirrors for few cycle pulses in the near-infrared spectral range

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SPEAKER BIOGRAPHY: Not Available

ABSTRACT TEXT: Ultra short laser applications in the fs regime require a strong phase management to counter the dispersion of laser irradiation. Beside prism and gratings special dielectric mirrors (CM's) can chirp laser pulses and enable the possibility to design the required spectral bandwidths and needed phase chirp more flexible to the specific laser sources. Typical CM`s for the near infra-red spectral range reach total design thicknesses almost 10 µm. Nowadays, well established Ion Beam Sputtering (IBS) technology in combination with high precise broad band monitoring (BBM) systems provides best manufacturing conditions of high end optics. Expanding the target holder, different fractions of at least two target materials can be sputtered and the electro optical properties can be tuned towards higher optical gaps. However, a main drawback of the manufacturing process of CM's is provided by the extreme layer sensitivity of the designs. Already small layer deviations of several nm lead to a total failure of the designed group delay dispersion. The process itself can be controlled more precisely by monitoring the phase directly instead of the recorded transmission applying an in-situ fiber based white light Michelson interferometer. Further the design structure imposes a complicated electric field distribution correlated to a classic high refractive mirror and can influence the level of the laser induced damage threshold (LIDT).

The present contribution introduces different approaches to influence the electric field distribution inside designed chirp mirrors for few cycle pluses at a center wavelength of 800nm. The study is initiated by a design synthesis to retrieve best target values inside a classic binary coating stack of a CM. For the following calculation this design will be modified, receptively. Layers affected by high electric field intensities are exchanged by ternary composites or modified layer structures. All calculated designs are compared towards the sensitivity of deposition errors. Taking advantage of a novel in-situ phase monitor system, the designs are manufactured applying IBS process.

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; composite materials; laser induced damage threshold; ultrshort pulses

10447-39, SESSION 10

Nonlinear response of dielectric optical coatings

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SPEAKER BIOGRAPHY: Vladimir Pervak received his MSc degree in Physics from the Kiev National Taras Schevchenko University, Ukraine, in 2004. In 2006, he received his PhD in Physics at the Max-Planck-Institute of Quantum Optics, Germany, and in Kiew National Taras Schevchenko University, Ukraine. Currently, he is leading his team in the research group of Prof. Ferenc Krausz at the Max-Planck-Institute of Quantum Optics and Ludwig-Maximillians-University both in Munich. He has more than 150 technical and scientific publications. His research interests include interference coatings, ultrafast sources, and nonlinear optics.

ABSTRACT TEXT: Optical interference coatings play a major role in laser applications because they provide an efficient way of controlling the spectral characteristics and phase properties over broadband spectral ranges. High laser induced damage thresholds of dielectric coatings allow using them at high intensities of 10-1000 GW/cm2. At such intensities optical coatings exhibit nonlinear effects. Namely, the Kerr effect (intensity dependent addition to the refractive index) causes a variation of the reflectance coefficient [1]. Dielectric multilayers with predictable increase of reflectance at high intensities can be used for the development of innovative elements for ultrafast optics.

We designed and produced special edge filters with an extremely steep reflectance slope near the central wavelength of 1030 nm. The filters' spectral characteristics are extremely sensitive to any change in refractive indices, layer thicknesses and angle of incidence [2]. Thin film material pairs Nb2O5/SiO2 and Ta2O5/SiO2 were used. The developed nonlinear multilayer filters consist of 69 layers and have total physical thickness of 8.7 and 9.3 µm, respectively. The filters were fabricated on fused silica substrates by magnetron sputtering at a Helios plant from Leybold Optics (Alzenau, Germany). The layer thicknesses were controlled by a well-calibrated time monitoring system [3]. Spectral photometric measurements showed that the filters exhibit the expected spectral performance and in particular, steep variation of the reflectance near the central wavelength.

The intensity dependent reflectance and transmittance of the produced samples were measured at a laser setup based on an Yb:YAG thin disk regenerative amplifier with a repetition rate of 50 kHz emitting 1 ps pulses around 1030 nm central wavelength [4]. The beam diameter on the sample was about 350 µm. The pulse intensity was adjusted by a half-wave plate followed by a polarization cube. The sample was placed on a rotational stage to adjust the angle of incidence and to achieve different initial reflectance and transmittance values corresponding to the lowest intensity of GW/cm2 at which no nonlinear effects in the sample are possible. The incident, reflected and transmitted powers were measured. The experiments were performed at intensities ranging from GW/cm2 up to the damage threshold values of about GW/cm2. The intensity dependent reflectance was calculated as a ratio of the reflected power and incident power. The surface temperature was monitored using an infrared camera and temperature increase was observed. The thermal effects are inevitable because of the absorption presented even in high quality multilayers. As thermal effects in the coating also increase the reflectance, it was necessary to minimize them. To exclude the thermal effect, the average power of the incident beam was reduced by a chopper wheel of 10% duty cycle without attenuating the peak intensity which drives the nonlinear process. The modulation depths at various reflectance levels corresponding to different angles of incidence were measured. The increase of reflectance indicates the presence of the nonlinear Kerr effect in the nonlinear coatings.

