SPIE

2012 Laser Damage

XLIV Annual Symposium on

Optical Materials for High-Power Lasers

23-26 September 2012

Abstract Book

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Location
National Institute of Standards and Technology (NIST)
Boulder, Colorado, USA

Conference
23–26 September 2012

Laser-Induced Damage Issues:

- Photonic bandgap materials
- High-power fiber lasers
- Fibers for high-power laser applications
- High-power/ultrafast lasers
- Multi-layer thin films
- Nonlinear optical and laser host materials

Mini-Symposium:

- Laser-induced plasma interactions

Other Laser-Induced Damage Related Issues:

- Measurement protocols
- Materials characterization
- Fundamental mechanisms
- Contamination of optical components
- Surface and bulk defects
- Metamaterials
- Thermal management of high-power lasers

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Laser Damage

XLIV Annual Symposium on

Optical Materials for High Power Lasers

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Laser Damage

Formerly Boulder Damage

XLIV Annual Symposium on

Optical Materials for High Power Lasers

Special Events

Sunday 23 September

17:30 to 20:30 **Registration Material Pick-up and Mixer at the Boulder Marriott** (2660 Canyon Blvd., Boulder)

18:00 to 19:00 **Roundtable Discussion at the Boulder Marriott**
Surface Versus Bulk Laser Damage Mechanisms

Panel Moderators: **Stavros Demos,** Lawrence Livermore National Lab.(USA); **Michael Feit,** Lawrence Livermore National Lab. (USA)

The main purpose of the roundtable is to warm up symposium participants intellectually and to prepare them for active discussions during the Symposium. This year, the Round Table discusses the mechanisms of laser induced damage in the bulk and on the surface of optical materials. The discussion starts with a joint presentation by the moderators involving both up to date experimental results and theoretical interpretations. The focus is to identify similarities and differences in important physical properties and localized conditions occurring during a damage event induced on the surface versus in the bulk, and the corresponding material response after energy deposition leading to the formation of damage sites, i.e. irreversible observable modification. Although mostly excitation with nanosecond pulses will be considered in this discussion, some similarities and differences when using ultrashort pulses will be addressed.

19:00 to 20:30 **Welcome and Social Mixer at the Boulder Marriott**
Registration Material Pick-up continues until 20:30

Monday 24 September

18:30 to 20:00 **ATFilms and Precision Photonics Open House and Reception**

Tuesday 25 September

19:00 to 20.30 **Wine and Cheese Tasting Reception at NCAR**

Wednesday 26 September

11:50 to 12:50 **NIST Facility Tours**

Monday AM • 24 September

07:30 to 16:00 **Registration Material Pick-up,** NIST Lobby Area

07:50 to 08:30 **Poster Placement at NIST**
Poster authors for the Monday poster session are to set up their posters at this time.

08:30 to 09:00 **Opening Remarks and 2011 Awards Presentation**
Joseph A. Menapace, Lawrence Livermore National Lab. (United States)

09:00 to 09:20 • INVITED SESSION

Overview of the Pacific Rim Laser Damage Meeting

Presenter: **Jianda Shao,** Shanghai Univ. of Optics and Fine Mechanics (China)

09:20 to 10:00 • SESSION I

Fundamental Mechanisms I

Session Chairs: **MJ Soileau,** Univ. of Central Florida Office of Research & Commercialization (USA); **Vitaly E. Gruzdev,** Univ. of Missouri-Columbia (USA)

9:20: **Mechanisms of femtosecond laser ablation of dielectrics revealed by double pump: probe experiment** *(Invited Paper)*, Stéphane Guizard, Alexandros Mouskeftaras, Nikita Fedorov, Sergey Klimentov, Commissariat à l'Énergie Atomique (France) . . . . [8530-1]

10:00 to 10:40 • Monday Poster Overview

Poster authors are asked to give a 2-minute/2-viewgraph overview of their posters in the order they appear in the program.

10:40 to 11:30 • Poster Session and Coffee/Refreshment Break

11:30 to 12:30 • SESSION 2

Fundamental Mechanisms II

Session Chairs: **Carmen S. Menoni,** Colorado State Univ. (USA); **Semyon Papernov,** Univ. of Rochester (USA)

11:30: **Dynamics of fracture inside a single crystal induced by a focused femtosecond laser pulse**, Masaaki Sakakura, Takaya Tochio, Yuki Ishiguro, Miki Nakabayashi, Yasuhiko Shimotsuma, Kazuyuki Hirao, Kiyotaka Miura, Kyoto Univ. (Japan) . . . . [8530-2]

11:50: **Spectroscopic investigation of fs laser-induced defects in polymer and crystal media**, Deepak L. N. Kallepalli Lakshmi Narayana, Lasers, Plasmas et Procédés Photoniques (France); Narayana Rao Desai, Univ. of Hyderabad (India). . . . . [8530-3]

12:10: **Temperature dependence of laser-induced damage thresholds by short pulse laser**, Katsuhiro Mikami, Shinji Motokoshi, Toshihiro Somekawa, Takahisa Jitsuno, Masayuki Fujita, Kazuo A. Tanaka, Osaka Univ. (Japan) . . . . [8530-4]

12:30 to 14:00 • Lunch Break

Mechanisms of femtosecond laser ablation of dielectrics revealed by double pump: probe experiment *(Invited Paper)*

Stéphane Guizard, Alexandros Mouskeftaras, Nikita Fedorov, Sergey Klimentov,
Commissariat à l'Énergie Atomique (France)

SPEAKER BIOGRAPHY: Stephane Guizard is a physicist working in the field of laser-solid interaction. Its studies concern electron excitation and relaxation mechanism, mainly in dielectrics: non linear excitation and propagation, electron phonon coupling and exciton trapping, ionising radiation effects and defect formation, optical breakdown and damaging, surface structuring by short laser pulses. Emphasis is put on exploring the dynamics of the processes using various time resolved femtosecond pump-probe techniques.

ABSTRACT TEXT: We study experimentally the basic processes leading to optical breakdown of dielectrics irradiated by short laser pulses (femtosecond and picosecond). To reveal the different mechanisms that occur during and after the interaction, we excite the samples with a pair of pump pulse of various wavelengths, durations, and at different delays. The evolution of the solid is probed by time resolve interferometry, allowing measuring the concentration of carriers and observing their relaxation. Contrasted behavior are observed in two important dielectrics. In SiO_2, we have obtained the first direct experimental evidence of electronic avalanche. This mechanism is not linked however to the optical breakdown since it occurs at higher intensities. In Al_2O_3, we do not observe any evidence of electron multiplication. The origin of these differences will be discussed. We have also measured the evolution of the excited carrier density as a function of pulse duration and intensity. Various important conclusions, concerning the criteria for defining the optical breakdown, and the parameter that can be used in simulations, can be derived from these studies.

Keywords: optical breakdown, dielctrics, femtosecond lasers, laser matter interaction, pump-probe expriments, electronic relaxation

8530-2, Session 2

Dynamics of fracture inside a single crystal induced by a focused femtosecond laser pulse

Masaaki Sakakura, Takaya Tochio, Yuki Ishiguro, Miki Nakabayashi, Yasuhiko Shimotsuma, Kazuyuki Hirao, Kiyotaka Miura, Kyoto Univ. (Japan)

SPEAKER BIOGRAPHY: Dr. Masaaki Sakakura, Born in Kyoto, Japan in 1976, Dr. Sakakura was educated at Kyoto University and obtained his his Ph.D. from Kyoto University in 2004. This April, he became an associate professor of Kyoto University. His research fields are physical chemistry, laser processing and measurement with ultrafast laser. Now, he is working on the investigation of mechanism of femtosecond laser processing inside transparent materials and the development of a novel laser processing system with a spatial light modulator.

ABSTRACT TEXT: Laser-induced deformation depends on the atomic structure of the material. In amorphous materials, the deformation is random or isotropic. On the other hand, in single crystals, anisotropic deformations occur in the specific directions, which is because of their regularly-arranged atomic structures. For example, when a fs laser pulse is focused inside rock-salt type crystalline materials (MgO, LiF, etc.) normal to the (001) plane, a void is formed in the photoexcited region and highly concentrated dislocation bands and cleavages are formed in the <110> and <100> directions, respectively. The directions of the dislocation bands and cleavages are often explained by the slip and cleavage planes of the crystals, however, stresses that induce these modifications have not been elucidated. In this study, we observed the dynamics of transient stress distributions after photoexcitation inside various single crystals by a pump-probe polarization microscope. After a femtosecond laser pulse was focused inside a MgO single crystal normal to the (001) plane, a void appeared in the photoexcited region and two stress waves (primary and secondary stress waves) were generated. In the primary stress wave, which propagated faster than the secondary one, the direction of the strain was identical to the propagation direction and the stress direction depended on the direction from the photoexcited region. In the secondary stress wave, there were tensile stresses normal to the (100) planes, which were identical to the cleavage planes. We will discuss the relation between the transient stress distribution and the laser-induced deformations in detail in the conference.

Keywords: pump-probe, transient stress, dynamics, femtosecond laser, single crystal, cleavage, dislocation, mechanism

8530-3, Session 2

Spectroscopic investigation of fs laser-induced defects in polymer and crystal media

Deepak L. N. Kallepalli Lakshmi Narayana, Lasers, Plasmas et Procédés Photoniques (France); **Narayana Rao Desai,** Univ. of Hyderabad (India)

ABSTRACT TEXT: We investigated formation of defects in four polymers namely Poly (methylmethacrylate) [PMMA], Polydimethylsiloxane [PDMS], Polystyrene [PS], and Polyvinyl alcohol [PVA] and crystal media such as Lithium Niobate [LiNbO3]. Spectroscopic studies of the femtosecond (fs) laser modified regions were systematically performed after fabricating several gratings and micro-channels. We observed emission from the fs laser modified regions of these polymers when excited at different wavelengths. Pristine polymers are not paramagnetic, but exhibited paramagnetic behavior upon fs irradiation. $LiNbO_3$ crystal has not shown any defect formation upon laser irradiation. Confocal micro-Raman studies were also performed to establish the formation of defects.

Keywords: Laser damage, Emission, Electron spin resonance, Confocal micro-Raman studies

8530-4, Session 2

Temperature dependence of laser-induced damage thresholds by short pulse laser

Katsuhiro Mikami, Shinji Motokoshi, Toshihiro Somekawa, Takahisa Jitsuno, Masayuki Fujita, Kazuo A. Tanaka, Osaka Univ. (Japan)

SPEAKER BIOGRAPHY: Katsuhiro MIKAMI was born in 1986. He is doctor student in Osaka University.

ABSTRACT TEXT: Temperature dependences of laser-induced damage thresholds for dielectric optical coatings were evaluated Ti:sapphire laser (wavelength 800 nm, pulse width 100 fs, 2 ps, and 200 ps) and Nd:YAG laser (wavelength 1064 nm, pulse width 4 ns). Experimental samples were a silica substrate and single-layer coatings of different materials; SiO_2, MgF_2, Al_2O_3, HfO_2, ZrO_2, and Ta_2O_5. The temperature dependence at short pulse width became weaker than that at long pulse width. From the results, we considered effects of temperature with separated laser-induced damage mechanisms; photoionization, multi-photon absorption, electron avalanche and plasma heating. As conclusions, free-electron generation in dielectric material (photoionization and multi-photon absorption) and plasma heating are almost independent on temperature. On the other hand, electron avalanche is dominant cause in the temperature dependence.

Keywords: Laser-induced damage, Temperature dependence, Pulse width dependence, Ultra-short pulse laser, Cryogenic cooled laser

Monday PM • 24 September

14:00 to 15:40 • SESSION 3

Fundamental Mechanisms III

Session Chairs: **Jianda Shao,** Shanghai Institute of Optics and Fine Mechanics (China); **Jonathan W. Arenberg,** Northrop Grumman Aerospace Systems (USA)

14:00: **Optical breakdown threshold and energy deposition in embedded nanostructures**, Karol A. Janulewicz, Chul Min Kim, Hak Jae Lee, Asep Hapiddin, Peter V. Nickles, Dickson Joseph, Kurt E. Geckeler, Gwangju Institute of Science and Technology (Korea, Republic of) . . [8530-5]

14:20: **Laser ablation mechanism of transparent dielectrics with picosecond laser pulses**, Mingying Sun, Fraunhofer-Institut für Lasertechnik (Germany) and Shanghai Institute of Optics and Fine Mechanics (China); Urs Eppelt, Fraunhofer-Institut für Lasertechnik (Germany) and RWTH Aachen (Germany); Claudia Hartmann, Fraunhofer-Institut für Lasertechnik (Germany); Christof Siebert, TRUMPF Laser- und Systemtechnik GmbH (Germany); Jianqiang Zhu, Shanghai Institute of Optics and Fine Mechanics (China); Wolfgang Schulz, Fraunhofer-Institut für Lasertechnik (Germany) and RWTH Aachen (Germany). . . . . [8530-6]

14:40: **Optical damage mechanism in borosilicate glass generated by a nanosecond pulsed laser at 1.064 micron**, Binh T. Do, Ball Aerospace & Technologies Corp. (USA); Mark W. Kimmel, Michael V. Pack, Randal L. Schmitt, Sandia National Labs. (USA); Arlee V. Smith, AS-Photonics, LLC (USA) . . . . [8530-7]

15:00: **Direct observation of UV laser-induced high-pressure glass-to-crystal transition and 3D visulization of structural dynamic evolution in fused silica**, Chunhong Li, Xin Ju, Univ. of Science and Technology Beijing (China) . . . . [8530-8]

15:20: **Surface and bulk effects in silica fibers caused by 405 nm CW diode laser irradiation and means for mitigation**, Cornell P. Gonschior, Karl-Friedrich Klein, Technische Hochschule Mittelhessen (Germany); Tong Sun, Kenneth T. Grattan, City Univ. London (United Kingdom) . . . . [8530-9]

15:40 to 16:30 • Poster Session and Refreshment Break

16:30 to 18:10 • SESSION 4

Fundamental Mechanisms IV

Session Chairs: **Amy L. Rigatti,** Univ. of Rochester (USA); **Stavros G. Demos,** Lawrence Livermore National Lab. (USA)

16:30: **Correlation of UV damage threshold with post-annealing in CVD-grown SiO_2 overlayers on etched fused silica substrates**, Manylibo J. Matthews, Nan Shen, Selim Elhadj, Phillip E. Miller, Arthur J. Nelson, Theodore A. Laurence, Julie Hamilton, Lawrence Livermore National Lab. (USA). . . . . [8530-10]

16:50: **Evaporation chemistry of CO_2-laser heated silica**, Selim Elhadj, Manylibo J. Matthews, Steven T. Yang, Diane J. Cooke, Lawrence Livermore National Lab. (USA) . . . . [8530-11]

17:10: **On the Einstein relation under optical absorption coefficient in nanostructured materials in the presence of laser**, Subhamoy Singha Roy, JIS College of Engineering (India) . [8530-12]

17:30: **Modeling laser irradiation of dielectrics: a road map to breakdown**, Oliver Brenk, Baerbel Rethfeld, Technische Univ. Kaiserslautern (Germany) . . . . [8530-13]

17:50: **Oscillatory term of the Keldysh formula**, Vitaly E. Gruzdev, Univ. of Missouri-Columbia (USA) . . . . [8530-14]

18:10 to 18:20 • Closing Remarks

18:30 to 20:00 • Open House and Reception

Optical breakdown threshold and energy deposition in embedded nanostructures

Karol A. Janulewicz, Chul Min Kim, Hak Jae Lee, Asep Hapiddin, Peter V. Nickles, Dickson Joseph, Kurt E. Geckeler,
Gwangju Institute of Science and Technology (Korea, Republic of)

SPEAKER BIOGRAPHY: Prof. Karol A. Janulewicz, MSc and PhD, both in quantum electronics from Warsaw university of Technology (WUT); also appointments at Institute of Plasma Physics and Laser Microfusion in Warsaw, WUT, University of York, Max Born Institute Berlin and GIST(S. Korea)

ABSTRACT TEXT: Very fast development in nanotechnology combined with optics is bringing on the forefront the question about the limits of application of the nanostructures in a strong optical field. Nano-materials have already started to be very promising targets at the the relativistic laser-matter interaction. As a target we used carbon nanotubes and multilayer graphene deposited on a sapphire wafer surface and embedded in a layer of protein. A 25 fs, p-polarised pulses from a 1 kHz-Ti;sapphire laser of energy up to 3 mJ were focused by a f/4 off-axis parabola (OAP) on a target positioned within an integrating sphere. The target surface morphology was characterized by transmission electron and atomic force microscopes. Beam intensity was controlled by a calibrated position along an axis of the integrating sphere. We measured reflected, and transmitted parts of the pump signal and from them calculated energy deposited in the material. Average thickness of the coating was about 200 nm with different, dependent on the material RMS. The measurements were conducted for two incident angles of 8 deg and 45deg, the former being the closest to s-polarisation case. The absorption measured up to an intensity of 2×10^{16} W/cm^2 showed a level in excess of 80%, increasing with the intensity. This is in contrast to metal nano-foils showing this level of absorption not until relativistic intensities. An intensity gap between the breakdown threshold (10^{13} W/cm^2) and the beginning of ablation was identified. The physical background of the effect will be discussed in detail.

Keywords: intense laser, nanomaterial, embedded nanostructure, absorption, ultra-short laser pulses

Laser ablation mechanism of transparent dielectrics with picosecond laser pulses

Mingying Sun, Fraunhofer-Institut für Lasertechnik (Germany) and Shanghai Institute of Optics and Fine Mechanics (China); **Urs Eppelt,** Fraunhofer-Institut für Lasertechnik (Germany) and RWTH Aachen (Germany); **Claudia Hartmann,** Fraunhofer-Institut für Lasertechnik (Germany); **Christof Siebert,** TRUMPF Laser- und Systemtechnik GmbH (Germany); **Jianqiang Zhu,** Shanghai Institute of Optics and Fine Mechanics (China); **Wolfgang Schulz,** Fraunhofer-Institut für Lasertechnik (Germany) and RWTH Aachen (Germany)

SPEAKER BIOGRAPHY: Mingying Sun is currently working on his joint doctorate of Fraunhofer Institute and Chinese Academy of Science (CAS). Between 2007 and 2009, He studied in Shanghai Institute of Optics and Fine Mechanics, CAS. From 2010, He works in the modeling and simulation group in Fraunhofer Institute of Laser Technology. His main topic is modeling and simulation of glass cutting with ultrashort laser pulses.

ABSTRACT TEXT: Thin glass sheets (thickness < 1mm) have a great potential in OLED and LCD displays. While the conventional manufacturing methods, such as mechanical scribing and breaking, result in poor edge strength, ultra-short-pulsed laser processing could be a promising solution, offering high-quality cutting edges. However laser precision glass cutting suffers from unwanted material modification and even severe damage (e.g. cracks and chipping). Therefore it is essential to have a deep understanding of the ultra-short-pulsed laser ablation mechanism of transparent dielectrics in order to remedy those drawbacks.

In this work, the laser ablation mechanism of transparent dielectrics irradiated by picosecond laser pulses has been studied. The laser ablation model describing the nonlinear absorption in transparent dielectrics and laser beam propagation in nonlinear media is presented. Using a single rate equation of electron density, ultrafast dynamics of free electrons are analyzed including multi-photon ionization, avalanche ionization and loss terms. Nonlinear absorption of photons, based on the dynamics of free-electron density, and laser beam propagation in transparent dielectrics are described and combined in the ablation model. The ablation criterion is based on the critical free-electron density, above which the plasma becomes strongly reflective and absorbing and thereby is found to be dense enough to cause either thermo-mechanical damage or even ablation. Based on our model, simulations and experiments have been performed to study the morphology and evolution of the ablation crater as well as the modified/damaged region induced by multiple incident ps laser pulses in glass. Both simulation and experimental results show good agreement, offering great potential for optimization of laser processing in transparent dielectrics.

Keywords: laser ablation mechanism, nonlinear absorption, beam propagation, transparent dielectrics, picosecond laser

8530-7, Session 3

Optical damage mechanism in borosilicate glass generated by a nanosecond pulsed laser at 1.064 micron

Binh T. Do, Ball Aerospace & Technologies Corp. (United States);
Mark W. Kimmel, Michael V. Pack, Randal L. Schmitt,
Sandia National Labs. (United States); **Arlee V. Smith,** AS-Photonics, LLC (United States)

SPEAKER BIOGRAPHY: Dr. Binh T. Do is a test engineer.

ABSTRACT TEXT: We studied theoretically the laser-plasma interaction, and performed experiments to show that the process leading to optical damage for nanosecond pulses is as follows: Multi-photon absorption and impact ionization initiate the optical breakdown. When the electron gas density is equal to the critical density, the electron gas strongly absorbs the laser beam through collective excitation since the frequency of the laser beam is equal to the plasma frequency. The laser beam drives the electron gas at its resonant oscillating frequency. The energy absorbed through collective excitation is much larger than that of the multi-photon absorption and impact ionization and this energy is mainly responsible for the damage morphology.

In our experiments, we used a single-longitudinal-mode, TEM00 spatial mode, 8-ns pulsed laser at 1.064 micron. To keep the damage threshold power below the SBS threshold, and also to minimize the effect of self focusing, we tightly focus the laser beam into the Borosilicate glass. The experimental result shows the change of the refractive index of the focusing region as the density of the electron gas in the glass induced by the laser absorption changes from sub-critical to critical, and the experimental results also show that the laser beam is reflected by the over-critical plasma. This reflection keeps the electron gas density to be not much larger than the critical density.

The time leading to physical damage was investigated previously by studying the optical damage in Borosilicate glass induced by a burst of laser pulses from a 100-femtosecond laser operating at 800 nm with a 25 MHz repetition rate. The result of this experiment shows that the plasma survives during duration the burst: it can be several minutes and the physical damage happens only after the plasma ceased. The result of this experiment also shows that the plasma exists longer than the 40-ns period of these laser pulses, and this experimental evidence shows that physical damage generated by nanosecond laser pulses in Borosilicate glass happens long after the laser pulse ceased.

Keywords: Optical breakdown, Borosilicate glass, Collective excitation, Multiphoton absoption, impact ionozation

8530-8, Session 3

Direct observation of UV laser-induced high-pressure glass-to-crystal transition and 3D visulization of structural dynamic evolution in fused silica

Chunhong Li, Xin Ju, Univ. of Science and Technology Beijing (China)

SPEAKER BIOGRAPHY: Prof. Xin Ju is a famous scholar in field of application of nuclear technology and methods in physics and materilas study. His group have obtained series of important acievements in damage mechanism study in nuclear materials induced by ions,electrons and laser beam.

ABSTRACT TEXT: Studies of glassy fused silica under extreme conditions such as high fluence laser irradiation are of increasingly significant scientific and technological importance. Here we show new physical interpretation of laser-induced damage initiation and evolution in amorphous silica. For the first time, we present systematic in-situ data disclosing the laser-driven phase transformation of amorphous silica to rutile-type and d-NiAs-type stishovite phases. We present 3-D morphologies of the complex damage structure including spherical-like voids and crack networks both of which were localized beneath the crater bottom. The coupling mechanism among adjacent voids and cracks was carefully discussed. The interaction between the formed stishovite phase, voids and cracks and the laser pulses will be intensive. This will significantly lower the damage threshold and increase damage growth. We propose a new model based on the shock-wave-propagation-induced phase transformation and the formation of voids and cracks. This work will provide insight into the damage behaviour of network forming glassy materials under extreme conditions.

Keywords: laser damage, fused silica, high pressure, phase transition, 3-D visulization, synchrotron X-ray, X-ray CTX-ray diffraction

Surface and bulk effects in silica fibers caused by 405 nm CW diode laser irradiation and means for mitigation

Cornell P. Gonschior, Karl-Friedrich Klein, Technische Hochschule Mittelhessen (Germany); **Tong Sun, Kenneth T. Grattan,** City Univ. London (United Kingdom)

SPEAKER BIOGRAPHY: Cornell Gonschior is a PhD student at City University London and conducts his research at the Technische Hochschule Mittelhessen. He received his diploma degree in Communications in 2007 with work on "100Gb Optical Communications". After that he found more interest in the basic physics of fiber-optics and the main area of research is defects and degradation of silica fibers due to exposure to ultraviolet light.

ABSTRACT TEXT: Surface and bulk effects in silica optics due to high intensity laser light are well known using short pulse and high power laser systems. Surfaces are quickly destroyed if not properly prepared and thoroughly cleaned. Linear and non-linear Absorption of high intensity laser light in the bulk of the optics causes material modifications. These can manifest in the formation of voids and cracks. In ablation experiments with very short pulses on wide band-gap dielectrics, periodic surface structures in the form of ripples were found. Surprisingly, we found similar structures on fiber end-faces after long-term irradiation with 405 nm CW laser light. Power densities on the end-face are in the range of 1 MW/cm^2, three magnitudes of order below the damage threshold. Nevertheless a ripple structure perpendicular to the polarization direction of the laser was formed and grows with irradiation time. The vertical cross-section of the structure was examined with transmission electron microscopy (TEM) and an amorphous silica layer with density lower than the bulk was found. The surface of this layer exhibits a porous structure with voids. An increased absorption band at 214 nm (E' center) along the fiber was discovered by spectral absorption measurements. E' centers at 214 nm can be generated by 405 nm laser light in the bulk, therefore defects on the surface are possible as well. The generation of defect centers on the silica surface can enhance the formation of an unstable surface layer. We suggest that the surface structure is formed by self-organization of a thin unstable surface layer due to surface ionization and Coulomb repulsion. It will be shown that this effect can be mitigated by increased fiber end-face quality, reducing the roughness, and by using end-caps or very short launch fibers, reducing the power density.

Keywords: fiber damage, surface damage, ripples, periodic surface structures, UV defects, two-photon absorption, single-mode fiber, single-mode laser

Correlation of UV damage threshold with post-annealing in CVD-grown SiO_2 overlayers on etched fused silica substrates

Manylibo J. Matthews, Nan Shen, Selim Elhadj, Phillip E. Miller, Arthur J. Nelson, Theodore A. Laurence, Julie Hamilton,
Lawrence Livermore National Lab. (United States)

SPEAKER BIOGRAPHY: Manyalibo Matthews has been in the laser program at Lawrence Livermore National Laboratory (LLNL) since 2006 researching optical damage mitigation methods for high-power laser optics. Prior to LLNL he was a Member of Technical Staff at Bell Labs in Murray Hill NJ working on photonic materials R&D. He holds a doctorate in physics from M.I.T. and bachelor's in applied physics from U.C. Davis. He has coauthored over 40 referred journal articles and holds 4 U.S. patents.

ABSTRACT TEXT: The damage threshold of fused silica optics used in high average power systems is thought to be limited by photoactive impurities in the near surface (polishing) layer, and electronic defects associated with fracture surfaces. However, a detailed understanding of the surface chemistry or structures associated with intrinsic absorbers, such as those associated with fracture surfaces has proven to be a difficult task given the stochastic nature of damage events. Furthermore, initiated damage sites possess other attributes besides photochemistry such as fractured surfaces and light scattering centers which can contribute to the overall damage mechanism in varying amounts not easily partitioned through experiment. Ideally a surface, decorated with absorbers but otherwise free of fracture and other macroscopic defects, might allow the study of damage as influenced by intrinsic photochemical changes alone. In the present work, a set of plasma-enhanced CVD (PE-CVD) and low-pressure (LP-CVD) SiO_2 films deposited onto high damage threshold SiO_2 substrates was studied in terms of damage threshold, annealing parameters and surface chemistry. A SiH4/N2O precursor mix was used to deposit a series of 1 to 6 µm thick layers of SiO_2 over HF etched and piranha cleaned SiO_2 substrates. X-ray Photoelectron Spectroscopy showed that the films were of high purity with Si:O ratios in the range of 1:2 to 1:2.5. A CO_2 laser was used to locally anneal the surface by scanning at 5-50 µm/s while monitoring in situ the instantaneous surface temperatures through micropyrometry. R-on-1 small beam damage testing shows that, while as-deposited films have relatively low damage thresholds, localized CO_2 laser annealing can be used to produce surfaces possessing damage thresholds equal to or in excess of the original etched substrate. Using Fourier transform infrared spectromicroscopy, the low damage threshold of the as-deposited films could be correlated with a high density of non-bridging (dangling bond) oxygen units, which also leads to a softening of the Si-O-Si asymmetric stretch mode and a decrease in average Si-O-Si bond angle relative to bulk annealed SiO_2. Time-resolved photoluminescence also showed a high density of apparent damage precursors that first increased in intensity, then decreased, as a function of peak treatment temperature. Taken together, our measurements yield an instructive view into a highly defective, poorly polymerized Si-O network which correlates with a low damage threshold, and how such a structure can be thermally annealed to yield improved damage performance.

Keywords: chemical vapor deposition, optical damage, Fourier transform infrared spectroscopy, thermal annealing, thin films, high power lasers, photoluminescence, x-ray photoelectron spectroscopy

8530-11, Session 4

Evaporation chemistry of CO_2-laser heated silica

Selim Elhadj, Manylibo J. Matthews, Steven T. Yang, Diane J. Cooke,
Lawrence Livermore National Lab. (United States)

SPEAKER BIOGRAPHY: Dr. Selim Elhadj works on the advanced damage mitigation development effort at LLNL (CA, USA)to address optics re-processing of LLNL's fusion-class laser. My area of focus is on laser-matter coupling, and solid-gas chemistry of fused silica. My formal background is in chemical engineering (PhD).

ABSTRACT TEXT: Evaporation rate data of CO_2-laser heated surfaces of silica is presented, along with a near-equilibrium analysis for heating temperatures ranging from 2500 K - 3000 K. Under reducing gas conditions (hydrogen) rates of evaporations are highest, while oxygen reduces evaporation rates below neutral conditions. The specific influence of these gases on the rates of evaporation is interpreted on the basis of reaction equilibrium at the heated spot, where temperature is measured by infrared imaging. Under “short” laser exposure conditions (<0.1 sec), the process of evaporation is purely pyrolitic and alternate solid-gas phase reaction pathways cease to play a role. Measurements under gas flow conditions show that evaporation rates are dependent on forced convection, thus the evaporation rate model presented describes both the transport kinetics via the mass transfer coefficient, and the reactions equilibrium via the temperature-dependent equilibrium constant. Reaction free energies can thus be extracted and compared to published results for validation. In addition, the results of these studies on bulk silica are used to model silica micron-sized particles heating with a CO_2-laser beam to determine the extent of laser-material coupling during particle evaporative shrinking.

Keywords: Silica, laser, gas, hydrogen, heating, thermodynamic, mass transport

On the Einstein relation under optical absorption coefficient in nanostructured materials in the presence of laser

Subhamoy Singha Roy, JIS College of Engineering (India)

SPEAKER BIOGRAPHY: Subhamoy Singha Roy, Ph.D, scientist

ABSTRACT TEXT: For the opposite inequality, the OAC oscillates with the modified photon energy without the consideration of the Wannier-Stark levels, which generally exists in a band due to the presence of a laser. In both the cases, the OAC exhibits the singularity when the incident photon energy ( ) tends to and the magnitude of the OAC depends to a large extent on the numerical values of the energy band constants of the said optoelectronic materials.

Keywords: optical absorption coefficient, optical matrix element

8530-13, Session 4

Modeling laser irradiation of dielectrics: a road map to breakdown

Oliver Brenk, Baerbel Rethfeld, Technische Univ. Kaiserslautern (Germany)

ABSTRACT TEXT: When a dielectric is irradiated with an ultrashort laser pulse the transparent material can become opaque and absorb the laser energy very efficiently. The onset of this strong absorption is called dielectric breakdown. Depending on the laser parameters the dielectric can then be heated, melted, or some material might even be ablated. For process material and to protect optical elements it is important to understand the absorption processes and the dielectric breakdown. Applying the multiple rate equation (MRE) introduced in [Rethfeld, PRL, 92:187401 (2004)] we investigate the conditions for breakdown focusing on the conduction band electron density.

The MRE is a numerical tool to simulate the transient conduction band electron density in a dielectric during irradiation with an ultrashort laser pulse. The model includes photoionization by applying the Keldysh formula [Keldysh, sovjet Physics, JETP, 20(5):1307 (1965)]. Tracing the energy of a conduction band electron during single photon absorption allows us to determine when the electron can perform impact ionization.

The results for the transient electron density are in very good agreement with a full kinetic approach using Boltzmann collision integrals [Kaiser et. al., PRB, 61(17):11437 (2000)]. The MRE, however, requires much less computational effort and therefore makes it easier to model different parameter sets.

The MRE now includes optical parameters which improves the accuracy of our simulations. The optical parameters, like reflectivity and refractive index, depend on the conduction band electron density. The reflectivity determines the intensity that is transmitted into the bulk, while the refractive index influences the field amplitude in the bulk and therewith the ionization and absorption rates inside the material. Thereby the optical parameters influence the time evolution of the conduction band electron density. Another optical parameter, the absorption coefficient, can be used to calculate the single photon absorption rate in a self consistent manner.

Having the optical parameters at hand we take a closer look at breakdown. The common approach to breakdown is to follow the conduction band electron density, when it reaches a certain critical density breakdown is supposed to happen. Using the MRE we are independent of such an assumption. Knowing the optical parameters and the conduction band electron density at any time we can follow breakdown without the need for any critical density criterion.

Knowing the photon absorption rates at any time we also included a depth dimension into the MRE model to simulate the conduction band electron density in the depths of the material. This allows us to estimate the depths up to which breakdown occurs and the therewith material modification can take place. Similar to [Christensen et. al. PRB, 79, 155424 (2009)]

The MRE was used to create “maps” showing when breakdown occurs for different parameters, like fluence and wavelength of the laser. This maps can serve as a guide to the choice of laser parameters in order to modify a material, or to avoid damage of optical components.

Keywords: ultrashort laser pulses, breakdown, dielectrics, femtosecond, multiple rate equation, damage threshold

8530-14, Session 4

Oscillatory term of the Keldysh formula

Vitaly E. Gruzdev, Univ. of Missouri-Columbia (United States)

SPEAKER BIOGRAPHY: Vitaly Gruzdev graduated from St. Petersburg Institute of Fine Mechanics and Optics with honors in 1994. In 2000 he received Ph. D. from S. I. Vavilov State Optical Institute (St. Petersburg, Russia). In 2001-2003 he was a visiting researcher at the group of Prof. Dr. D. von der Linde (University of Essen, Germany). Since3 2005 he is with the Department of MEchanical and Aerospace Engineering, University of Missouri.