A new method calculating intensity dependent spectral characteristics of multilayer optical coatings in the case of nonlinear interaction with high intensity laser pulses has been developed. The method is based on the numerical solution of a boundary-value problem derived from the system of Maxwell equations describing the propagation of light through a multilayer system. The method takes the distribution of the refractive index and electric field along the coating coordinate into account. The method opens a way to synthesis optical coatings with predictable nonlinear properties. A comparison of our numerical modelling with experimental data enabled us to accurately determine the Kerr coefficients of the widely-used thin-film materials Ta2O5 and Nb2O5.

References

[1] B. M. Bass, “Handbook of Optics”, Vol. IV, McGraw Hill (2010)

[2] E. Fedulova et al., Kerr effect in multilayer dielectric coatings, Opt. Express 24, 21802-21817 (2016)

[3] V. Pervak et al., “1.5-octave chirped mirror for pulse compression down to sub-3 fs,” Appl Phys B 87, 5–12 (2007).

[4] W. Schneider et al., “900-fs, 330muJ pulses from a 100-W regenerative Yb:YAG thin-disk amplifier at 300 kHz and THz generation in LiNO3” Optics Letters 39, 6604-6607 (2014).

KEYWORDS: nonlinear optical coatings; nonlinear dielectric optical coatings; nonlinear multilayers; Kerr effect in multilayers; nonlinear response of dielectric coatings

10447-40, SESSION 10

Comparison of aging effects in Hafnia and Titania thin films on the laser damage resistance of high reflection coatings for 1054nm

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SPEAKER BIOGRAPHY: Not Available

ABSTRACT TEXT: Optical coatings deposited using electron beam evaporation are subject to aging effects that change the spectral characteristics of the optical coating. The aim of this study was to determine whether aging effects can also negatively impact the laser damage resistance of an optical coating. Maintaining high resistance to laser damage is particularly important for the performance of high fluence laser systems. In 2013, we deposited high reflection coatings for 1054 nm containing HfO_2/SiO_2, TiO_2/SiO_2, and $HfO_2/TiO_2/SiO_2$ layers. For this study, we re-measured the laser damage thresholds of these coatings at 3.5 ns to determine if aging effects cause the laser damage threshold to decline, and to compare whether HfO_2 or TiO_2 is superior in terms of long term laser damage resistance.

KEYWORDS: Not Available

10447-41, SESSION 10

Characterization of hafnium oxide thin films with varying oxygen content

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SPEAKER BIOGRAPHY: Not Available

ABSTRACT TEXT: Hafnium oxide thin films with varying oxygen content deposited using ion-beam sputtering (IBS) and electron-beam (e-beam) deposition were characterized using optical absorption, luminescence, x-ray photoelectron spectroscopy, x-ray diffraction, nano-Kelvin calorimetry (absorption spectroscopy), and laser-damage-threshold measurements. Near-ultraviolet (UV) film absorption for both types of films (IBS and e-beam) showed continuous increase with reduced oxygen content and appeared to be sensitive to the power density of laser radiation probing absorption. The sensitivity to power density was very strong in e-beam films and relatively weak in IBS films. Luminescence excited by continuous-wave near UV laser in e-beam films was at least one order of magnitude more intense than luminescence in IBS films, which almost completely disappeared in IBS films with reduced oxygen content. The difference in the absorption/luminescence behavior of IBS and e-beam films during interaction with near-UV radiation can be linked to different films' morphology, bulk-like structure of IBS films, and highly porous, columnar structure of the e-beam films. Similar to absorption, luminescence excited in e-beam films showed a strong quenching effect with increased excitation laser power density. This effect also appeared to be spectrally dependent, which made it possible to establish correlation of some spectral bands with missing oxygen sites in the film lattice structure. Laser-damage investigation also showed damage-threshold dependence on oxygen content in hafnium oxide films.

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KEYWORDS: Absorption, luminescence, hafnium oxide thin films, laser damage

10447-42, SESSION 10

Laser damage of Scandium oxide and Hafnium oxide thin films in ultrahigh vacuum

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SPEAKER BIOGRAPHY: Not Available

ABSTRACT TEXT: Understanding of the damage mechanisms at sub-nanosecond pulse duration in vacuum is important for increasing power extraction in near infrared terawatt and petawatt solid state laser systems. Pulse compressor optics, space based optics, cryogenic active mirrors and others have all demonstrated a significant decrease in the laser induced damage threshold (LIDT) performance of the amorphous oxide coatings when used in a vacuum environment. This decrease in the LIDT performance has been known for some time but the reasons for this decrease remain uncertain. Water impregnation in the film, carbon contamination, decreased thermal conductance and oxygen dissociation have all been proposed as possible explanations for this behavior [1, 2].

This paper describes results of a systematic study of the laser damage performance of amorphous Sc2O3, and HfO2 in controlled air and ultrahigh vacuum (UHV) environments. Laser induced damage threshold (LIDT) measurements were carried out using a 100-on-1 protocol implemented with an all-diode-pumped, chirped pulse amplification (CPA) Yb:YAG system producing pulses of 375 ps duration [3]. The results show a marked reduction in the LIDT under vacuum conditions, which is more pronounced for Sc2O3. We will also show that a 10 nm cap layer of a different oxide added to the thin films can enhance or decrease their LIDT in vacuum.

Work supported by DoD Office of Naval Research, and the High Energy Laser Program from the DoD Joint Technology Office through grants No. N00014-07-1-1068, N00014-09-1-0049 and ARO W911NF-11-1-007.

References:

[1] X.L. Ling, Y.N. Zhao, D.W. Li, J.D. Shao, and Z.X. Fan, “Damage investigations of AR coating under atmospheric and vacuum conditions,” Optics and Laser Technology, 41(7): p. 857-861.(2009).

[2] D.N. Nguyen, L.A. Emmert, P. Schwoebel, D. Patel, C.S. Menoni, M. Shinn, and W. Rudolph, “Femtosecond pulse damage thresholds of dielectric coatings in vacuum,” Optics Express, 19(6): p. 5690-5697.(2011).

[3] C. Baumgarten, M. Pedicone, H. Bravo, H. Wang, L. Yin, C. S. Menoni, J. J. Rocca, and B. A. Reagan, “1?J, 0.5?kHz repetition rate picosecond laser”, Optics Letters, 41, 3339-3342, (2016).

KEYWORDS: Not Available

10447-43, SESSION 10

Link between mechanical strength and laser damage threshold for antireflective coating made by sol-gel

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SPEAKER BIOGRAPHY: Hervé Piombini has an engineer diploma from Institute of Optics Graduate School and a bachelor's degree in Mathematica. He has worked in CEA since 1987, first at CEA/Saclay where he has designed laser channels for ALVIS project. Then he has investigated optical components and their thin layers (shape, flatness, absorption, scattering, laser damage, losses) to improve with manufacturers their properties (to reduce the losses and increase the laser damage threshold). In 1997, he rejoined CEA/Le Ripault to be in charge of optical materials. He has set up several benches to characterize materials and has developed the KDP activity and laser conditioning for LMJ project. He has owned several patents in optical area.

ABSTRACT TEXT: The laser resistance of large optical components remains an important limitation for the performances and the maintenance costs in LMJ or NIF projects. Many studies about the stacks or the thin layer were made in the past about the laser damage. But only few papers deal with the link between real mechanical properties of the thin layer and the laser damage. The mechanical property measurements of the optical stack by non-destructive investigations are complex notably due to their frequency dependence [1]. As nanosecond laser pulses, such as LMJ pulses, excite several mechanical modes in thin layers, it can be interesting to know the mechanical response of these layers and the elastic modulus at different frequencies. In case of LMJ project, CEA/LR develops and improves sol-gel layers. These layers, made by dip coating (both faces of optical component are coated at the same time) are employed mostly as antireflective coatings at 1 and 3 . The thicknesses of colloidal silica layers are respectively 210 nm (1 layer) or 70 nm (3 layer) as a result of the refractive index of this material which is equal to 1.22. These layers are then cured by ammonia process before assembly of optical components to increase mechanical properties and improve the handling during the transport, the warehousing, the assembly and the use [2]. They are also known to resist to laser damage. This ammonia treatment induces some changes of the layer such as chemical change, shrinkage and sometime crazing. To decrease the price and to increase the production rate, it is necessary to reduce the duration time of ammonia process keeping all the properties of the layers, above all the high laser damage.

With the advent of femtosecond laser and the picosecond acoustics technique, it is possible to investigate the mechanical properties of the thin layer in the thickness range of LMJ layers (resolution of tens of nanometers). Thanks to this technique, we can study the elastic modulus as a function of ammonia process parameters which allow us to make a link between the elastic modulus and the threshold laser damage of these layers. The elastic modulus M is determined by M = v^2, where v is the sound speed measured by the picosecond acoustics pump-probe experience and is the layer density calculated thanks to the knowledge of refractive index. The refractive index n is determined from spectral transmission measurements and a fit made with envelops method [3] where the refractive index and the extinction coefficient follow Cauchy's laws. This bench will be described and these obtained results will be given.

To measure the laser induced damage threshold (LIDT), we use a Powerlite 9050 laser manufactured by Continuum at 3 including an oscillator and two amplifiers. The duration pulse is about 6 ns, its work frequency is 50 Hz and its pulse energy goes up to 180 mJ. The size of optical table forces us to work in far field. The equivalent lens is above 4 meters to avoid creating plasma in air. The sample is set into holder motorized in x, y and z. The laser beam profile is recorded by a camera XCD V60 put on a parallel way at equivalent location. The beam going towards the camera is attenuated by transmission, several reflections and a /2 plate motorized with polarizer. The damage detection is made with HeNe laser scattering and a camera behind the sample also checks if there is laser damage. The temporal profile is measured by speed oscilloscope (DS06102A) and a fast photodiode (UPD-40 UVIR-D). The energy is measured by a photodiode put behind an integrating sphere and a SR830 locking amplifier and also a powermeter. The power variation of this laser is made thanks to DG 535 which changes the time between the oscillator pulse and Q-switch trigger. With a current configuration the sample will carry out according to an S/1 method. The new laser damage test bench will be introduced with the beam shape (temporal and spatial) and their stability. The first LIDT on

the layers measured by photoacoustic will be shown during the lecture and a link will be made.