ABSTRACT TEXT: The Keldysh formula is very frequently utilized for simulation of laser-induced photo-ionization in transparent solids. In spite of its popularity, its properties still have not been investigated in details. This talk is devoted to introduction of an oscillatory correction factor into the Keldysh formula. The original Keldysh formula was derived by neglecting the oscillatory terms [1] that were claimed to oscillate fast and therefore to reduce to the constant factor of 2. We have investigated the oscillatory contribution in details and confirm that it reduces to the constant factor of 2 only in the tunneling regime. In the multiphoton regime as well as for adiabatic parameter close to 1, the oscillations can give a significant (up to one order of magnitude) contribution to the photo-ionization rate that depends on laser and material parameters. We discuss dependence of that contribution on band structure and its relation to laser-induced variations of electronic bands.

[1] L. V. Keldysh, Sov. Phys. - JETP, v. 20 (5), pp. 1307-1314 (1965).

Keywords: laser ionization, photo-ionization, Keldysh formula, multiphoton ioniation, tunneling ionization, laser damage

Fundamental Mechanisms

10:40 to 11:30 and 15:40 to 16:30

Modeling energy transfer and transport in laser-excited dielectrics, Oliver Brenk, Nils Brouwer, Anika Raemer, Technische Univ. Kaiserslautern (Germany); Orkhan Osmani, Donostia International Physics Ctr. (Spain); Bärbel Rethfeld, Technische Univ. Kaiserslautern (Germany) . . . . [8530-46]

Stimulated Raman scattering damage in KDP crystal and its suppression, Wei Han, China Academy of Engineering Physics (China) . . . . [8530-47]

Comparison of material response following exit surface laser-induced breakdown in fused-silica and KDP, Stavros G. Demos, Raluca A. Negres, Rajesh N. Raman, Michael D. Feit, Lawrence Livermore National Lab. (USA) . . . . [8530-82]

Thin Films

10:40 to 11:30 and 15:40 to 16:30

Oxide mixtures for UV coatings, Céline Gouldieff, Frank R. Wagner, Institut Fresnel (France); Lars O. Jensen, Mathias Mende, Laser Zentrum Hannover e.V. (Germany); Jean-Yves Natoli, Institut Fresnel (France); Detlev Ristau, Laser Zentrum Hannover e.V. (Germany) and Ctr. for Quantum Engineering and Space-Time Research (Germany) . . . . [8530-48]

Laser-induced damage thresholds for 355nm AR coatings on LBO crystals, Shinji Motokoshi, Osaka Univ. (Japan) and ALPROT (Japan); Koji Tsubakimoto, Noriaki Miyanaga, Osaka Univ. (Japan); Masayuki Fujita, Osaka Univ. (Japan) and ALPROT (Japan) . . . . [8530-49]

Databases on damage threshold for HR and AR coatings in UV region, Shinji Motokoshi, Kota Kato, Katsuhiro Mikami, Takahisa Jitsuno, Osaka Univ. (Japan) . . . . [8530-50]

Applying hafnia mixtures to enhance the laser-induced damage threshold of coatings for third-harmonic generation optics, Mathias Mende, Lars O. Jensen, Henrik Ehlers, Laser Zentrum Hannover e.V. (Germany); Stefan Bruns, Michael Vergöhl, Fraunhofer-Institut für Schicht- und Oberflächentechnik (Germany); Peer Burdack, InnoLight GmbH (Germany); Detlev Ristau, Laser Zentrum Hannover e.V. (Germany) and Ctr. of Quantum Engineering and Space-Time Research (Germany) . . . . [8530-51]

Measured and simulated nanosecond laser damage probabilities of niobia-silica and zirconia-silica mixtures coatings, Xinghai Fu, Institut Fresnel (France); Andrius Melninkaitis, Vilnius Univ. (Lithuania); Laurent Gallais, Institut Fresnel (France); Simonas Kicas, Ramutis Drazdys, Institute of Physics (Lithuania); Valdas Sirutkaitis, Vilnius Univ. (Lithuania); Mireille Commandré, Institut Fresnel (France) . . . . [8530-52]

Optical resistance of GaN and InGaN thin films, Mindaugas Šciuka, Mantas Dmukauskas, Tomas Grinys, Andrius Melninkaitis, Vilnius Univ. (Lithuania) . . . . [8530-53]

Optimization of ion beam sputtered Y_2O_3 for high laser damage resistance, Dinesh Patel, Peter F. Langston, Laura M. Imbler, Colorado State Univ. (USA); Luke A. Emmert, Wolfgang Rudolph, The Univ. of New Mexico (USA); Ashot S. Markosyan, Roger K. Route, Stanford Univ. (USA); Martin M. Fejer, The Univ. of New Mexico (USA); Carmen S. Menoni, Colorado State Univ. (USA) . . . . [8530-54]

Laser-induced damage thresholds and optical properties of TiO_2 and Al_2O_3 coatings prepared by atomic layer deposition, Lars O. Jensen, Heinrich Mädebach, Detlev Ristau, Laser Zentrum Hannover e.V. (Germany); Jarmo Maula, Beneq Oy (Finland); Karlheinz Gürtler, Consultant (Germany) . . . [8530-55]

Temperature dependence of the optical absorption in amorphous Ta_2O_5 and SiO_2 dielectric thin films, Ashot S. Markosyan, Roger Route, Martin M. Fejer, Stanford Univ. (USA); Dinesh Patel, Carmen S. Menoni, Colorado State Univ. (USA) . . . . [8530-56]

10:40 to 11:30 and 15:40 to 16:30

Study of the LIDT degradation of optical components by intentional organic contamination, Benoit Mangote, Isabelle Tovena-Pecault, Jérôme Néauport, Commissariat à l'Énergie Atomique (France) . . . . [8530-57]

Scratch repair on fused silica optics by using a CO_2 laser, Philippe Cormont, Commissariat à l'Énergie Atomique (France); Laurent Gallais-During, Institut Fresnel (France); Laurent Lamaignère, Jean-Luc Rullier, Patrick Combis, Commissariat à l'Énergie Atomique (France) . . . . [8530-59]

Effect of conventional fused silica preparation and deposition techniques on surface roughness, scattering, and laser damage resistance, Simona Liukaityte, Gintare Bataviciute, Egidijus Pupka, Mindaugas Šciuka, Vilnius Univ. (Lithuania); Irena Kraujaliene, Dainius Tumosa, Alfridas Skrebutenas, Kestutis Juškevicius, Optolita UAB (Lithuania); Ramutis Drazdys, Rytis Buzelis, Tomas Tolenis, Simonas Kicas, Institute of Physics (Lithuania); Andrius Melninkaitis, Vilnius Univ. (Lithuania). . . . . [8530-61]

Cleaning practices and facilities for the national ignition facility, James A. Pryatel, Lawrence Livermore National Lab. (USA) . . . . [8530-62]

Laser-induced damage resistance of UV coatings on fused silica and CaF_2, Byungil Cho, Andy Lyu, Newport Corp. (USA); Mark Feldman, Spectra-Physics®: A Newport Corp. Div. (USA) . . . . [8530-83]

Modeling energy transfer and transport in laser-excited dielectrics

Oliver Brenk, Nils Brouwer, Anika Raemer, Technische Univ. Kaiserslautern (Germany); **Orkhan Osmani,** Donostia International Physics Ctr. (Spain); **Bärbel Rethfeld,** Technische Univ. Kaiserslautern (Germany)

ABSTRACT TEXT: Understanding laser interaction with dielectrics is of great importance for theoretical predictions and practical applications. To control material modification one needs to know how the energy of a laser pulse is transferred to the lattice and how the heat is spread. We apply different approaches depending on the timescale of interest:

For the description of ultrashort laser pulses and a timescale on the subpicosecond range a variety of different models is available. If one is interested in modeling specific physical details a kinetic approach is suitable. We solve complete Boltzmann collision integrals [Kaiser et. al., PRB 61:11437, (2000); Rethfeld et. al., APA 109, 19 (2010)] to calculate the transient electron and phonon distribution functions while also modeling the dynamics within the valence band. Relaxation processes like thermalization, electron-phonon coupling and recombination are followed in detail. This accuracy comes at the price of high computational costs and a limited numerical flexibility. Here the multiple rate equation (MRE) enters the stage.

The multiple rate equation, introduced in [Rethfeld, PRL, 92:187401 (2004)], consists of a system of coupled ordinary differential equations and focuses on the evolution of the conduction band electron density keeping track of the energy of each electron. This narrow view allows for high flexibility while still giving accurate results compared to the Boltzmann approach. But the two models are not mutually exclusive: The Boltzmann approach can verify calculations done with the MRE, while the MRE can scan the parameter space and show points of interest worthy of a closer look using a full kinetic approach like the Boltzmann equation.

So far both models mentioned before neglect the effect of heat and density transport in the material which is reasonable on the femtosecond and subpicosecond time range. Here the density dependent two temperature model (nTTM) can carry on with modeling heat relaxation and transport in dielectrics [Van Driel, PRB, 35:8166 (1987)]. In the frame of the nTTM, the laser energy is at first transmitted to the electronic system and then transferred to the lattice via electron-phonon coupling. The nTTM assumes that each system is equilibrated and respective temperatures can be defined. It also considers the conduction band electron density and can be used to simulate time periods up to several hundred picoseconds.

We combine the individual strengths of our models. From the Boltzmann approach we extract the density-dependent electron-phonon coupling parameter which serves as an input for the nTTM. The density evolution of the conduction band electrons is obtained using either the MRE or Boltzmann approach. We investigate the effect of transport on the threshold fluence for laser damage.

The variety of different connected models allows us to model a vast range of different materials and laser pulses on a timescale of several hundred picoseconds.

Keywords: dielectrics, damage threshold, multiple rate equation, heat relaxation, transport, Boltzmann approach

8530-47, Session PSM1

Stimulated Raman scattering damage in KDP crystal and its suppression

Wei Han, China Academy of Engineering Physics (China)

SPEAKER BIOGRAPHY: Mr. Wei Han majored in optics engineering.

ABSTRACT TEXT: Bulk pinpoint damage of a ‘double-lungs’ pattern with the near symmetry axis parallel to the polarization of the pump laser, has been experimentally observed in a 33-cm diameter KDP type II third harmonic generation crystal at an unexpected low irradiance. Theoretical investigation demonstrates a great connection between this damage pattern and transverse stimulated Raman scattering (TSRS) effect. The result of numerical simulations shows that the scattered light propagating transversely has a relatively lower fluence but exceedingly high intensity.

In order to suppress the transverse stimulated Raman scattering effect in KDP crystals, we deliberately used nanosecond pulses at the wavelength of 527nm to initiate pinpoints which are in a line parallel to extraordinary axis at the central of the crystal. These pinpoints build a wall to intercepts the TSRS scatter light on its transverse transmission, thus reduce the growth path of transverse scattered light. We conducted an experiment to investigate the effectiveness of the proposed method. This will be discussed in the paper too.

Keywords: laser-induced damage, KDP crysral, stimulated Raman scattering

Comparison of material response following exit surface laser-induced breakdown in fused-silica and KDP

Stavros G. Demos, Raluca A. Negres, Rajesh N. Raman, Michael D. Feit,
Lawrence Livermore National Lab. (United States)

SPEAKER BIOGRAPHY: Stavros G. Demos is an experimental physicist and has been involved in the field of Laser Damage since he jointed Lawrence Livermore National Laboratory in 1997. Stavros has served in the organizing committees for numerous conferences including CLEO and Photonics West. He has coauthored over 200 journal publications and conference proceedings and 20 patents in the fields of laser-defect interactions in optical and laser materials, laser damage, optical characterization and diagnostics instrumentation and, biomedical photonics.

ABSTRACT TEXT: Fused silica and potassium dihydrogen phosphate (KDP) are key optical materials in ICF class laser systems. They both exhibit limitations in performance under high fluence irradiation associated with laser-induced damage. Laser damage is associated with localized energy deposition into the material due to the presence of pre-existing light absorbing defects. The subsequent material response involves material heating, modification, evaporation, fracture, and ejection and ultimately leads to the formation of either a void in the bulk or a crater on the surface.

These two materials are required to be exposed to similar laser energy fluences. However, their material properties are distinctly different. Fused silica is amorphous while KDP is a tetragonal crystal. Fused silica has very low thermal expansion coefficient and a high temperature has to be reached before evaporation is significant. KDP has a thermal expansion coefficient about 50 times larger than that of silica and a very low melting temperature so evaporation can be significant at much lower temperatures. Therefore, one expects the dynamic response in each material following ns pulse laser energy deposition to be, at least in part, influenced by their respective material properties. To address the impact of these material property differences, we have extended our previous studies of the material behavior following exit surface damage in fused silica with corresponding experiments performed on KDP. The results demonstrate a very different early stage behavior where the evaporation and ejection of material exhibit different kinetics between the two materials. After this initial period, an ejected material jet forms in KDP that is similar to that observed in fused silica. Furthermore, the temporal duration of the material ejection process is much longer in KDP, extending to more than 100 μsec from the initiation pulse compared to about 20 μsec measured with fused silica.

Comparison of the results in KDP and fused silica indicates the importance of melting and evaporation temperatures in determining the material response when both materials are subjected to similar initial temperatures and pressures during a damage event. The results also suggest temperature differences within the affected material volume play an important role in the material ejection process.

Oxide mixtures for UV coatings

Céline Gouldieff, Frank R. Wagner, Institut Fresnel (France);
Lars O. Jensen, Mathias Mende, Laser Zentrum Hannover e.V. (Germany);
Jean-Yves Natoli, Institut Fresnel (France); **Detlev Ristau,** Laser Zentrum Hannover e.V. (Germany) and Ctr. for Quantum Engineering and Space-Time Research (Germany)

SPEAKER BIOGRAPHY: Frank Wagner obtained his MSc degree in Physics 1997. (University of Göttingen, Germany). He finished his PhD thesis on the surface properties of excimer laser ablated polymers in 2000 (EPFL, Lausanne, Switzerland). He then developed the water-jet guided laser as R&D Engineer at Synova SA (Switzerland) until 2004. Finally, he joined the high power photonics group of the Fresnel Institute in Marseille, France, as an assistant professor.

ABSTRACT TEXT: In the past years, the usage of oxide mixtures, for example in "rugate" filters, lead to an important improvement of laser damage thresholds of coated components at infrared wavelengths. One reason for this improvement is the absence of abrupt interfaces in the coating, where usually higher defect and impurity concentrations are present.

In the UV wavelength range, the difference between an interface and the "bulk" of a thin film is less marked, as the laser damage threshold of the pure materials decreases. In fact, UV photons more easily couple to the material and may generate defects or charge existing point defects thus creating additional absorption centers.

We present nanosecond laser damage measurements of pure oxides and binary mixtures at 355 nm giving hints on the potential of oxide mixtures in UV applications. We then analyze the experimental results paying particular attention to the possibility of light induced laser damage precursors.

Keywords: laser damage, oxide mixture, suv coating, slight induced damage precursors, nanosecond laser induced damage, $Al_2O_3HfO_2SiO_2$

8530-49, Session PSM2

Laser-induced damage thresholds for 355nm AR coatings on LBO crystals

Shinji Motokoshi, Osaka Univ. (Japan) and ALPROT (Japan);
Koji Tsubakimoto, Noriaki Miyanaga, Osaka Univ. (Japan);
Masayuki Fujita, Osaka Univ. (Japan) and ALPROT (Japan)

SPEAKER BIOGRAPHY: His main works are developments of high-power lasers and their high-resistance optics. Since 2010, he also has worked on harmonic conversion for high-average power lasers in Advanced Laser and Process Technology Research Association (ALPROT).

ABSTRACT TEXT: High-average power lasers with over 10-kHz repetition pulses have been required in laser material processing. For some materials, in addition, laser pulses at UV region are needed because of the large absorptions and the fine processings. So, harmonic conversion technologies with high damage resistance are important problems. We have evaluated the damage thresholds for AR coating on LBO crystals. The AR coatings were prepared on a common LBO crystal by some of coating makers with high damage resistances on "Database Test" of ILT. The damage thresholds were determined by N-on-1 method at 355-nm wavelength and 8-ns pulse width.

Keywords: Damage threshold, LBO crystal, AR coating, 355 nm, High average power laser

Databases on damage threshold for HR and AR coatings in UV region

Shinji Motokoshi, Kota Kato, Katsuhiro Mikami, Takahisa Jitsuno,
Osaka Univ. (Japan)

SPEAKER BIOGRAPHY: He is chief researcher for laser and optical technologies, and has developed the optics for high power lasers since 1994. His other work is the development of solar pumped solid-state laser systems.

ABSTRACT TEXT: Institute for Laser Technology in Japan has opened the examinations of damage threshold for various optical devices required from optics makers since 2005. We have proceeded to construct of database on damage threshold of optics for high-power lasers, cooperating with many Japanese coating makers. It will be connected with the design of laser systems and the improvement of optical technologies. We had presented the database on damage thresholds for HR and AR coatings at wavelengths of 1064 and 532 nm in the symposiums.1, 2) In this time, databases on the damage threshold for UV optics would be presented. The optics, that is HR and AR coatings at each wavelength of 355 nm and 248 nm, were prepared by 11 to 17 coating makers. The average thresholds of HR and AR coatings at 355 nm with 9-ns pulse width were 25 - 30 J/cm^2 and 5 - 10 J/cm^2, respectively. The results would be compared with that of damage competition in the symposium 2010.3) And also, the average thresholds at 248 nm with 10 ns were about 3 J/cm^2 both for HR and AR coatings.

1) S.Motokoshi, et al., Database on Laser-Induced Damage Thresholds for AR and HR Coatings in Japan, Proceedings of SPIE Vol. 7842 (2011) 7842-14.
2) S.Motokoshi, et al., Database on Damage Thresholds of Picoseconds Pulse for HR Coatings, Proceedings of SPIE Vol. 8190 (2012) 8190-57.
3) C.J.Stolz, et al., DBS Thin Film UV Antireflection Laser Damage Competition, Proceedings of SPIE Vol. 7842 (2011) 7842-6.

Keywords: Database, Damage threshold, HR coating, AR coating, 355 nm, 248 nm

8530-51, Session PSM2

Applying hafnia mixtures to enhance the laser-induced damage threshold of coatings for third-harmonic generation optics

Mathias Mende, Lars O. Jensen, Henrik Ehlers, Laser Zentrum Hannover e.V. (Germany); **Stefan Bruns, Michael Vergöhl,** Fraunhofer-Institut für Schicht- und Oberflächentechnik (Germany); **Peer Burdack,** InnoLight GmbH (Germany); **Detlev Ristau,** Laser Zentrum Hannover e.V. (Germany) and Ctr. of Quantum Engineering and Space-Time Research (Germany)

SPEAKER BIOGRAPHY: Mathias Mende was born in Hannover in 1981. He studied physics at the Leibniz Universität Hannover were he received his diploma in 2009. Since March 2009 he is developing ion beam sputtering processes at the Laser Components Department of the Laser Zentrum Hannover.

ABSTRACT TEXT: The generation of third harmonic radiation (THG) is required for many pulsed solid state laser applications in industry and science. In this contribution, the coatings for two necessary optical components, dichroic mirrors and nonlinear optical (NLO) crystals are in the focus of investigation. Because of the high bulk damage threshold Lithium Triborate (LBO) crystals are applied for this study. HfO2/SiO2 mixtures are employed as high refractive index material to improve the power handling capability of the multilayers. All coatings are produced by Ion Beam Sputtering (IBS) using a zone target assembly for the deposition of material mixtures. The atomic composition and the oxidation ratio of different hafnia silica mixtures are analyzed by X-ray photoelectron spectroscopy (XPS). The influence of different deposition temperatures and post annealing on the optical properties and the amorphous microstructure of the films is investigated by UV/Vis/NIR spectroscopy and X-ray diffraction (XRD). The laser induced damage thresholds at 355nm wavelength for nanosecond pulse durations are measured in a 10000on1 experiment complying with the standard ISO21254. Furthermore the optical components are tested under real application conditions.

Keywords: IBS Hafnia Mixtures, LBO, THG, XPS, XRD, Laser Damage

8530-52, Session PSM2

Measured and simulated nanosecond laser damage probabilities of niobia-silica and zirconia-silica mixtures coatings

Xinghai Fu, Institut Fresnel (France); **Andrius Melninkaitis,** Vilnius Univ. (Lithuania); **Laurent Gallais,** Institut Fresnel (France); **Simonas Kicas, Ramutis Drazdys,** Institute of Physics (Lithuania); **Valdas Sirutkaitis,** Vilnius Univ. (Lithuania); **Mireille Commandré,** Institut Fresnel (France)

ABSTRACT TEXT: Mixed metal oxide coatings of ZrO_2 / SiO_2, and Nb_2O_5 / SiO_2 as well as films of pure SiO_2, ZrO_2 and Nb2O5 have been prepared by the Ion Beam Sputtering (IBS) technique and characterized on their physical properties. The Laser-Induced Damage Thresholds (LIDT) of these samples have been measured at 1064 nm laser with the 1-on-1 mode in the nanosecond regime. The optical resistance results obtained from laser damage probability curves indicate a decrease of the LIDT in both sets of the mixtures when the content of the high index material is increased. A model has been employed in order to relate the laser damage probability with the material properties of the mixtures and the initiating defects. The influence of the initiating defects properties and the thermal properties of the mixtures on the laser probability is then studied by using this model. Following this analysis, discussions are made on the relationship between the defect density and the property of both initiating defect and mixtures.

Keywords: Optical coatings,laser induced damage,nanosecond,mixture oxides

8530-54, Session PSM2

Optimization of ion beam sputtered Y_2O_3 for high laser damage resistance

Dinesh Patel, Peter F. Langston, Laura M. Imbler, Colorado State Univ. (United States); **Luke A. Emmert, Wolfgang Rudolph,** The Univ. of New Mexico (United States); **Ashot S. Markosyan, Roger K. Route,** Stanford Univ. (United States); **Martin M. Fejer,** The Univ. of New Mexico (United States); **Carmen S. Menoni,** Colorado State Univ. (United States)

SPEAKER BIOGRAPHY: Dinesh Patel received the B.Sc. and Ph.D. degrees from the university of Surrey, England. He is currently a research associate at the Electrical and Computer Engineering Department, Colorado State University. His present research areas are coatings for high laser damage coatings in the visible, IR, UV and ultra-fast optics using ion beam sputter deposition system. He also has ongoing interests in chemically assisted ion-beam etching, high vacuum evaporation, optical and structural characterization of materials.

ABSTRACT TEXT: Renewed interest in Y_2O_3 has shown enhancement in the index and bandgap engineering to the levels of present high index HfO_2 optical coating. To this end we have investigated the ion beam sputtering of Yttrium oxide (Y_2O_3) as an alternative for high index layers in interference coatings for high power lasers. An attractive property of this material is its high thermal conductivity. We will present results on how the material properties are influenced by the deposition conditions including the dependence on the target material, if it is an oxide or metal. Studies of the laser damage performance at ~ 1 micron wavelength over a broad range of laser pulsewidth will be presented.

This work is supported by ONR grant No. N00014-07-1-1068

Keywords: ion beam sputtering, oxide films Y_2O_3

Laser-induced damage thresholds and optical properties of TiO_2 and Al_2O_3 coatings prepared by atomic layer deposition

Lars O. Jensen, Heinrich Mädebach, Detlev Ristau,
Laser Zentrum Hannover e.V. (Germany); **Jarmo Maula,** Beneq Oy (Finland);
Karlheinz Gürtler, Consultant (Germany)

ABSTRACT TEXT: Atomic Layer Deposition (ALD) allows for the deposition of homogeneous and conformal coatings with superior microstructural properties and well controllable thickness. As a consequence, ALD-processes have moved into the focus of optical thin film research during the last decade. In contrast to this, only a relatively small number of investigations in the power handling capability of ALD-coatings have been reported until now. The present contribution summarizes results of a study dedicated to the optical properties of single layers and high reflecting coating systems of TiO_2 and Al_2O_3 deposited by ALD which has been performed in a cooperation of Beneq Oy with research institutes during the last years. Besides Laser Induced Damage Threshold (LIDT) values, the spectral characteristics as well the absorption and scatter losses are discussed and compared to typical parameters of competing process concepts. LIDT data were measured using a Nd:YAG-laser in 1000 on 1 mode (ISO 21254) at 1.064 µm with a beam diameter of 330 µm and a pulse duration of 8 ns. For the determination of absorption losses a laser calorimeter (ISO 11551) operated in conjunction with a cw Nd:YAG laser was employed. Scatter losses were characterized on the basis of a TS-measurement facility (ISO 13696) at the wavelength 633 nm. The results indicate a promising potential of ALD-processes for the production of laser coatings.

Keywords: Atomic Layer Deposition, LIDT Multilayer Coating

Temperature dependence of the optical absorption in amorphous Ta_2O_5 and SiO_2 dielectric thin films

Ashot S. Markosyan, Roger Route, Martin M. Fejer, Stanford Univ. (United States);
Dinesh Patel, Carmen S. Menoni, Colorado State Univ. (United States)

SPEAKER BIOGRAPHY: Dr. Ashot S. Markosyan , Physical Sciences Research Associate at E.L. Ginzton Laboratory, Stanford University.

ABSTRACT TEXT: Ta_2O_5 and SiO_2 are high-index and low-index materials commonly used in interference coatings for high average-power lasers. These coatings can change their performance due to substantial amount of heat released at the surface when exposed to intensities above 100 kW/cm^2. The temperature variation of the optical absorption of amorphous thin films Ta_2O_5 and SiO^2 has been measured with the use of the photothermal common-path interferometric (PCI) technique in the temperature range 22 - 350°C. Results will be presented on the temperature dependence of the absorption at 1064 nm and 266 nm wavelengths. The results provide insight on the role of the optically active defects in affecting absorption losses.

Keywords: Thin films, Optical absorption

Study of the LIDT degradation of optical components by intentional organic contamination

Benoit Mangote, Isabelle Tovena-Pecault, Jérôme Néauport,
Commissariat à l'Énergie Atomique (France)

ABSTRACT TEXT: The lifetime of optical components submitted to high laser fluences is degraded under organic contaminated environment. Our previous studies have shown that chemical species outgassed from materials present in the laser environment of the Ligne d'Intégration Laser (LIL) and in the optics packaging (phthalates, silicones, and aromatic compounds) are potential contaminants for optics. In order to avoid the presence of such molecules in the Megajoule Laser (LMJ) environment, a new comprehensive program is started up using a qualified Micro-chamber/ Thermal Extractor (M-CTE250 Markes International) for controlled contaminations of optics. The final target is the development of a qualification procedure to determine the compatibility of materials used for the building of the LMJ with the LMJ optics. First results of this program will be presented.

Keywords: Laser induced damage threshold, Organic contamination, Outgassing

Scratch repair on fused silica optics by using a CO_2 laser

Philippe Cormont, Commissariat à l'Énergie Atomique (France);
Laurent Gallais-During, Institut Fresnel (France); Laurent Lamaignère,
Jean-Luc Rullier, Patrick Combis, Commissariat à l'Énergie Atomique (France)

SPEAKER BIOGRAPHY: Philippe Cormont has been at CEA since 1987 working in optical components characterizations, first for the Atomic Vapor Laser Isotope Separation and later in the Laser Megajoule facility. He is currently in charge of the fabrication of the phase plates and the flat windows for LMJ. His research interests are in ways to increase the lifetime of optical components.

ABSTRACT TEXT: Fusion class power laser facilities such as National Ignition Facility (NIF) or Megajoule laser (LMJ) need large optical components with high wavefront quality and high resistance to laser-induced damage. High surface quality in terms of flatness can be obtained with long time polishing and frequent control. On the other hand, it is necessary to limit time polishing and optic handling if you do not want scratches on surface because scratches have been identified as a major contributor to laser damage.

We propose here a process after polishing in order to remove the unwanted scratches. This process consists to locally melt the silica in the scratched area. This has been performed with a CO_2 laser.

We present observations made with confocal microscopy. The observations of the scratches were made before and after reparation. Scratches have an important amount of cracks under the surface. The cracks under the surface, that are not completely repaired, can be detected with these observations. 3D optical profiler was also used to check the small deformation of the surface after the repair.

The characterizations were completed by laser damage tests that finally prove the effectiveness of the repair.

Keywords: Fused silica, laser mitigation, CO_2 laser, optics surface defects

Effect of conventional fused silica preparation and deposition techniques on surface roughness, scattering, and laser damage resistance

Simona Liukaityte, Gintare Bataviciute, Egidijus Pupka, Mindaugas Šciuka, Vilnius Univ. (Lithuania); **Irena Kraujaliene, Dainius Tumosa, Alfridas Skrebutenas, Kestutis Juškevicius,** Optolita UAB (Lithuania); **Ramutis Drazdys, Rytis Buzelis, Tomas Tolenis, Simonas Kicas,** Institute of Physics (Lithuania); **Andrius Melninkaitis,** Vilnius Univ. (Lithuania)

SPEAKER BIOGRAPHY: Simona Liukaityte obtained bachelor's degree in Vilnius University, Faculty of Physics in 2011 and continues master studies in Laser physics and optical technologies. Since 2009 she is working on optical components characterizations at Laser Research center.

ABSTRACT TEXT: Despite of growing improvement in optical polishing and deposition technologies optical resistance of the laser components used for high-power UV applications remains insufficient in many cases. In this study influence of different fused silica substrate preparation, post treatment processing and deposition techniques are examined in terms of surface scattering, roughness and optical resistance. The conventional techniques of polishing, etching, annealing and finally surface cleaning of substrates were investigated. Further a part of samples were also coated with SiO2 monolayer by Ion Beam Sputtering (IBS) technique. Surface quality was characterized prior and after the treatment and deposition processes by the means of total integrated scattering (TIS) and atomic force microscopy (AFM). The experimental results of surface roughness measurements exhibited a good correlation between AFM and TIS methods. Further optical resistance was characterized for 355 nm, 50 Hz, 10 ns laser radiation performing 1-on-1 sample exposure test with high resolution micro-focusing approach. A dominating damage precursor ensembles produced during manufacturing processes were indentified and directly compared. Finally the conclusions about the quality influencing factors of investigated processes were drawn.

Keywords: laser induced damage, total integrated scattering, surface roughness, polishing, etching

Cleaning practices and facilities for the national ignition facility

James A. Pryatel, Lawrence Livermore National Lab. (United States)

Speaker Biography: Mr. James A. Pryatel , after receiving a B.S. degree in Mechanical Engineering from Carnegie Mellon University in 1970, James Pryatel had an extensive engineering and management career in the nuclear power industry. In 1997 Pryatel joined the NIF project at LLNL and has been developing processes for cleaning and maintaining the cleanliness of the laser system optics and is presently the Cleanliness Protocol Manager for the NIF.

ABSTRACT TEXT: The emphasis on cleanliness on the NIF is necessary to minimize the potential for contamination-induced laser damage of the optical surfaces in high powered lasers. In addition, there is a need for low obscuration to assure that high laser transmission efficiency is maintained.

A major challenge for the NIF was the precision cleaning of large stainless steel and aluminum parts and structures, which included vessels as large as freight cargo containers. In addition there was the challenge of cleaning thousandes of optics, some with sensitive sol gel coatings. In order to meet the stringent MIL STD 1246 Level 83 A/10 cleanliness requirements (A/10 is one tenth the typical organic cleanliness requirements for satellite components), specialized cleaning procedures and large scale cleaning facilities were developed.

These specialized processes included large volume surfactant sprays, ultrasonic baths and various solvent and “dry” wiping for mechanical components. In addition, to minimize organic contamination, many components required baking in customized vacuum ovens. Accordingly, specialized verification processes were developed at the NIF for verification of the required cleanliness. For optics, cleaning included traditional solvent wiping (IPA, ethanol and acetone) and more sophisticated baths and surface preparation processes, including toluene sprays. Now that NIF is in operation, the continued cleanliness of the optics must be maintained including in-situ cleaning with gas knives (past SPIE paper). These specialized procedures, verifications and facilities will be discussed in this paper.

Keywords: cleaning, contamination, particles, AMCs, organics, damage, clean roomoptics

Laser-induced damage resistance of UV coatings on fused silica and CaF_2

Byungil Cho, Andy Lyu, Newport Corp. (United States);
Mark S. Feldman, Spectra-Physics®, a Div. of Newport Corp. (United States)

ABSTRACT TEXT: Laser damage resistance (LDR) is a measure of the laser fluence that a coating can withstand without damaging when exposed to a large number of pulses. The LDR of UV coatings has been studied at 266 nm and 193 nm on two common substrate materials. Significantly higher values for the LDR have been measured for the same coating deposited on CaF_2 substrate compared to fused silica substrates. Various parameters such as surface roughness, subsurface damage, and absorption were measured for both substrate materials. The surface damage morphology was also studied along with the physical properties of these quite different materials in an effort to explain the performance difference.

Keywords: laser damage resistance, laser damage threshold, UV coatings, 266 nm, 193 nm, fused silica, calcium efluoride

07:30 to 16:00 **Registration Material Pick-up,** NIST Lobby Area

07:30 to 08:20 **Poster Placement at NIST**
Poster authors for the Tuesday poster session are to set up their posters at this time.

8:20 to 10:00 • SESSION 5

Thin Films I

Session Chairs: **Joseph A. Menapace,** Lawrence Livermore National Lab. (USA); **Gregory J. Exarhos,** Pacific Northwest National Lab. (USA)

8:20: **What role do defects play in the last damage behavior of metal oxides?** *(Invited Paper)*, Carmen S. Menoni, Peter Langston, Erik M. Krous, Dinesh Patel, Colorado State Univ. (USA); Luke A. Emmert, The Univ. of New Mexico (USA); Ashot S. Markosyan, Stanford Univ. (USA); Brendan A. Reagan, Keith Wensing, Colorado State Univ. (USA); Roger Route, Martin M. Fejer, Stanford Univ. (USA); Jorge J. Rocca, Colorado State Univ. (USA); Wolfgang Rudolph, The Univ. of New Mexico (USA) . . . . [8530-15]

9:00: **An exhaustive study of laser damage in ion-beam sputtered pure and mixture oxide thin films at 1030 nm with 500 fs pulse durations**, Laurent Gallais, Benoit Mangote, Mireille Commandré, Institut Fresnel (France); Mathias Mende, Lars O. Jensen, Henrik Ehlers, Marco Jupé, Detlev Ristau, Laser Zentrum Hannover e.V. (Germany); Andrius Melninkaitis, Valdas Sirutkaitis, Vilnius Univ. (Lithuania); Simonas Kicas, Tomas Tolenis, Ramutis Drazdys, Institute of Physics (Lithuania) . . . . [8530-16]

9:20: **Effect of laser durations on laser-induced damage threshold of multilayer dielectric gratings in vacuum**, Fanyu Kong, Yunxia Jin, Weixiao Chen, Meiping Zhu, Tao Wang, Dawei Li, Zhaoyang Li, Guang Xu, Hongbo He, Jianda Shao, Shanghai Institute of Optics and Fine Mechanics (China) . . . . [8530-17]

9:40: **Brewster Angle Polarizing Beamsplitter Laser Damage Competition**, Christopher J. Stolz, Lawrence Livermore National Lab. (USA); Jeff Runkel, Quantel USA (USA) . . . . [8530-18]

10:00 to 10:30 • Tuesday Poster Overview

Poster authors are asked to give 2-minute/2-viewgraph overviews of their posters in the order they appear in the program.