1.F. Compoint et al, "Sol-gel processed hybrid silica -PDMS layers for the optics of high-power laser flux systems", Journal of Materials Science, Vol. 51, Issue 11 pp50-5031 (2016).

2.P. Belleville et al, "Ammonia hardening of porous silica antireflective coatings," Proc. SPIE 2288, (1994).

3.J.Mouchart, G. Lagier, and B. Pointu, "Détermination des constantes optiques n et k de matériaux faiblement absorbants" Applied Optics, Vol.24, N°12 (1985).

KEYWORDS: laser damage; acoustics picosecond; sol-gel; ammonia curing; elastic modulus; antireflective coating

10447-44, SESSION 10

Deciphering mechanistic sources of high-power laser induced damage in dielectric coatings fabricated by ion beam sputtering method

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SPEAKER BIOGRAPHY: Not Available

ABSTRACT TEXT: Dielectric coatings are an integral part of high-power laser systems for beam combination, beam steering and diffraction gratings. The performance of high-power laser systems can be fluence-limited by multilayer dielectric (MLD) coatings in the optical components due to laser-induced damage. Such limitations also hinder future utilization of lasers under exposure to higher fluence and high intensity. A fundamental understanding of the physical nature of MLD damage precursors important for extreme conditions is needed in order to develop transformative technologies that enable the manufacturing of high performance MLD coatings. In the present study, single layer, layer pairs, and multilayer dielectric coatings of silica and hafnia deposited by ion beam sputtering process are used to investigate the relevant damage precursors. Diagnostics including time-resolved photoluminescence, cathodoluminescence spectroscopy and photothermal microscopy are utilized to identify the physical responses of coating defects leading to laser damage. Chemical analysis is used to examine the compositional anomaly in coating layers. The impact of non-stoichiometric clusters on coating laser performance is also evaluated. The laser damage testing at various fluences is performed in ambient conditions, off-normal angle incidence ("P" polarization at 42? from the surface normal) via raster scanning with a ~0.6 mm 1064 nm laser beam (10 ns) over 4 mm x 4 mm areas on the samples. Damage site density and morphology are determined by post image processing. Electric field intensification due to coating defects is evaluated by simulation and is correlated to the observed coating damage. By combining laser damage testing with theoretical modelling and diagnostics along with post damage analysis, the underlying mechanisms by which precursors control the coating behavior will be studied.

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KEYWORDS: Not Available

10447-45, SESSION 11

Nanosecond multiple pulse measurements and the different types of defects *(Keynote Presentation)*

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SPEAKER BIOGRAPHY: Frank Wagner obtained his MSc degree in Physics in 1997 at the University of Göttingen, Germany. He then did his PhD in 2000 at the EPFL, Switzerland. Thereafter he developed the water-jet guided laser as R&D Engineer at Synova SA (Switzerland) until 2004. Finally, he joined the Light Matter Interaction group of the Fresnel Institute in Marseille, France, where he does research on laser induced damage in optical materials and passed his habilitation in 2012.

ABSTRACT TEXT: Laser damage measurements with multiple pulses at constant fluence (S-on-1 measurements) are of high practical importance for design and validation of high power photonic instruments. Using nanosecond lasers, it has been recognized long ago that single pulse laser damage is linked to fabrication related defects. Models describing the laser damage probability as the probability of encounter between the high fluence region of the laser beam and the fabrication related defects are thus widely used to analyze the measurements.

Nanosecond S-on-1 tests often reveal the “fatigue effect”, i.e. a decrease of the laser damage threshold with increasing pulse number. Most authors attribute this effect to cumulative material modifications operated by the first pulses and some authors anyway apply the mentioned precursor presence models to interpolate S-on-1 data.

In this presentation we want to discuss the different situations that are observed upon nanosecond S-on-1 measurements of several different materials using different wavelengths and speak in particular about the defects involved in the laser damage mechanism.

These defects may be fabrication-related or laser-induced, stable or evolutive, cumulative or of short lifetime. We will show that the type of defect that is dominating an S-on-1 experiment depends on the wavelength and the material under test and give examples from measurements of nonlinear optical crystals, fused silica and oxide mixture coatings.

For some situations the available models are still rather coarse and further investigations will be needed.

KEYWORDS: Laser damage; S-on-1 experiments; empirical models; nanosecond lasers; KTiOPO4; LiB3O5; fused silica; oxide mixture coatings

10447-46, SESSION 11

Multiple pulse nanosecond laser induced damage threshold on hybrid mirrors

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SPEAKER BIOGRAPHY: Not Available

ABSTRACT TEXT: Research and development of innovative materials and components, in particular optical coatings, is a key in achieving powerful and versatile laser systems. Hybrid mirrors are example of such novel components, allowing advantaging both broadband operation of metallic mirrors and high damage threshold of dielectric mirrors. In the past was the most attention focused on solid state lasers based on titanium doped sapphire with wavelengths around 800 nm. However, development in Yb:YAG and similar based systems operating around 1030 nm and demand from industrial and other applications created pressure to move towards longer wavelengths. This introduced another degree of complexity considering laser system components – it is very difficult to prepare structures based on dielectric thin films for wavelengths around 2 µm or longer. In the same manner requirements for broadband components with considerable damage threshold capable operating at longer wavelengths has arisen, as many wavelength tuning grown to be broadly available. Uses of metallic or metallic film based components are no longer an option, as they provide relatively low damage threshold and propensity towards damage. Here can be utilized hybrid mirror, where damage threshold of component can be, for certain band of wavelengths, significantly improved by introducing proper dielectric layers structure while broadband operation of mirror at other wavelengths will be preserved. This way, in parametric down conversion system, high energy pumping laser at 1030 nm and broadband tuning system with output range 2000 nm - 3000 nm can use the same beam path to reduce complexity and increased reliability of the whole system.

Accurate determination of LIDT of hybrid mirrors is in major interest for development of development respective laser source. In following paper, we will describe process of LIDT testing of various protected silver and hybrid mirrors in order to compare their performance at pumping wavelength 1030 nm. Further, we will test two bundles of samples prepared by different deposition techniques, namely PVD and IAD. All measurements will be done on our newly developed LIDT station following ISO compliant methodology to ensure maximum reliability and comparability with commercially available metallic mirrors.

KEYWORDS: LIDT; laser; hybrid mirror

10447-47, SESSION 11

Large-area defect mapping for laser damage prediction

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SPEAKER BIOGRAPHY: Sam Richman has a bachelor's degree in physics from Princeton University and a Ph.D. in physics from the University of Colorado at Boulder. After two postdocs in the fields of gravitational physics and precision measurement he joined Research Electro-Optics, Inc. in 2000. He works in the R&D group on issues of laser damage, metrology, and process development.

ABSTRACT TEXT: The laser damage performance of optical components is often limited by the presence of sparse defects rather than intrinsic material properties. In this regime, it is costly to perform destructive laser damage testing over areas large enough to make statements of damage likelihood in non-tested parts or regions with high confidence.

However, it is feasible to record non-destructively the sizes and locations of all defects (larger than some detectability limit) over a much larger area. It is also straightforward to do selective laser damage testing centered on defects over a subset of the defect-mapped area. This latter measurement will yield a matrix that quantifies damage probability as a function of fluence and defect size. Combining the complete defect map and the damage probability matrix allows unambiguous laser damage prediction at every location over the whole area of interest.

It may still be time-consuming and thus costly to make a complete defect map, so certain questions naturally arise: How representative of the entire area (of a very large part or very many small parts) is the defect map of a given subregion? Can we use the subregion defect map plus damage probability matrix to predict the outcome of standard LIDT testing, or perhaps to comment on the validity of that kind of small-area testing? In this paper we explore these questions by performing large-area defect mapping and analysis of real-world coated optics. We use previous defect damage probability results in combination with defect mapping to make damage predictions. These predictions may then be evaluated by destructive testing using different protocols.

KEYWORDS: laser damage threshold; surface quality; defect mapping; non-destructive testing; damage prediction; test protocol; sparse defects

10447-48, SESSION 11

A real-time laser conditioning technique coupled with photothermal lens probe on 1064nm mirror

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SPEAKER BIOGRAPHY: Dr. Liu works in the Optical Manufacture Department of Research Center of Laser Fusion in China. The main research fields are the fabrication and testing of optical thin films

ABSTRACT TEXT: In high-power laser facility, the laser-resistance capacity of optical thin-film is significant for the final output energy. Laser conditioning (LC) is universally regarded and verified as an effective way to promote the laser induced damage threshold (LIDT) of optics, especially, the thin-film reflectors. The conventional LC procedure usually includes several full-aperture raster-scanning steps with an increment of exposure fluence from low to the level comparable with LIDT, called fluence ramp. By use of this method, the defects, which play the role of damage inducement, could be removed or pre-triggered. A problem is that the laser induced damage (LID) risk follows with LC. Defect-removal effect has chance to become destructive if the laser exposure is too strong. Therefore, in conventional LC, the fluence ramp usually starts from a low level to ensure safety. But this is a compromised choice: The low fluence treatment conservatively protects the defective cells from catastrophic breakdown. However, on normal reflective thin-films the cells without evident defect are the majority, and conservative treatment is unnecessary for these non-defective cells. They need an aggressive fluence to collect enough "dose" and generate LC effect. Considering all these points, conventional LC strategy usually contains several scanning steps to cover the fluence range from conservative to aggressive. For large-aperture optics, the time consumption of this strategy is enormous. If a LC strategy combines the conservative and aggressive plans together, it can realize a balance between damage-proof and dose harvest in one step, which would be benefit for LC efficiency.

Photo-thermal lens (PTL) probe technique has been widely applied to characterize the quality of optical materials and LC effect. Comparing with other non-contact characterization methods, such as optical microscopy, light-scattering, and fluorescence emission, photo-thermal lens probe (PTLP) is better at discovering the defects more responsible for LID, because photo-thermal absorption is the main damage mechanism under 1064nm nanosecond laser. Particularly for reflective thin-film, PTLP can detect the absorptive inclusions hiding in the coating layers. Our idea is, if the defects can be detected by PTLP, the exposure fluence could be dynamically controlled: for the high absorptive cell, weaken the fluence to avoid damage, otherwise, provide sufficient fluence to generate conditioning effect. This is a way to combine conservative and aggressive treatment together and named as adaptive laser conditioning (ALC).