10:30 to 11:20 • Poster Session and Refreshment Break

11:20 to 13:00 • SESSION 6

Thin Films II

Session Chairs: **Mireille Commandré,** Institut Fresnel (France); **Vitaly E. Gruzdev,** Univ. of Missouri-Columbia (USA)

11:20: **Damage study of HR coatings irradiated from substrate-side by 1064 nm nanosecond laser pulses**, Xinbin Cheng, Jiangtao Lu, Bin Ma, Zhanshan Wang, Tongji Univ. (China) . . . . [8530-19]

11:40: **Continued advancement of laser damage resistant optically functional microstructures**, Douglas S. Hobbs, Bruce D. MacLeod, Ernest Sabatino, TelAztec LLC (USA). . . . . . . [8530-20]

12:00: **Multiple wavelength laser-induced damage of multilayer beam splitters**, Lei Yan, Chaoyang Wei, Yuanan Zhao, Kui Yi, Jianda Shao, Shanghai Institute of Optics and Fine Mechanics (China) . . . . [8530-21]

12:20: **A statistical correlation study between surface quality and LIDT at 1064 nm**, Trey Turner, Quentin Turchette, Alex R. Martin, Research Electro-Optics, Inc. (USA). . . . . [8530-22]

12:40: **Thin film formation for strong adhesion with substrate and laser tolerance by photo-oxidized silicone oil**, Masataka Murahara, Tokai Univ. (Japan); Yuji Sato, Tokyo Institute of Technology (Japan); Takahisa Jitsuno, Osaka Univ. (Japan); Etsuo Fujiwara, Univ. of Hyogo (Japan); Yoshiaki Okamoto, Okamoto Optics Works (Japan) . . . . [8530-23]

13:00 to 14:20 • Lunch Break

8530-15, Session 5

What role do defects play in the last damage behavior of metal oxides? *(Invited Paper)*

Carmen S. Menoni, Peter Langston, Erik M. Krous, Dinesh Patel, Colorado State Univ. (United States); **Luke A. Emmert,** The Univ. of New Mexico (United States); **Ashot S. Markosyan,** Stanford Univ. (United States); **Brendan A. Reagan, Keith Wensing,** Colorado State Univ. (United States); **Roger Route, Martin M. Fejer,** Stanford Univ. (United States)**; Jorge J. Rocca,** Colorado State Univ. (United States); **Wolfgang Rudolph,** The Univ. of New Mexico (United States)

ABSTRACT TEXT: There are experiments and models that provide insight on the laser damage behavior of metal-oxide coatings for a variety of pulsewidth scenarios in the infrared. The models include defects that are native and laser created [1,2]. This talk will present results of an extensive investigation of the role of defects in the laser damage behavior of Sc_2O_3 in different pulse regimes, ranging from nanosecond to femtosecond pulsewidth. The thin film Sc_2O_3 were grown by ion beam sputtering under different conditions. Extensive metrology of the films provides insight on different type of native defects present in the films.

1. B.C. Stuart et al, Phys. Rev. Lett. Vol. 74, 2248 (2005).
2. M. Mero, et al, Phys. Rev. B71, 115109 (2005)

Work supported by ONR through grant N00014-06-1-0523. This work uses equipment developed at the NSF Center for Extreme Ultraviolet Science and Technology, Award No. EEC 0310717.

An exhaustive study of laser damage in ion-beam sputtered pure and mixture oxide thin films at 1030 nm with 500 fs pulse durations

Laurent Gallais, Benoit Mangote, Mireille Commandré, Institut Fresnel (France); **Mathias Mende, Lars O. Jensen, Henrik Ehlers, Marco Jupé, Detlev Ristau,** Laser Zentrum Hannover e.V. (Germany); **Andrius Melninkaitis, Valdas Sirutkaitis,** Vilnius Univ. (Lithuania); **Simonas Kicas, Tomas Tolenis, Ramutis Drazdys,** Institute of Physics (Lithuania)

SPEAKER BIOGRAPHY: L. Gallais received a Master degree in Engineering from the Ecole Nationale Supérieure de Physique in 1999 and a Research Master degree in 1999 from the Aix-Marseille University. His PhD degree in Physics was obtained in 2002, after a work on laser damage in optical components. Since 2003, he is an assistant professor at the Ecole Centrale Marseille and his research activities, conducted at the Institut Fresnel, deal with high power laser/optical materials interactions. At the moment his research interests concern laser damage of optical interference coatings in the femto to nanosecond range, and the development of processes to "repair" damaged optics.

ABSTRACT TEXT: We report on the laser damage resistance of thin films prepared by Ion Beam Sputtering. The samples are fused silica substrates coated with single layer films of pure oxides (SiO_2, Nb_2O_5, ZrO_2, HfO_2, Ta_2O_5, Al_2O_3, $Sc_2OSc_2O_3Sc_2O_3/SiO_2$). For this study the LIDT of more than 60 different samples is measured at 1030nm with pulse durations of 500fs in the single shot mode. The results are expressed and compared in terms of LIDT as a function of the measured band gap energy and the refractive index.

For pure oxide materials a linear evolution of the LIDT with bandgap is observed. The results are in accordance with our simulations based on photo-ionisation and avalanche-ionisation. In the case of mixtures however, deviations from the previous behaviors are evidenced. The evolution of the LIDT as a function of the refractive index is analyzed and an empirical description of the relation between refractive index and LIDT is proposed.

Keywords: Optical coatings, laser induced damage, femtosecond, picosecond, oxides, mixture oxides

8530-17, Session 5

Effect of laser durations on laser-induced damage threshold of multilayer dielectric gratings in vacuum

Fanyu Kong, Yunxia Jin, Weixiao Chen, Meiping Zhu, Tao Wang, Dawei Li, Zhaoyang Li, Guang Xu, Hongbo He, Jianda Shao,
Shanghai Institute of Optics and Fine Mechanics (China)

SPEAKER BIOGRAPHY: Yunxia Jin has been in coating research group at Key Laboratory of Materials for High Power Laser, Shanghai Institute of Optics and Fine Mechanics since 2004 working on optical coating and novel structured thin film.

ABSTRACT TEXT: Laser induced damage threshold of multilayer dielectric gratings were measured on the OPCPA laser system with different pulse durations of 660fs, 2ps, 10ps and 60ps. Samples were prepared by coating deposition, exposure, reactive ion beam etching, and all have good diffractive efficiency over 95% at 1053nm with incidence of 70° and TE model. LIDT distributes from ~2J/cm^2 to ~9J/cm^2 according to 660fs and 60ps, respectively. The damage with increasing energy under the same laser pulse duration will be investigated. The mechanism will also be discussed.

Keywords: Laser induced damage threshold, multilayer dielectric gratings, laser pulse duration

8530-18, Session 5

Brewster Angle Polarizing Beamsplitter Laser Damage Competition

Christopher J. Stolz, Lawrence Livermore National Lab. (United States);
Jeff Runkel, Quantel USA (United States)

SPEAKER BIOGRAPHY: Christopher Stolz has been in the laser program at Lawrence Livermore National Laboratory (LLNL) since 1989 researching high-power laser coatings. He is currently responsible for the Optics Production group for the National Ignition Facility (NIF). Chris has served as a cochair or program chair for numerous conferences including Laser Induced Damage in Optical Materials (a.k.a. Boulder Damage Symposium) and Optical Interference Coatings. He has coauthored over 80 journal and proceeding articles and 2 book chapters.

ABSTRACT TEXT: Brewster angle plate polarizing beamsplitters play a critical role in splitting and combining beams within high power laser systems. A laser damage competition of polarizer beamsplitter coatings will create the opportunity to survey private industry, governmental institutions, and university sectors to allow a direct comparison because the samples will be tested under identical conditions. The requirements of the coatings are a minimum transmission of 95% at "P" polarization and minimum reflection of 99% at "S" polarization at 1064 nm and 56.4 degrees angle of incidence. The choice of coating materials, design, and deposition method were left to the participant. Laser damage testing was performed according to the ISO 11254 standard utilizing a 1064 nm wavelength laser with a 20 ns pulse length operating at 20 Hz. A double blind test assured sample and submitter anonymity so only a summary of the results are presented. In addition to the laser resistance results, details of deposition processes, coating materials and layer count, and spectral results will also be shared.

8530-19, Session 6

Damage study of HR coatings irradiated from substrate-side by 1064 nm nanosecond laser pulses

Xinbin Cheng, Jiangtao Lu, Bin Ma, Zhanshan Wang, Tongji Univ. (China)

ABSTRACT TEXT: The irradiation direction for the high reflection coatings on laser crystals is from the substrate-side. Flat bottom pits are typical damage morphologies that result from the combined action of nano-sized absorbers in the subsurface of laser crystals and the electric-field strength. In order to better ascertain the distribution of nano-sized absorbers in the subsurface, two 1064 nm HR coatings with different electric-field distributions in the subsurface were prepared. The damage test results revealed that the location of the most sensitive nano-sized absorbers is within 100 nm from the substrate surface. We could predict that the redeposition layer of the laser crystals had a thickness about 100 nm. Moreover, gold nano-particles were implanted into the film-substrate interface to explore the importance of electric-field strength. The damage test results showed that electric-field strength played a key role in the laser damage. In the case that the electric-field strength was close to zero, even the highly absorbing gold nano-particles could not trigger the laser damage. By knowing the factors that limit the laser damage resistance of high reflection coatings on laser crystals, some design and fabrication procedures were proposed to improve the laser induced damage threshold.

Keywords: HR coatings, Substrate-side irradiation, Nano-sized absorbers, Electric-field strength

8530-20, Session 6

Continued advancement of laser damage resistant optically functional microstructures

Douglas S. Hobbs, Bruce D. MacLeod, Ernest Sabatino III,
TelAztec LLC (United States)

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 and imaging sensors. Doug serves as President of TelAztec, a research and development company he co-founded in 2000. His earlier experience includes developing holographic elements for optical correlators at Grumman, advancing an electro-optic laser beam director at Raytheon, and fielding a production capable interference lithography tool system at his first startup company. Doug holds 14 U.S. Patents and has published numerous journal articles.

ABSTRACT TEXT: Micro- and nano-structured optically functional surface textures continue to exhibit higher performance and longer term survivability than thin-film coatings for an increasing number of materials used within high power laser systems. Anti-reflection (AR) microstructures (ARMs) produce a graded refractive index yielding wide bandwidth operation and omni-directionality, all with a chemical, mechanical and laser damage resistance inherited from the bulk optic material. Pulsed laser induced damage threshold (LiDT) data taken at a wavelength of 1064nm and a pulse width of 10ns, indicates a damage resistance for ARMs built in fused silica and quartz between 2 and 5 times greater than AR coatings. Further damage studies of ARMs fabricated in sapphire, neodymium-doped YAG, spinel, fused silica, N-BK7, zinc selenide (ZnSe), zinc sulfide (ZnS) and metal-ion doped ZnSe and ZnS, will be presented and compared with thin-film AR coatings for wavelengths of 532nm, 694nm, 800nm, 1064nm, 1538nm, and 2095nm. Theoretical performance modeling for ARMs in these materials will also be shown in relation to the measured spectral reflection and transmission curves. The continuous wave (cw) laser damage resistance of ARMs treated and thin-film AR coated windows will be discussed in the context of standardized surface absorption measurements.

Keywords: Optical Microstructures, Antireflection, AR Motheye, Laser Damage Resistance, High Power Lasers, Polarizers, HEL

Multiple wavelength laser-induced damage of multilayer beam splitters

Lei Yan, Chaoyang Wei, Yuanan Zhao, Kui Yi, Jianda Shao,
Shanghai Institute of Optics and Fine Mechanics (China)

SPEAKER BIOGRAPHY: Yuanan Zhao received PhD degree in 2005 at the Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Sciences. His current research interests include laser-induced damage to optical coatings and measurement of properties of optical coatings.

ABSTRACT TEXT: Experimental and theoretical progress on multiple wavelength laser induced damage of multilayer beam splitters is reviewed. Test method for multiple lasers-induced damage thresholds were proposed based on ISO 21254. Single and multiple laser-induced damage performance of the splitters, including damage probabilities, damage thresholds and damage morphologies, were investigated respectively in order to obtain better understanding of the damage mechanism at 355, 532 and 1064 nm. A judgment criterion for coupling effect of different lasers in inducing damages was proposed and the detailed coupling efficiency was also obtained. The temperature distribution model, small absorbing particle model and defect statistical model were put forward to explain the experimental results. In addition, damage performance when the lasers arrived at the films with nanosecond-delay in time was researched. Generally, the third harmonics play a key role in the damage initiation.

Keywords: multiple wavelength, laser damage, multilayer beam splitter

8530-22, Session 6

A statistical correlation study between surface quality and LIDT at 1064 nm

Trey Turner, Quentin Turchette, Alex R. Martin,
Research Electro-Optics, Inc. (United States)

Speaker Biography: Trey Turner is Chief Technology Officer at REO, where his technical contributions have included co-invention of a solid state laser based system for aerosol particle characterization, development of a new approach to controlling the resonance parameters of Fabry-Perot etalons, and creation of a number of novel designs for thin film optical coatings. He has three patents currently issued or pending for his work at REO. He holds a Bachelor of Science degree in Physics from Lawrence University and a Master of Science degree in Physics from the University of Texas at Austin.

ABSTRACT TEXT: In many common regimes of laser-induced damage (that is, many combinations of fluence, repetition rate, pulse duration and wavelength that give rise to damage) of thin-film optical coatings, damage occurs at defects in the coating at levels well below inherent material limits. Defect sizes and densities present on an optic are indicated by surface quality specifications. In this study, we look at correlations between several quantitative surface quality metrics and laser induced damage threshold in optics coated for and tested at 1064 nm. We report results for testing at 20 ns, 20 Hz, with up to 100 J/cm^2 on optics with measured defects ranging from ~1 to 50 µm.

Keywords: LDT, LIDT, HLDT, laser damage, thin films, optical coatings, laser induced damage, surface quality

8530-23, Session 6

Thin film formation for strong adhesion with substrate and laser tolerance by photo-oxidized silicone oil

Masataka Murahara, Tokai Univ. (Japan); **Yuji Sato,** Tokyo Institute of Technology (Japan); **Takahisa Jitsuno,** Osaka Univ. (Japan); **Etsuo Fujiwara,** Univ. of Hyogo (Japan); **Yoshiaki Okamoto,** Okamoto Optics Works (Japan)

SPEAKER BIOGRAPHY: Masataka MURAHARA, Professor, Innovative Research Initiatives, Tokyo Institute of Technology; Professor Emeritus, Tokai University. Masataka Murahara has specialized in laser engineering and photochemical surface modification for more than thirty years. He graduated from School of Science and Technology, Waseda University, in 1969 and received a Doctor of Engineering from the University in March 1979.

ABSTRACT TEXT: It is, in general, necessary to raise the temperature of a substrate in order to form a hard film using a deposition method. At present, the substrate temperature is controlled to 270 to 300ºC because the property of the substrate changes with the treatment; there exists no film except the photo-oxide film of silicone oil that is resistant against laser, strong in adhesiveness and cohesion, thermal resistant, non-inflammable, waterproof, not cracked by contraction stress, and transparent in the range of ultraviolet rays.

An oxidizing agent is needed for silicone oil to be photo-oxidized with Xe2 excimer-lamp. Air or oxygen has been used as the oxidizing agent so far. However, the Xe2 excimer-lamp light (172nm) did not reach the silicone oil on the interface of the substrate satisfactorily because the oxygen absorbed the light in its path, and the physical properties of the film formed were deficient in reproducibility in terms of the gas pressure of oxygen, the strength of vacuum ultraviolet light, and the distance between substrate and light source. In order to clarify the conditions for supplying just enough oxidizing agent to silicone oil, therefore, the experimental conditions of i) purpose, ii) working condition, iii) equipment, and iv) production process were identified each for 1) pretreatment of substrate, 2) application of silicone oil, 3) an oxidizing agent in silicone oil, and 4) high efficiency of photo-reaction.

Firstly, the vacuum ultraviolet light that has passed the silicone oil layer was made fluoresce in the phosphor to monitor the progress of the photo-oxidation reaction. The luminous intensity of the phosphor increased as the proportion of the silicone oil vitrified by photo-oxidation reaction expanded. Accordingly, the change in luminous intensity was detected and reflected to the oxidizing agent supply and the irradiation intensity and time of vacuum ultraviolet light, and the new method to form a transparent, photo-oxidized thin film efficiently has been established.

By the photo-oxidizing reaction monitor, it was observed the movements what the oxidizing agent mixed in or being in contact with the outside of silicone oil beforehand was supplied enough when it was photo-reacted with the silicone oil layer.

The results clarified that if silicone oil is applied after forming a metallic oxide that can supply the surface with oxygen on the coating surface of the substrate, it is possible to form a transparent thin film of photo-oxidation layer on the light receiving surface of the sample because there is no oxidizing agent in the light path and accordingly no vacuum ultraviolet rays absorption by the oxygen in the atmosphere. And, it is the most effective way to supply an oxidizing agent; that is, a solid oxidizing agent should be used rather than gas or liquid.

In this study, an oxide film was formed on the substrate beforehand, which was used as a solid oxidizing agent. Using it as a substrate, the plate of copper (Cu) was oxidized by heat in oxygen atmosphere to form a thin film of copper oxide (CuO). Silicone oil with viscosity of 1cs was applied on the surface of the copper oxide; with the part masked, the sample was exposed to Xe2 excimer lamp irradiation in vacuum atmosphere. When the sample was rinsed with xylene, the silicone oil that remained on the part unexposed dissolved to expose CuO, and the part exposed became a glassy film (SiO_2); which was observed by the infrared (IR) spectroscopy.

Keywords: photo-oxidized silicone oil, photo-oxidizing reaction monitor, luminous intensity, Xe2 excimer-lamp, oxidizing agent, copper oxide, solid oxidizing agent, infrared (IR) spectroscopy

Tuesday PM • 25 September

14:20 to 15:40 • SESSION 7

Materials and Measurements I

Session Chairs: **Christopher J. Stolz,** Lawrence Livermore National Lab. (USA);
James E. Andrew, AWE plc (United Kingdom)

14:20: **Dispersive multilayer optics: toward high-power applications** *(Invited Paper)*, Vladimir Pervak, Ludwig-Maximilians-Univ. München (Germany) and Ultrafast innovations GmbH (Germany) . . . . [8530-43]

15:00: **Coatings of oxide composites** *(Invited Paper)*, Lars O. Jensen, Detlev Ristau, Laser Zentrum Hannover e.V. (Germany) . . . . [8530-24]

15:40 to 16:30 • Poster Session and Refreshment Break

16:30 to 18:10 • SESSION 8

Materials and Measurements II

Session Chairs: **Michelle D. Shinn,** Thomas Jefferson National Accelerator Facility (USA);
MJ Soileau, Univ. of Central Florida Office of Research & Commercialization (USA)

16:30: **The role of polymer-mediated dopant correlations in damage moderation and self healing**, Mark G. Kuzyk, Shiva K. Ramini, Washington State Univ. (USA) . . . . [8530-26]

16:50: **The influences of key optical component performances to optical efficiency in high-power Yb:YAG thin-disk laser**, Jianli Shang, Huazhong Univ. of Science and Technology (China) and Wuhan National Lab. for Optoelectronics (China) and Wuhan Meiman Technology (Group) Co., Ltd., (China) . . . . [8530-27]

17:10: **A high-energy fibre-to-fibre connection for direct optical initiation systems**, Michael D. Bowden, Sarah L. Knowles, Matthew C. Cheeseman, AWE plc (United Kingdom) . . . [8530-28]

17:30: **Energy losses in thermally cycled optical fibers constrained in small bend radii**, Eric M. Guild, Gregg L. Morelli, Honeywell Federal Manufacturing & Technologies, LLC (USA) . . . . [8530-29]

17:50: **Neutron testing of high-power optical fibers**, Matthew C. Cheeseman, Michael D. Bowden, AWE plc (United Kingdom); Adrian A. Akinci, Los Alamos National Lab. (USA); Sarah L. Knowles, Lee Webb, AWE plc (United Kingdom) . . . . [8530-30]

18:10 to 18:20 • Closing Remarks

19:00 to 20:30 • Wine and Cheese Tasting Reception at NCAR

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8530-43, Session 7

Dispersive multilayer optics: toward high-power applications
(Invited Paper)

Vladimir Pervak, Ludwig-Maximilians-Univ. München (Germany)
and Ultrafast innovations GmbH (Germany)

ABSTRACT TEXT: A dispersive-optics-based laser permits a simplification of high-power femto- and atto-second systems. Dispersive optics afford promise for further development towards user-friendly laser systems with shorter pulse durations, higher pulse energy and higher average powers. The result of the continuous development of dispersive mirrors permits pulse compression down to single cycle pulses duration.

Dispersive mirrors together with the recently developed wave synthesizer technology [1, 2] pave a way to sub-2 fs pulses. A sub-2 fs pulse has a spectrum of 350-1050 nm and corresponds to a sub-cycle optical pulse [2]. The generation of ultrashort pulses with large pulse energies is constrained by the laser-induced damage threshold (LIDT) of the optics involved. In particular, the LIDT of the dispersive optics is one of the bottlenecks in the development of high-power ultrafast systems. In femtosecond regime, dispersive coatings had damage thresholds close to that of a single layer of the high index material used for the respective coating [3-5]. The dispersive mirrors consist of Ta_2O_5 and Nb_2O_5 as high refractive index material have damage of ~0.3 J/cm^2 [3] for Ti:Sapphire laser yielding 1 mJ, 30 fs pulses at 500 Hz repetition rate at 790 nm central wavelength. Increasing of current LIDT will make possible for high power femtosecond and attosecond applications to reach the higher intensity and higher energy levels.

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8530-24, Session 7

Coatings of oxide composites *(Invited Paper)*

Lars O. Jensen, Detlev Ristau, Laser Zentrum Hannover e.V. (Germany)

ABSTRACT TEXT: During the last decade, coating processes have been extended to the reproducible deposition of composite materials on the basis of simultaneous evaporation or sputtering. Especially ion beam sputtering from a zone target in conjunction with sophisticated optical broadband monitoring offers several advantages for the production of oxide coatings with defined mixture ratios and even rugate filter systems with a continuous variation of the composition ratio in the depth of the layer structure. With only two materials on the zone targets, a large dynamic range of refractive index values covering the indices of the pure materials can be achieved.

Recent studies on the properties of the produced oxide composites indicate a variety of interesting aspects opened by this new class of material. Among others a blue shift of the absorption characteristic was observed for ternary oxides and an increased LIDT, particularly for sub-picosecond coatings, has been reported. Also a number of investigations in fundamental damage mechanisms could be carried out by considering the tunable band gap energy of the coating material. In this endeavor, a group of international collaborators joined in modeling, testing and evaluating the properties of a variety of ternary oxide systems. A verification of principal material qualities was transferred to applicable multi-layer coatings in a combined effort. In this paper, a brief overview on the achievements of these current studies is presented before the background of high power laser applications.

Keywords: Ion Beam Sputtering, Broadband Optical Monitoring, LIDT

8530-26, Session 8

The role of polymer-mediated dopant correlations in damage moderation and self healing

Mark G. Kuzyk, Shiva K. Ramini, Washington State Univ. (United States)

SPEAKER BIOGRAPHY: Mark G. Kuzyk received his Ph.D. degree at the University of Pennsylvania in 1985, and then was a member of technical staff at Bell Labs in Princeton, New Jersey from 1985 to 1990. He has been a Professor of Physics and Astronomy at Washington State University since 1990, where he has served as Associate Chair of Physics, Chair of the Materials Science Program, and Chair of Graduate Studies in Physics. He is now a Regents Professor and Fellow of SPIE, American Physical Society, and Optical Society of America.

ABSTRACT TEXT: Self healing in dye-doped polymers after photodegradation is an interesting phenomena from the perspective of basic science in the fundamental questions that it raises about irreversibility. Understanding the mechanisms of self healing and material hardening through laser cycling, on the other hand, has implications for the design of better materials and processing techniques for high intensity materials applications. In this contribution, we introduce a new model that correctly predicts a wealth of observations with only three fixed parameters.

We first show that the mechanisms of photothermally-induced diffusion and orientational hole burning are ruled out by experiment, suggesting that a more exotic process is at work. The model is based on three key observations; (1) for fixed fluence, the degradation time constant increases and the degree of damage decreases with dopant concentration, (2) the recovery rate increases with concentration, and (3) self healing is observed in a dye-doped PMMA polymer, but not in liquid MMA monomer.

The experimental observations suggest that the healing process requires a solid polymer host and interactions between the dopants. As such, we propose that the polymer mediates interactions between the chromophores, which leads to recovery. The model has two parts. The healing process is assumed to scale as the size of a correlated region of chromophores, while the size distribution of correlated regions is calculated using a chemical potential to quantify the interaction strength between chromophores. This model is shown to be consistent with all measurements in the model system DO11 dye in PMMA.

Keywords: self healing, photodegradation, dye-doped polymer, DO11 dye, PMMA polymer, molecular correlations

The influences of key optical component performances to optical efficiency in high-power Yb:YAG thin-disk laser

Jianli Shang, Huazhong Univ. of Science and Technology (China) and Wuhan National Lab. for Optoelectronics (China) and Wuhan Meiman Technology (Group) Co., Ltd., (China)

SPEAKER BIOGRAPHY: Shang Jianli was born in Lanzhou, China,in 1986. He received bachelor degrees from the Huazhong University of Science and Technology in 2008.Since 2008 has been working towards the Ph.D. degree, in optical engineering at Huazhong University of Science and Technology, His research interests include high-power solid-state laser and laser technology.

ABSTRACT TEXT: High optical efficiency, high power and high beam quality output can be achieved using Yb:YAG thin-disk laser. Efficient multi-pumping system is necessary to achieve high absorption efficiency because of the special shape of gain medium. A novel multi-pumping design for higher output power is present in this paper. But some optical components which are difficult to produce need to be used in this design. And they must have high damage threshold and other optical performances. The difficulties of producing these components are discussed. In other hand, a calculation model based on quasi-three energy levels system is created. In this model, the multi-pumping, temperature and power loss in every elements are considered carefully. The whole processes of power conversion in CW laser, Q-switch and cavity dumping are all present respectively. The relationships between optical efficiency and parameters of key optical component with different pumping power or repetition frequency are researched. It can be found that the optical efficiency changed linearly with the efficiencies of some components (for example: shaper, collimation and etc.), but the optical efficiency is very sensitive to the performances of other components (for example: parabolic mirror, Q-switch and etc.). We found that the strength of saturation effects influences the sensibility of laser optical efficiency to these key optical component performances. The requirements of these components are established in CW, Q-switch and cavity dumping respectively. Additionally, the power densities on surfaces which have risk of damage can be obtained using this calculation model.

Keywords: High power laser, Solid-state laser, Thin-disk laser, High power density

A high-energy fibre-to-fibre connection for direct optical initiation systems

Michael D. Bowden, Sarah L. Knowles, Matthew C. Cheeseman,
AWE plc (United Kingdom)

SPEAKER BIOGRAPHY: Mike Bowden is a scientist working on explosive component design, including high-speed optical diagnostic development. He specialised in the development of high-surety detonators, including laser and electrical slapper detonators.

ABSTRACT TEXT: Direct Optical Initiation (DOI), uses a moderate energy Q-switched Nd:YAG laser to shock initiate secondary explosives, via either a flyer plate or exploding metal foil. DOI offers significant performance and safety advantages over conventional electrical initiation. Optical fibers are used to transport the optical energy from the laser to the explosive device.

Energy densities in the region of 35 J cm^{-2} are required for initiation, above the damage threshold of typical optical fibers. Laser-induced damage is typically caused by laser absorption at the input face due to imperfections in the surface polishing. To successfully transmit energy densities for DOI, a high quality fiber end face finish is required.

A DOI system comprises a laser, one or more optical fibres, and one or more laser detonators. Realisation of a DOI system is greatly eased by the use of fibre to fibre connections, allowing for easy integration into bulkheads or other interfaces, such as firing tanks and environmental test chambers. Fibre to fibre connectors capable of transmitting the required energy densities are not commercially available.

A fibre to fibre connection utilizing micro-lens array injection into a large-core, tapered optical fibre, a hermetic fibre bulkhead feedthrough, and a disposable test fibre has been developed. This permits easy connection of test detonators or components, with the complex free-space to fibre injection reduced to a one-time operation for each system or configuration. The disposable test fibre is a simple plug-and-play connection.

The damage threshold and transmission losses of the fibre to fibre connection have been established for each interface.

Keywords: Direct Optical Initiation, Laser Detonators, High Power Fibres, Laser Damage

8530-29, Session 8

Energy losses in thermally cycled optical fibers constrained in small bend radii

Eric M. Guild, Gregg L. Morelli,
Honeywell Federal Manufacturing & Technologies, LLC (United States)

SPEAKER BIOGRAPHY: Eric Guild possesses a BSEE from Wright State University and a Master's in Optical Science Engineering from the Air Force Institute of Technology (AFIT) at Wright-Patterson Air Force Base (WPAFB) in Ohio. DoD contractor at WPAFB for 3 years working for the AFRL Sensors Directorate and as a laser laboratory research assistant. Employed at the Honeywell FM&T for 1 year working on production optical techniques, optical designs and fiber optics for robust high energy systems.

ABSTRACT TEXT: Energy losses were observed in a 365µm diameter fiber optic cable constrained in small radii of curvature bends resulting in a catastrophic failure. Q-switched laser pulses, from a 1061nm flashlamp pumped, solid-state laser, were injected into the cables. An infrared camera was utilized to observe the spatial intensity profile at the exit face of the fiber. An asymmetric intensity profile was generated with one half the fiber core having a higher peak-to-average energy distribution. Prior to testing, the cables were thermally cycled while constrained in the small radii of curvature bends. Single, double, and U-shaped geometries were implemented to characterize the various scenarios.

Keywords: Fiber, Small, Bend, Thermal, Radii, Optical

8530-30, Session 8

Neutron testing of high-power optical fibers

Matthew C. Cheeseman, Michael D. Bowden, AWE plc (United Kingdom);
Adrian A. Akinci, Los Alamos National Lab. (United States);
Sarah L. Knowles, Lee Webb, AWE plc (United Kingdom)

SPEAKER BIOGRAPHY: Mr. Matthew C. Cheeseman graduated with a BSc in Physics. He has has since been working on laser and optical fibre systems at AWE for almost five years, primarily studying high energy transmission, damage effects and radiation effects.

ABSTRACT TEXT: High-power optical fibres are used for delivering intense laser sources and have a large number of practical uses within industry. In some circumstances, these optical fibres may be exposed to harsh ionising radiation environments, such as in space flight, and nuclear reactor regimes.

Over the past three decades, it has been extensively documented that optical fibres are susceptible to the effects of ionising radiation, exhibiting detrimental behaviours such as reduced transmission. However, there are limited, if any, publications regarding optical fibre transmission of high pulsed powers during high dose rate irradiation.

A selection of commercially available high-power optical fibres have been characterised for radiation susceptibility in Sandia's Annular Core Research Reactor (ACRR) - a high power pulsed research reactor. The fibres were subjected to a total combined gamma and neutron dose of >2 Mrad(Si) in a 7 ms pulse. The neutron fluence was $>10^{15}$ n/cm^2. The changes in the transmission characteristics of optical fibres carrying high energy, short duration laser pulses (power densities of around of 1.5 GW/cm^2) were measured. In laboratory conditions, this optical power density is close to the damage threshold of the fibres.

All fibres survived at least two consecutive radiation exposures, showing a typical transient transmission loss of around 20%. Post radiation exposure, the transmission characteristics of the fibres returned to those of pristine fibres within one minute.

Keywords: High-power optical fibers, ACRR, Annular Core Research Reactor, Neutron irradiation of optical fibers, Radiation induced attenuation, Nd:YAG laser

Materials and Measurements

10:30 to 11:20 and 15:40 to 16:30

Materials and Measurements

10:30 to 11:20 and 15:40 to 16:30

Laser removal of positive-tone diazonaphthoquinone/novolak (DNQ/novolak) resist without occurring laser-induced damage to the silicon wafer, Hiroki Muraoka, Yuki Yanama, Yoshiaki Matsura, Tomosumi Kamimura, Osaka Institute of Technology (Japan); Hideo Horibe, Kanazawa Institute of Technology (Japan) . . . . [8530-76]

Investigation of laser damage initiation and the defect volume density in transparent YAG ceramics, Yuki Yamana, Tomosumi Kamimura, Hiroki Muraoka, Haruki Nakagawa, Osaka Institute of Technology (Japan); Katsuhiro Mikami, Shinji Motokoshi, Takahisa Jitsuno, Osaka Univ. (Japan); Takayuki Okamoto, Okamoto Optics Works (Japan); Yan Lin Aung, Akio Ikesue, World Lab Co., Ltd. (Japan) . . . . [8530-77]

Sandwich concept: enhancement for direct absorption measurements by laser-induced deflection (LID) technique, Christian Mühlig, Simon Bublitz, Institut für Photonische Technologien e.V. (Germany) . . . . [8530-79]

Automated test station for laser-induced damage threshold measurements according to ISO 21254-1,2,3,4 standards, Aurel Stratan, National Institute for Lasers, Plasma and Radiation Physics (Romania); George Nemes, ASTiGMAT (USA) and National Institute for Lasers, Plasma and Radiation Physics (Romania); Alexandru Zorila, Laurentiu Rusen, Sandel Simion, Constantin Blanaru, Constantin G. Fenic, Liviu Neagu, National Institute for Lasers, Plasma and Radiation Physics (Romania) . . . . [8530-80]

Parallel use of detection channels for LIDT testing in the UV range, Stefan Schrameyer, Marco Jupé, Lars O. Jensen, Detlev Ristau, Laser Zentrum Hannover e.V. (Germany) . . . . [8530-81]

Thermal management of kJ class laser amplifiers for operations at high-repetition rates

Paul J. Phillips, Klaus Ertel, Paul D. Mason, Saumyabrata Banerjee, Justin Greenhalgh, John L. Collier, Rutherford Appleton Lab. (United Kingdom)

ABSTRACT TEXT: Currently lasers producing multi kJ ns pulsed lasers are based on flash lamp pumped technology. These show poor electrical to optical efficiencies and due to their limitation in thermal management, can only be operated at low repetition rates (few shots per day). A new approach in the form of diode pumping can overcome the limitations, thereby advancing research into areas such as fundamental laser plasma research, enabling solutions for OPCPA, Ti:Sapphire pumping and inertial fusion energy production. Running at high energies and repetition rates requires fundamental changes in control of the thermal management of the amplifier medium. In this paper we present a concept for a kJ class laser based on cryogenic gas cooled multi-slab Yb:YAG technology. A scale down prototype producing energies of 10.1 J at 1 Hz (4-pass) and 6.4 J at 10 Hz (3-pass) is also presented. The corresponding optical-to-optical efficiencies were 21% and 16% respectively. The paper emphasises on the thermal management of kJ amplifiers for high repetition rates and describes multi-slab architecture with carefully chosen doping concentration of the gain medium for achieving uniform heat load across the amplifier. The paper also tries to attract attention towards the suitability of damage thresholds for coated surfaces in the cryogenic cooled amplifier chain.