We have presented a novel ALC concept that uses PTLP to detect defects in-situ and then carries out adaptive control of exposure fluence. The best advantage of ALC is that during conditioning procedure, the damage risk hiding in the defective cells can be suppressed to a low level, and in the meanwhile, the LIDT income of those non-defective cells can be earned sufficiently by one exposure. Thermal conductive function of spheric particle describes the theoretical connection between absorption and damage. Experiment actualizes the close-loop operation and verifies the performance of ALC. Results show that ALC possesses prominent advantages in damage-proof and laser dose supply thanks to its particular fluence control strategy. Future work will address the efficiency promotion to fit for the application on large-aperture optics. The time consumption of PTLP signal build-up could be shortened by increasing the pumping power and modulation frequency of the chopper, and by then ALC could operate in a several ten hertz repetition frequency.

KEYWORDS: laser conditioning; laser induced damage; photothermal deflection; reflective thin film

10447-49, SESSION 11

Photo-thermal measurements of the optical absorption in LBO with a “proxy pump” calibration technique

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SPEAKER BIOGRAPHY: Not Available

ABSTRACT TEXT: Photo-thermal technology provides sub-ppm level measurements of the optical absorption in many transparent bulk materials and coatings from UV to Mid IR radiation range. In order to obtain the absolute absorption numbers these methods require a proper calibration since they are based on comparison of the photo-thermal signal from the reference standard and the material under test.

In this work a new calibration approach with the use of a “proxy pump” with a wave length at which the material exhibits high optical absorption is described. This pump is shaped to have the same beam spot size as the main pump at which the optical absorption of the material is to be determined. The wavelength of the proxy pump is selected to get at least 20% absorption on the object to be able to make accurate absorption evaluation via direct loss measurements. Once the thermal field at the pump/probe overlap area in the material has the same profile both with the proxy and main pump, the sample is self-referenced. Consecutive tests with proxy and main pumps provide absolute absorption numbers for both.

LBO crystals are notorious objects for which the photo-thermal response is not easy to calibrate since the photo-thermal response is low and varies with the crystal orientation. In order to calibrate these materials using the above approach we used 2.4 and 2.3 nm pump radiation as a proxy pump. In this range LBO absorb about or more than 30 % per cm length. For the Type I SHG orientation close to the X-axis the photo-thermal response was found to be 4 times weaker than for fused silica and 3 times weaker than for Schott glass NG12 with the same absorption. With these coefficients taken into account, fused silica or NG12 glass can hence be used further as a reference calibration material in order to study the optical absorption of LBO crystals.

KEYWORDS: Photo-thermal methods for optical absorption measurement; Optical absorption of lithium triborate

10447-50, SESSION 12

U.S. National Committee proposed revision to the ISO Laser Damage Standard

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SPEAKER BIOGRAPHY: Donna Howland is Northrop Grumman Aerospace Systems (NGAS) Global Logistics and Operational Support (GLOS) Integrated Product Team Manager for Directed Energy Programs. She previously held the position of GLOS Functional Homeroom Manager. Prior to that, she held the position of Northrop Grumman Electronic Systems (NGES) Sector Manager of the Optical Components Technology Domain Integrated Product Team within Supply Chain Management. Donna has 20 years of experience in optics and lasers. She received a BS in Physics at California Lutheran University, a MS in Physics from Washington State University specializing in ultra-fast lasers and a MBA from Pepperdine University. Prior to her position with NGES, she was at NGAS and supported programs such as The Joint High Power Solid State Laser Program and the James Webb Space Telescope. She was also the 2015-2017 Chair of the Board of Directors of the Optics and Electro-Optics Standards Council.

ABSTRACT TEXT: This paper describes a proposed revision to the ISO laser damage standard that is being developed by a US National committee. It is intended that this proposed revision will alleviate the ambiguities associated with the current standards. This paper opens with an analysis of the extrapolative methods on which the current standard is based and shows the fundamental reasons why in many cases these methods fail. The proposed method is introduced. Several use cases are introduced to show the wide range of cases this standard can be used in.

KEYWORDS: Standards; Laser; Damage; ISO; Optic; Loss; Defect; OEOSC

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Characterization of 1-on-1 damage in high reflectors using the spatially-temporally resolved optical laser-induced damage (STEREO-LID) technique

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SPEAKER BIOGRAPHY: Not Available

ABSTRACT TEXT: Spatio-TEmporally REsolved Optical Laser-Induced Damage, or STEREO-LID, is a novel laser damage measurement which measures the actual fluence (and intensity) at which damage occurs in a single pulse [1]. This is accomplished by measuring the initiation time during the pulse and the initiation position within the beam profile. This technique has been demonstrated in the measurement of the defect distribution of films and surfaces [2,3].