We detail planned experiments to explore the parameter space for the damage thresholds of the Yb:YAG surface coatings as well as bulk. Particular emphasis on different surface roughness of the Yb:YAG material with suitable coatings at cryogenic temperatures, high repetition rates and vacuum conditions.

Keywords: kJ class lasers, thermal management, multi-slab Yb:YAG amplifier

Characterization of laser-induced material modification in thin films using third-harmonic microscopy

Cristina Rodriguez, Reed A. Weber, Duy N. Nguyen, Luke A. Emmert, Wolfgang Rudolph, The Univ. of New Mexico (United States)

ABSTRACT TEXT: Third harmonic (TH) microscopy is particularly well suited for the inspection of thin films and coatings. We develop a model that analyzes in detail the TH signal generated from a thin film on top of a substrate and apply it to determine nonlinear susceptibilities of thin films. Using TH under circularly polarized (CP) illumination we were able to image film regions that had been exposed to a train of femtosecond (fs) pulses below the damage threshold. This sample incubation can hardly be detected with other traditional far-field microscopies, but is clearly visible with TH microscopy. We also demonstrate that the TH signal generated by a linearly polarized (LP) beam (with a fluence well below the damage threshold), focused into high quality coatings, displays a transient behavior, indicative of some material modification, which appears to be partially reversible. TH microscopy was also applied to analyze laser ablation craters produced by fs pulse trains. CP illumination produces a signal from the crater rim where possibly molten material resolidified into an anisotropic (perhaps crystalline) state. The signal generated under LP illumination, along with our theoretical model, is applied to determine material removal that is on the order of tens of nanometers.

Keywords: nonlinear microscopy, third harmonic, optical materials, thin films, damage precursors, femtosecond phenomena

8530-65, Session PST1

Separation of different loss channels in DUV optical elements

Klaus Mann, Bernhard Flöter, Uwe Leinhos, Julian Sudradjat, Bernd Schäfer,
Laser-Lab. Göttingen e.V. (Germany)

SPEAKER BIOGRAPHY: Klaus R. Mann received his M.S. degree in physics in 1981 and the PhD in 1984 from Univ. of Göttingen, the latter with a thesis written at the Max-Planck-Institut für Strömungsforschung. After a post-doctoral appointment at IBM Yorktown Heights (USA) and work in industry (Alcan Deutschland GmbH) he joined Laser-Laboratorium Göttingen in 1988, where he currently leads the ´Optics / Short Wavelengths´ group. His research activities cover projects in UV optics characterization, laser beam propagation, wavefront analysis, as well as generation and application of EUV/XUV radiation. He is author of more than 100 scientific publications.

ABSTRACT TEXT: As a consequence of steadily increasing average laser powers in the microlithographic process, the performance requirements of optics employed in DUV wafer steppers are rapidly growing. Further quality improvements strongly rely on comprehensive metrology techniques for assessment of the various loss channels. Thus, at Laser-Laboratorium Göttingen different measurement systems for quality assurance of optical material at 193 and 248nm are operated. In particular, a photo-thermal measurement device for quantitative determination of absorptance in DUV optics was developed. It is based upon a Hartmann-Shack wavefront sensor with extreme sensitivity, accomplishing spatially resolved monitoring of thermally induced wavefront distortions. Since the extent of deformation is directly proportional to the absorption loss, the new parallelized photo-thermal technique can be employed for a rapid assessment of the material quality. Monitoring the fluence dependence of the thermal lens effect accomplishes evaluation of both single- and two-photon absorption coefficients. Moreover, fast monitoring of degradation phenomena (e.g. laser-induced color center formation) is accomplished, as well as a separation of surface and bulk absorptance. Employing a collinear geometry of heating and probe beam, thermal wavefront distortions can be precisely characterized also for complex optical systems. Along with a description of the technique we present results from absorption measurements on fused silica, CaF_2 and dielectric coatings (both AR and HR) under 193nm irradiation. The data are compared with theoretical results obtained from a solution of the heat diffusion equation.

In addition, we present an optimized setup for total scattering (TS) measurements on optical elements at 248nm and 193nm, allowing a separation of forward and backward scattering losses. We also discuss attempts for angular and spatially resolved characterization of small-angle forward scattering, being responsible for contrast reduction in lithographic systems.

Keywords: deep UV, absorptance, wavefront, photothermal measurement, fused silica, total scattering, angular resolved scattering

8530-66, Session PST1

Improving laser damage threshold measurements: an explosive analogy

Jonathan W. Arenberg, Northrop Grumman Aerospace Systems (United States);
Michael D. Thomas, Spica Technologies, Inc. (United States)

SPEAKER BIOGRAPHY: Jon Arenberg is currently the Chief Engineer for the James Webb Space Telescope. He has been with Northrop Grumman over 23 years and working in the optical and laser engineering field for over 30 years. He is a graduate of UCLA in physics and engineering and has worked in a wide variety of optical and space technologies. He is a frequent contributor to these proceedings and holds 11 patents.

ABSTRACT TEXT: Laser damage measurements share similarities with testing of explosives, namely the sample or sample site is damaged or modified during the measurement. An extensive literature exists for the measurement of the "all fire" and "no fire" levels for explosives. These levels hold direct analogy to the "all damage" or 100% probability of damage or the "all safe" or 0% probability of damage. This paper presents a review of the literature and adaptation of the techniques from the measurements of explosives to the field of laser damage. Several typical samples are measured using the ISO 21254, binary search and the new adapted methods. The results are compared and analyzed.

Keywords: threshold measurement, binary search, damage frequency method, ISO 21254, optimal design

Automated test station for characterization of optical resistance with ultrashort pulses at multikilohertz repetition rates

Andrius Melninkaitis, Mindaugas Šciuka, Gintare Bataviciute, Julius Mirauskas, Saulius Bucka, Valdas Sirutkaitis, Vilnius Univ. (Lithuania)

SPEAKER BIOGRAPHY: Andrius Melninkaitis is working in the field of laser damage since 2003. Recently he has gained a position of senior researcher and associate professor at Vilnius University in Lithuania

ABSTRACT TEXT: The repetition rates of modern femtosecond systems are constantly increasing thus pushing optics towards new operation regimes. Due to high average and peak generated optical power so called fatigue laser damage phenomena of optical components becomes a lifetime limiting factor of such systems. In order to avoid these limitations and further develop laser components of high power femtosecond lasers a fundamental understanding of fatigue damage effects is required. Accordingly an appropriate laser-induced damage threshold (LIDT) characterization system operating at high repetition rate is required. Within a context of such demand a new automated LIDT test bench based on Yb:KGW laser irradiation source was implemented at Laser Research Center of Vilnius University. The system is capable to test optical components in very broad range of operational parameters. These parameters include tunable repetition rate (from 0.02 Hz to 200 kHz) while sustaining single shot measurement resolution, different wavelengths (1030, 515, 343 and 257 nm) and also adjustable pulse durations (from ~300 femtoseconds to several tens picoseconds). The introduced system was fully automated and enables to perform either so called 1-on-1 or S-on-1 tests in computer controlled manner. In order to demonstrate its new capabilities the apparatus was characterized and demonstrated by performing optical resistance tests on various dielectric coatings at different wavelengths and repetition rates.

Keywords: lidt test bench, lidt test station, S-on-11-on-1, laser damage, laser damage testing

An empirical investigation of the laser survivability curve: III

Jonathan W. Arenberg, Northrop Grumman Aerospace Systems (United States);
Wolfgang Riede, Alessandra Ciapponi, Paul Allenspacher,
Deutsches Zentrum für Luft- und Raumfahrt e.V. (Germany);
Jonathan H. Herringer, Arrow Thin Films, Inc. (United States)

SPEAKER BIOGRAPHY: Jon Arenberg is currently the Chief Engineer for the James Webb Space Telescope. He has been with Northrop Grumman over 20 years and working in the optical and laser engineering field for over 30 years. He is a graduate of UCLA in physics and engineering and has worked in a wide variety of optical and space technologies. He is a frequent contributor to these proceedings and holds 11 patents.

ABSTRACT TEXT: In this paper, we report on a continuing multi-year empirical investigation into the nature of the laser survivability curve. The laser survivability curve is the onset threshold as a function of shot number. This empirical investigation is motivated by the desire to design a universal procedure for the measurement of the so-called S on 1 damage threshold. Analysis is carried on the test results from a large set of planned measurements from identical samples produced for this investigation and DLR archival data from an ESA flight program. The sample set and test conditions which include a number of wavelengths, coating designs and ambient pressure conditions.

Keywords: Laser damage testing, Laser optics qualification, S on 1 testing, ISO 11254-2ISO 21254-2

Commissioning of the ELI-beamlines LIDT test station

Daniel Kramer, Bedrich Rus, Efstratios Koutris, Jan Hrebicek,
Institute of Physics of the ASCR, v.v.i. (Czech Republic)

SPEAKER BIOGRAPHY: Dr. Daniel Kramer is the chief optical designer of the ELI beamlines project since 2011. He was working before within the Beam Instrumentation group and the Emerging Energy Technologies group at CERN in Switzerland. He was working in the field of ultrahigh radiation detection and aspherical or spherical optics designs for particle physics experiments.

ABSTRACT TEXT: The ELI-beamlines project will contain several types of high power ultrafast lasers with high average powers up to 1.5kW. The peak powers range from 10TW with a repetition rate of 1kHz up to 10PW with one shot per minute. The project presents a major challenge in terms of damage threshold of ultrafast coatings.

The concept of the three floor facility places the pulse compressors into the laser halls while the experimental halls are located several tens of meters away in the bottom floor. In order to transport the beams with minimum diffraction effects and maximum pointing stability, the dual Cassegrain relay telescope systems are employed. The disadvantage of this solution is the increased fluence on the secondary mirrors.

In order to test the coatings required for the ultrafast mirrors and contribute to their development, a laser induced damage test station was constructed in the PALS facility in Prague. The chamber uses a 25TW 10Hz Ti:Sapphire laser. Most of the tests are performed by using a compressed zero order mode extracted from the first grating.

The main interaction chamber is painted, so the initial tests are performed with and without the silica gel in order to assess the influence of organic contamination on the LIDT of MLD coatings. A second unpainted chamber is being prepared for comparison tests.

Most of the testing is done at central wavelength of 800nm but some of the testing will be also carried out at 900nm, 1030 and at 1055 nm (required for the 10PW laser) when the front end lasers are ready.

Keywords: test station, organic contamination, ultrafast pulses, damage threshold, multilayer dielectric coating

8530-70, Session PST1

Automated laser damage threshold test systems of different test modes for optical elements

Bin Ma, Yanyun Zhang, Hongping Ma, Hongfei Jiao, Xinbin Cheng, Pengfei He, Tongji Univ. (China); **Huasong Liu, Yiqin Ji,** Tianjin Jinhang Institute of Technology Physics (China); **Zhanshan Wang,** Tongji Univ. (China)

ABSTRACT TEXT: The automated laser damage test systems of different test modes, including s-on-1, r-on-1 and raster scan, are developed recently with micron-scale damage events automated detection, location and re-inspection. The systems are carried out using a 10 ns pulsed Nd:YAG laser with a repetition rate of 10 Hz. The sample is illuminated by a He-Ne laser, and the scatter lights are being inspected by an in-situ microscope. In view of the requirement of micron-scale damage events identification during dynamic scans, we pay more attention to the raster scan protocol. The automated laser damage threshold test system is enabled by the pulsed stage movement method. A one pulse to one image correspondence have been set up during each scans, which is available for the later confirmation of the automated damage detection results and the growth study at specified test sites. It is noted that the judgement of damage sites is based on the difference between the pre-pictures and the current pictures at the same place. Our automated test systems are able to implement the different modes of tests according to the relevant standards, providing real-time information to further research on the laser damage phenomenon of different optical elements. Currently, the defect comparison rules and tolerance are being optimized to improve the accuracy of the test systems.

Keywords: automated system, raster scan, damage site, defect comparison rule

8530-71, Session PST1

Laser-induced damage threshold test of optical components for high-peak-power OPCPA systems

Andrey Lyachev, Trevor B. Winstone, Ian O. Musgrave, Marco Galimberti, Alexis Boyle, David A. Pepler, Cristina Hernandez-Gomez, Ian N. Ross,
Rutherford Appleton Lab. (United Kingdom)

SPEAKER BIOGRAPHY: Andrey Lyachev gained his PhD degree in Laser-Plasma interactions from the University of Strathclyde in 2007 and since then has been working in the VULCAN laser group at the Rutherford Appleton Laboratory.

ABSTRACT TEXT: V1ULCAN laser is a well known high power laser facility capable of delivering 1PW output power with focused intensity at 1021 W/cm^2 [1]. An upgrade project has been started in recent years for the development of a 10PW capability for the VULCAN laser based on large scale OPCPA to produce pulses with focused intensities > 1023 W/cm^2 [2]. This capability will be achieved by delivering pulses centered at 910nm with sufficient bandwidth > 150nm to support pulse energy > 300J in < 30fs.

The optics in the final stages of compression and beam delivery will require a damage threshold greater than 160mJ/cm^2. We have established a research collaboration with Plymouth Grating Laboratory (PGL) to develop the gratings required for the project capable of meeting our spectral and damage threshold parameters. We have received several promising grating samples and have measured their diffraction efficiency within the specified range of wavelengths using a tunable laser source [3]. Laser-induced damage threshold (LIDT) tests of the samples have been conducted at the Vilnius University Laser Research Center (VULRC). However, the pulses used were centered at 800nm with 33nm bandwidth and a 10Hz repetition rate [4], whilst this gives an indication of the LIDT. The difference of the center wavelength might introduce a discrepancy due to a potential change in the behavior of the grating and consequently its LIDT, so we are establishing our own LIDT facility.

In this paper we present the latest progress in the development of our LIDT test facility for the optical components of the VULCAN laser 10PW upgrade project. A suitable laser system has been designed, built and commissioned to produce pulses centered at 910nm with sufficient bandwidth [5] to support < 30fs pulses and energy up to the joule level delivered at 2Hz repetition rate [6]. The output from this laser will be focused onto the test sample hosted in a vacuum chamber and positioned using a 3D motorized stage. These tests will be N-on-1 type at both S- and P- polarizations for a range of fluencies up to 500mJ/cm^2.

References:
[1] C.N. Danson et al., Nucl. Fusion 44, 239 (2004)
[2] I.N. Ross et al., Opt. Commun. 144, 125 (1997)
[3] A. Lyachev et al., Central Laser Facility Annual Report 2008-2009
[4] T.B Winston et al., Central Laser Facility Annual Report 2010-2011
[5] Y. Tang et al., Opt. Lett. 33(20), 2386 (2008)
[6] A. Lyachev et al., Opt. Express 19(17), 15824 (2011)

Keywords: LIDT, OPCPA, High power lasers, Femtosecond pulses, Gratings

Effective area of pulsed laser spots within ISO 21254-1,2,3 standards: critical analysis, extensions, and measurements in near ultraviolet: near infrared domain

George Nemes, ASTiGMAT (United States) and National Institute for Lasers, Plasma and Radiation Physics (Romania); **Aurel Stratan, Alexandru Zorila, Laurentiu Rusen,** National Institute for Lasers, Plasma and Radiation Physics (Romania)

SPEAKER BIOGRAPHY: George Nemes is a laser and optics scientist with expertise in solid-state lasers, nonlinear optics, laser beam characterization, unconventional optics. Currently he is the President of ASTiGMAT(TM), CA, USA, and Project Director of the Romanian project ISOTEST. He is involved in developing/improving ISO standards for beam characterization and for laser-induced damage in optical components.

ABSTRACT TEXT: The concept of effective area used to determine the fluence and the irradiance damage threshold within ISO 21254-1,2,3 standards, dedicated to laser-induced damage experiments, is critically analyzed. This concept is different than the "effective irradiation area" defined in ISO 13694 standard (dedicated to laser energy/power distribution), and it does not explicitly consider any spot shape, irrespective of the criteria that might be used to define such a spot shape (clip level or second-order moments). However, in ISO 21254-1 standard, an effective diameter is defined based on the effective area concept, by implicitly assuming a circular spot shape. Also, quantities related to the specific beam profile, useful for better understanding of the damage process (e.g., flatness factor, beam uniformity, plateau uniformity), are not considered in ISO 21254-1,2,3, either.