In this paper, we demonstrate the technique to characterize laser-induced damage in high-reflectors by single 10 ns pulses at 1064 nm. The high reflectors were quarter-wave stack of HfO_2/SiO_2 on a fused silica substrate. Applying STEREO-LID to high reflectors required a change in geometry as the technique previously used light transmitted through the optic. Instead, the initiation time is identified by a disruption of reflection and scattered light. The initiation position is determined by imaging the backscattered laser light.

The results of STEREO-LID measurement will be compared to a traditional 1-on-1 damage probability measurement using the same number of test sites.

1. Y. Xu, L. A. Emmert, and W. Rudolph, "Spatio-TEmporally REsolved Optical Laser Induced Damage (STEREO LID) technique for material characterization," Opt. Express 23, pp. 21607-21614 (2015).

2. Y. Xu, A. Khabbazi, T. Day, A. Brown, L. A. Emmert, J. J. Talghader, E. Field, D. Kletecka, J. Bellum, D. Patel, C. S. Menoni, and W. Rudolph, "Comparative STEREO-LID (Spatio-TEmporally REsolved Optical Laser-Induced Damage) studies of critical defect distributions in IBS, ALD, and electron-beam coated dielectric films," Proc. of SPIE 9632, 963215 (2015).

3. Y. Xu, M. R. Abdulameer, L. A. Emmert, T. Day, D. Patel, C. S. Menoni, and W. Rudolph, "Comparison of defects responsible for nanosecond laser-induced damage and ablation in common high index optical coatings," Opt. Eng. 56, 011019 (2017).

KEYWORDS: LIDT measurement; defect density; high reflector; 1064 nm; ISO standard; ns pulse

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Damage resistance of nematic liquid crystal materials at femtosecond, picosecond, and nanosecond pulse lengths

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SPEAKER BIOGRAPHY: Dr. Tanya Z. Kosc received her PhD from the Institute of Optics in 2003 at which time she joined the Optical Materials Group at the Laboratory for Laser Energetics (University of Rochester) working on short pulse damage testing. Eventually she moved to the Laser System Science group and spent nearly a decade working on the OMEGA laser. She has recently rejoined the Optical Materials Group with research interests in the area of optical materials and specifically, liquid crystals.

ABSTRACT TEXT: Liquid crystals (LC) are unique optical materials in that they flow like a fluid but their molecules maintain positional order like a crystal. While most-frequently encountered in the display industry, LC devices are also commonly used to control light and manipulate polarization in various optical applications. Although liquid crystal optical elements such as circular polarizers and wave plates have been key components in the near-infrared portion of the 351-n, 1-ns, 40-TW OMEGA laser at the Laboratory for Laser Energetics (LLE) for over 30 years, to date they have not been widely considered for short-pulse (<1-ns) laser applications. To explore their potential use in ultrashort-pulse laser applications, the damage thresholds of a series of typical nematic LC fluids have been measured at 1053 nm at several pulse lengths between 600 fs and 1 ns to produce a benchmark database. Testing at a pulse repetition rate of 540 Hz was also conducted for pulse lengths <1 ns to simulate quasi-continuous-wave irradiation conditions. Candidates in this series of nematic LC materials were selected to explore the effect of varying degrees of ϖ-electron delocalization and electron density on their damage thresholds.

Bulk measurements were performed using LC materials in the nematic phase with no long-range preferred molecular alignment direction. This study collected additional data at 1-ns for some candidates, which had been evaluated for laser damage at 1053 nm, 1 ns in the 1980s when OMEGA was constructed, to take into account improvements in both LC materials synthesis and purification and in upgrades to LLE's laser-damage testing facilities. Damage detection relies on comparison of pre-shot and post-shot images of the test site. A test site was considered damaged either upon the formation of gas bubbles or the detection of a permanent change in the site appearance.

Damage-test values generally varied inversely with the degree of molecular ϖ-electron delocalization. Materials that possess no ϖ-electrons (e.g., consisted primarily of a fully saturate hydrocarbon skeleton) or only a relatively small amount of ϖ-electron delocalization showed higher damage thresholds than those containing benzene rings joining with linking groups to enhance ϖ-electron overlap, which had lower damage thresholds. At 600 fs, damage thresholds of ~2 J/cm2 were measured for several materials, which approaches values for fused silica in the short-pulse regime.

The experiments to date suggest that liquid crystal devices may be viable for use in ultrashort-pulse, high-peak-power laser applications to control intensity, phase, polarization, and other laser characteristics because of their unique properties such as high birefringence and optical nonlinearity. Future work will include testing at different laser wavelengths, investigation of damage thresholds of aligned LC devices, and detailed characterization of the performance of such devices under simulated operational conditions.

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KEYWORDS: short-pulse laser damage; nematic ; liquid crystals

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Convection- and radiation-dependent laser-induced damage thresholds for continuous-wave irradiation of coated, free-standing polymer films

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SPEAKER BIOGRAPHY: Keith Slinker has a PhD in physics from the University of Wisconsin and over 10 years of research experience in the aerospace and defense industry. He currently supervises a team of Universal Technology Corporation researchers developing multifunctional composite materials for the Materials and Manufacturing Directorate at the Air Force Research Laboratory. A current focus of his work is understanding high energy laser and materials interactions through determination of laser damage thresholds and mechanisms.

ABSTRACT TEXT: The emergence of efficient, solid state lasers is driving the need for novel approaches to optical components for deformable mirrors, beam shaping, incoherent beam combining, and reliably predicting the laser-induced damage threshold of such novel materials. One approach is the development of inorganic coatings on flexible substrates, which require <10 μm thicknesses of inorganic coatings to enable application to curved/deformable surfaces without significant risk of spallation. For such applications, it is now common to work with beam diameters greater than the thermal diffusion length of the material even for hundreds of seconds of irradiation. In this work the laser-induced damage thresholds (LIDT) of polymer (polyethylene terephthalate, PET) films with a variety of reflective inorganic coatings are assessed. The flexible polymer films (2.54 cm x 2.54 cm) are 55 μm thick, and the coatings (comprised of no more than 7 layers) are ≤ 1 μm. A single mode, 1.07 μm wavelength laser capable of 1 kW of continuous output was used with a beam expander to output either Gaussian beams or flat-top beams (with additional beam shaping optics) at the substrate plane with a typical beam diameter of 1.5 cm. The temperature rise and ultimate failure of the specimens, mounted in an unconstrained condition, were captured through time-synced visible and midwave infrared imaging. It is shown through theory and experiment that the temperature rise in each specimen is a predictable function of the laser power (with known density, heat capacity, thermal conductivity, and spectral absorptance of the specimen at the laser wavelength), and the expected interaction of the specimen with the environment through free convection and radiation. While the continuous-wave LIDT is traditionally measured in terms of the linear power density [1,2], here the LIDT measured in irradiance is demonstrated to be independent of the beam diameter and exposure time but dependent on the convection coefficient and spectral emittance of the specimen. Similar to the general method used for short exposure times when convection is negligible, it is shown that the in-plane thermal conduction can be ignored when predicting the maximum temperature rise in these specimens even for long exposure times. Further, these characteristic behaviors are predicted to be true for any specimen and laser conditions for which r^2 >≈ l k / h_eff where r is the beam diameter, l is the specimen thickness, k is the thermal conductivity, and h_eff is the effective convection coefficient including an approximation for radiation. Such understanding drives damage threshold prediction and design principles (e.g. substrate selection) beyond the materials interrogated in this study.

[1] R. M. Wood, “Laser-Induced Damage by Thermal Effects,” In D. Ristau [Laser-Induced Damage in Optical Materials] Taylor & Francis, 9-23 (2014).

[2] ISO 21254-1:2011, Lasers and laser-related equipment–Test methods for laser-induced damage threshold – Part 1: Definitions and general principles.

KEYWORDS: laser damage; flexible; convection; radiation; continuous wave; thin film; thermal diffusion

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Optical properties of a float-zone rectified and Czochralski grown in a steady magnetic field crystalline Si

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SPEAKER BIOGRAPHY: Research Associate at E.L. Ginzton Laboratory

ABSTRACT TEXT: In the Advanced Laser Interferometer Gravitational-wave Observatory (AdLIGO) design the circulating power in the interferometer arms will increase to 850 kW, which may limit the further improvement of the facility due to the increased mechanical/thermal losses in amorphous fused silica test masses. Alternatively crystalline silicon is being considered as a possible substrate material for the next generation of LIGO with available high-power 1.55 or 2.0 μm sources. With the use of crystalline test masses, the operational temperature of the LIGO interferometers can be reduced to cryogenic temperatures with a subsequent reduction of thermal noises. The required optical absorption for this material is estimated to be < 20 ppm/cm and the operational temperature can be around 125 K where the thermal expansion coefficient of Si is close to zero.

In this work, the optical absorption of single-crystal silicon grown with different methods is studied in the temperature range 80 – 300 K by the photo-deflection technique.

The lowest room-temperature optical absorption, 1.5 ppm/cm (at 1.55 ?m) and 5.5 ppm/cm (at 2.0 ?m) was measured for float-zone (FZ) rectified crystalline Si with sheet resistivity R greater than 30 kΩ-cm. The high-quality FZ Si offered by industry has a diameter up to 6 inches, which is far below the diameter required for LIGO Voyager, up to 12 inches. Single-crystal Si grown by the Czochralski (CZ) process is available in the required diameter however with the optical absorption greater than 100 ppm/cm and the electrical resistivity R up to 500 Ω-cm.

Single crystal silicon grown by a Czochralski process in the presence of a magnetic field (MCZ silicon) to suppress convective transport of oxygen from the crucible walls is a possible solution, with adequately low absorption and large enough diameter. The MCZ Si, grown at Shin-Etsu Handotai America, with R close to 4 kΩ-cm has shown room-temperature optical absorption as low as 2.5 ppm/cm and 6 ppm/cm at 1.55 and 2.0 ?m, respectively. The samples studied were cut from the boules of 8 inches in diameter and the method is capable to pull boules of 12 inches. The radial and axial homogeneity of the MZC Si was studied on disks cut from boules of 8 inch in diameter; MCZ boules as large as 12 inch have been grown.

This study opens the perspectives of application of the crystalline Si in future generations of the LIGO interferometers.

KEYWORDS: optical properties; crystalline silicon


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