We extend the effective area concept and consider some new measurable quantities useful for laser-induced damage experiments. Thus, we associate an effective boundary of the spot that normally is characterized only by the effective area, by using a scaled version of the second-moments definition for the sizes of the appropriate spot. Consequently, we extend the effective diameter concept to elliptical spots, by defining the effective principal sizes of the corresponding spot and the orientation (azimuth angle) of the spot.

We describe a real-time method for measuring the effective area of the laser beam spots in a specific transverse plane, and the other associated quantities already defined, by using a Si-based CCD laser beam profiler. The influence of the background energy and of the size of the integration area on the accuracy of the effective area measurements are evaluated by MATLAB simulation of the beam profile and of the CCD camera noise. Experimental results obtained on different laser spots from a nanosecond, 1064 nm Nd:YAG laser are presented, and their standard uncertainty is evaluated.

This work is sponsored by the National Authority for Scientific Research (ANCS - POSCCE), Romania, Project ISOTEST No. 172/2010.

Keywords: effective area, effective diameter, laser-induced damage, ISO 21254 standards, CCD beam profiler, laser beam characterization

Bayesian approach of laser-induced damage threshold analysis and determination of error bars

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

SPEAKER BIOGRAPHY: Gintare Bataviciute is a PhD student in Vilnius University (Lithuania) and works in department of optics characterization in Laser Research Center (VULTC). Her current research interest includes both theoretical and experimental laser-induced damage threshold studies under normal and extreme conditions.

ABSTRACT TEXT: In this study a reproducibility problem in Laser-Induced Damage Threshold (LIDT) determination procedure when using widely known Damage Frequency Method (DFM) is addressed. A simplified computer model representing the statistical interaction between laser irradiation and randomly distributed damage precursors is applied for Monte Carlo experiments. The reproducibility of LIDT predicted from DFM is examined under both idealized and realistic laser irradiation conditions by performing numerical 1-on-1 tests. It is shown that well accepted least square and weighted least square fits suffer from nondeterministic statistical nature of laser damage. This results in systematic errors when estimating LIDT and its error bars for finite area specimens. As a possible solution Bayesian approach was proposed. A novel concept of parametric regression based on varying kernel and maximum likelihood fitting technique is introduced and studied both theoretically and experimentally. Such approach exhibited clear advantages over conventional linear fitting both in increased reproducibility and informative error bars estimation. Therefore, proposed improvements are of practical importance in LIDT metrology.

Keywords: Laser-induced damage threshold, Maximum-likelihood, Error bars estimation, Monte Carlo modelling, Bayesian statistics, Damage Frequency Method, 1-on-1 tests

Laser damage testing of optical components under cryogenic conditions

Jindrich Oulehla, Pavel Pokorny, Josef Lazar,
Institute of Scientific Instruments of the ASCR, v.v.i. (Czech Republic)

SPEAKER BIOGRAPHY: Jindrich Oulehla was Born 1981 in Brno, Czech Republic. In 2008 I finished master's degree in solid state physics at Masaryk University in Brno. Since 2009 I am a Ph.D student and working at the Institute of Scientific Instruments in coherence optics department. My field of interest is design and deposition of thin layer interference coatings.

ABSTRACT TEXT: In this contribution we present a technology for deposition and testing of interference coatings for optical components designed to operate in power pulsed lasers. The aim of the technology is to prepare components for high power laser facilities such as ELI (Extreme Light Infrastructure) or HiLASE. ELI is a part of the European plan to build a new generation of large research facilities selected by the European Strategy Forum for Research Infrastructures (ESFRI). These facilities rely on the use of diode pumped solid state lasers (DPSSL). The choice of the material for the lasers' optical components is critical. Some of the most important properties include the ability to be antireflection and high reflection coated to reduce the energy losses and increase the overall efficiency. As large amounts of heat need to be dissipated during laser operation, cryogenic cooling is necessary. The conducted experiments served as preliminary tests of laser damage threshold measurement methodology that we plan to use in the future. We designed a special apparatus consisting of a vacuum chamber and a cooling system. The samples were placed into the vacuum chamber which was evacuated and then the samples were cooled down to approximately 120K and illuminated by a pulsed laser. Pulse duration was in the nanosecond region. Multiple test sites on the sample's surface were used for different laser pulse energies. We used optical and electron microscopy and spectrophotometer measurements for coating investigation after the conducted experiments.

Keywords: laser damage, optical coating, thin layer

8530-75, Session PST1

Laser-induced damage performance of three kinds fluorophosphates glass with different doped ions

Fuquan Li, China Academy of Engineering Physics (China)

SPEAKER BIOGRAPHY: Prof. Fuquan Li majored in optical engineering

ABSTRACT TEXT: A kind of improved Fluorophosphates Glass was produced, and its components of large aperture have been obtained at present. We hope the new material could be used in the Final Optics Assembly (FOA) of the megajoule laser driver for Inertial Confinement Fusion (ICF). Acoording to the FOA's requirements, its components should followed two characteristic of high UV laser: high transmission (transmission efficiency and transmited wavefront), high damage threshold. Based on different laser tables, we have finished a few experiments. In these experiments, transmission efficiency and damage threshold were mainly measured. The result shows the new material exists a distance from use, so it has to do more work. Meanwhile, we build a test standard about new material and component for high energy and high power laser.

Keywords: Laser-induced damage, Fluorophosphates glass, filamentation

Laser removal of positive-tone diazonaphthoquinone/novolak (DNQ/novolak) resist without occurring laser-induced damage to the silicon wafer

Hiroki Muraoka, Yuki Yanama, Yoshiaki Matsura, Tomosumi Kamimura, Osaka Institute of Technology (Japan);
Hideo Horibe, Kanazawa Institute of Technology (Japan)

SPEAKER BIOGRAPHY: Hiroki Muraoka is graduate student at the Major in Electrical and Electronic Engineering of Graduate Schools Osaka Institute of Technology. He received his B.A. degree in Department of Electronics, Information and Communication Engineering of Osaka Institute of Technology in March 2012. He worked on the studying the laser processing.

ABSTRACT TEXT: Transistors are formed on substrates in the manufacturing process of semiconductors and LCD electronic devices by several repetitions of processes such as coating, patterning (resist coat, exposure, development), etching, and resist removal and cleaning. Large amounts of sulfuric acid, hydrogen peroxide, and amine type organic solvents are used in the resist removal process, and the chemical waste is causing environmental damage. In our past report, we succeeded in removing a resist by ablation with a pulsed ultraviolet laser (266nm). In contrast, the pulsed laser beam from visible to near-infrared was not able to remove the resist because laser damage occurred in the silicon wafer. In this study, we have investigated the laser stripping of positive-tone diazonaphthoquinone/novolak (DNQ/novolak) resist by using a pulsed laser beam from visible to near-infrared. A silicon wafer with resist was sunk in a liquid to utilize irradiated laser energy effectively. When the resist was irradiated with the fundamental wavelength of the Nd:YAG laser, the resist was stripped from the silicon wafer. No damage could be detected from the processed silicon wafer. We also show the stripping effect of the resist at different irradiated laser wavelengths.

Keywords: laser removal, positive-tone diazonaphthoquinone/novolak (DNQ/novolak) resist, laser-induced damage, silicon wafer, stripping effect

Investigation of laser damage initiation and the defect volume density in transparent YAG ceramics

Yuki Yamana, Tomosumi Kamimura, Hiroki Muraoka, Haruki Nakagawa, Osaka Institute of Technology (Japan); **Katsuhiro Mikami, Shinji Motokoshi, Takahisa Jitsuno,** Osaka Univ. (Japan); **Takayuki Okamoto,** Okamoto Optics Works (Japan); **Yan Lin Aung, Akio Ikesue,** World Lab Co., Ltd. (Japan)

SPEAKER BIOGRAPHY: Yuki Yamana is graduate student at the Major in Electrical and Electronic Engineering of Graduate Schools Osaka Institute of Technology. He received his B.A. degree in Department of Electronics, Information and Communication Engineering of Osaka Institute of Technology in March 2012. He worked on the studying the laser materials.

ABSTRACT TEXT: Laser-induced bulk damage of transparent YAG ceramics is related to optical heterogeneity (i.e., structural defects) such as residual pores and extra grain boundaries and so on. We have already reported the relationship among the bulk laser-induced damage threshold (LIDT) and various structural defects in YAG ceramics. Laser-induced damage of YAG material was strongly related to the scattering defect density. The decrease of scattering defect density can enhance the resistance of YAG ceramics against laser-induced bulk damage.

In this paper, we have investigated the laser damage initiation in YAG ceramic material. When 1064nm laser beam was irradiated to YAG ceramics, the laser damage occurred from the several scattering defects on the optical path. To examine the relation between the beam volume at the focusing spot and the defect volume density, scattering defect was observed in three dimensions by using a visible laser scattering tomography. The number of the scattering defect to be included in the unit volume was analyzed from the average particle diameter of the scattering body. In our laser irradiation condition, sample with low laser damage resistance had over 10,000 scattering defect at the focusing spot. In contrast the sample which had highest laser damage resistance was found to include only around 100 scattering defect. These results indicated that decreasing the scattering defects from the optical path had a greater impact on the LIDT of transparent YAG ceramics. We will also present the behavior of the scattering defect in the laser oscillating wavelength.

Keywords: YAG ceramics, Scattering defect, Laser-induced damage threshold (LIDT)

Sandwich concept: enhancement for direct absorption measurements by laser-induced deflection (LID) technique

Christian Mühlig, Simon Bublitz, Institut für Photonische Technologien e.V. (Germany)

ABSTRACT TEXT: We present the new sandwich concept for absolute photothermal absorption measurements using the laser induced deflection (LID) technique. The sandwich concept addresses both, common drawbacks of the LID technique (limitations for small sample size, additional polished sample side faces) as well as general limitations for photo-thermal techniques (photo-thermally insensitive materials, materials that are nontransparent for probe beam wavelength).

The basic idea of the sandwich concept is the decoupling of the optical materials for the pump and probe beams. A sample of investigation is placed in between two optical (sandwich) plates, which not necessarily need to be of the same material than the sample. Whereas the pump beam of the investigation wavelength is guided through the sample, the two probe beams are deflected by the thermal lens that is generated by heat transfer from the irradiated sample to the sandwich plates. This allows for a couple of advantages compared to a common setup: The currently required sample size for the transversal probe beam guiding is strongly reduced and is now mainly limited by the pump beam dimension. By choosing appropriate optical materials for the sandwich plates, the detection limit for photothermally insensitive materials can be significantly decreased (one order of magnitude or more possible). Furthermore, optical materials which are nontransparent to the probe beam wavelength (typically in the VIS spectral range) can now be investigated. Finally, the current requirement of two additionally polished sample side faces for the probe beam passing in the LID setup can be waived.

In the presentation we report on experiments regarding all of the above mentioned features, including tests of different optical materials for the sandwich plates with respect to their potentially sensitivity increase, measurements of HR coated (nontransparent) aluminum substrates, comparison of samples with polished and unpolished side faces. Furthermore, the sandwich concept is applied to investigate small laser crystals as well as nonlinear optical crystals. For several optical materials we demonstrate the benefit in sensitivity by applying the new concept compared to the common LID measurement concept. Finally, it is demonstrated that the established electrical calibration can be transferred to the new concept.

Keywords: absorption measurements, optical materials, nonlinear crystals, optical coatings

Automated test station for laser-induced damage threshold measurements according to ISO 21254-1,2,3,4 standards

Aurel Stratan, National Institute for Lasers, Plasma and Radiation Physics (Romania); **George Nemes,** ASTiGMAT (United States) and National Institute for Lasers, Plasma and Radiation Physics (Romania); **Alexandru Zorila, Laurentiu Rusen, Sandel Simion, Constantin Blanaru, Constantin G. Fenic, Liviu Neagu,** National Institute for Lasers, Plasma and Radiation Physics (Romania)

SPEAKER BIOGRAPHY: Aurel Stratan is senior scientist with Laser Dept., National Inst. for Laser, Plasma, and Radiation Physics, Magurele-Bucharest, Romania. His expertise consists in design and developing solid-state lasers, nonlinear optical devices, optical parametric oscillators, and studying processes and designing experiments related to laser-induced damage in different materials. Currently he is scientific manager of the project ISOTEST aiming at developing two test stations for LIDT using femtosecond and nanosecond lasers, and developing novel beam characterization methods.

ABSTRACT TEXT: Within the context of the new international research infrastructure, the Extreme Light Infrastructure - Nuclear Physics facility (ELI-NP), to be implemented in Bucharest, Romania during the next couple of years, a two-arm very high-power laser system will be developed, delivering an estimated 10 PW peak pulse power on each arm. As a result of the multiple technical challenges, foreseen or yet unknown, several smaller, independent projects were started. This paper reports an automated test station for laser-induced damage threshold (LIDT) measurements, aimed to implement the recommendations of the LIDT-dedicated ISO 21254-1,2,3,4 standards. The station is part of such an independent project named ISOTEST (http://ssll.inflpr.ro/isotest/index.htm). We believe the structure and the specifics of our station contain new results worth to be known by a wider audience of specialists in laser-induced damage.

The automated LIDT test station is built around a single longitudinal mode, 500 mJ pulse energy, 6 ns pulse-width, electro-optically Q-switched, 10 Hz repetition frequency, linearly polarized, Nd:YAG laser at 1064 nm, with 2-nd and 3-rd harmonic capabilities (Brilliant B-10-SLM, Quantel). The machine operates using the S-on-1 damage procedure (ISO 21254-2 standard), with S = 500. The Type 2 test for assurance of laser power/energy handling capabilities (i.e., the endurance, or the durability test of ISO 21254-3 standard) can be also directly performed on the machine by easy changing the spot size and the distribution of the sites on target. The main functional blocks of the station are: laser source; laser beam shutter; controllable beam attenuator; energetic, temporal, and spatial beam diagnostics system; focusing optics; target holder and moving system; real-time damage detector system; peripherals control unit (PCU); main personal computer (PC).

The spatial beam diagnostics system allows to measure the ISO 21254-1 defined effective area and effective diameter, as well as some new extensions of these quantities which we developed and implemented in measurement procedures.

The focusing optics consists of an optical system able to change the spot size in a broad range (0.2 mm - 4 mm diameter) while maintaining the target plane at a fixed working distance. These diameters are useful for both the S-on-1 procedure and the Type 2 durability test. Conventional focusing lenses can be used, too.

The PC with associated operating system and programs directly or indirectly controls all the peripheral devices located on the optical table (shutter, beam attenuator, probe positioning motorized stage, etc). For specific reasons, some of these peripherals are driven indirectly by the PC, via the PCU. The communication between the PC and the PCU is realized with a specific protocol, using the MASTER/SLAVE concept and technology. The MASTER is the PC and the SLAVE is the PCU. The PC and PCU allow the operator to initiate and start the test procedure, and/or, if necessary, to intervene at any time during the procedure and to stop or to modify it.

We also present preliminary results of LIDT using the S-on-1 test on HR coatings, AR coatings, and on substrates with different degrees of roughness. These test specimens were kindly provided by Ophir Optics SRL, Bucharest, Romania, a brand of Newport Corp.

This work is sponsored by the National Authority for Scientific Research (ANCS - POSCCE), Romania, Project ISOTEST No. 172/2010.

Keywords: automated test station, LIDT, ISO 21254-2,3 standards

Parallel use of detection channels for LIDT testing in the UV range

Stefan Schrameyer, Marco Jupé, Lars O. Jensen, Detlev Ristau,
Laser Zentrum Hannover e.V. (Germany)

ABSTRACT TEXT: The reliable online detection of damage events is a very important part in the measurement of multi-pulse laser-induced damage thresholds (LIDT) of optical components. In many measurement protocols, a certain threshold for radiation scattered by the test site is defined as damage criterion. Nevertheless, for example in the measurement of uncoated substrates or antireflective coatings online damage detection on the basis of scattering is often observed to be of less consistency. In such cases accumulation effects over a large number of pulses may appear and eventually result in a catastrophic failure of the optic before a significant indication of the scatter detectors. As a consequence, valuable information on the nature of the damage may be lost.

In this paper the use of online reflectance- and transmittance-measurements as a different kind of switch-off criterion for LIDT-measurements is considered. The measurements are performed at 266nm and 355nm using a Q-switched ns-laser-source. Advantages and disadvantages of the detection system are discussed and compared to a typical online scatter detection system. Slight changes in reflectance and transmittance might be used as a pre-indicator of a catastrophic failure of the optic and may allow for an interpretation of LIDT-measurements in the context of lifetime testing.

Keywords: LIDT, 266nm, 355nm, Reflectance, damage detection

Wednesday AM • 26 September

07:30 to 16:00 **Registration Material Pick-up,** NIST Lobby Area

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08:20 to 10:00 • SESSION 9

Materials and Measurements III

Session Chairs: **Klaus Mann,** Laser-Lab. Göttingen e.V. (Germany);
Semyon Papernov, Univ. of Rochester (USA)

8:20: **Analysis of residual absorptions in optical materials using OPO-based pulsed photoacoustic spectroscopy with ppm/cm sensitivity**, Niklas Waasem, Fraunhofer-Institut für Physikalische Messtechnik (Germany) and Albert-Ludwigs-Univ. Freiburg (Germany); Stephan Fieberg, Frank Kuehnemann, Fraunhofer-Institut für Physikalische Messtechnik (Germany); Karsten Buse, Fraunhofer-Institut für Physikalische Messtechnik (Germany) and Albert-Ludwigs-Univ. Freiburg (Germany) . . . . [8530-32]

8:40: **Photothermal common-path interferometry: capabilities beyond the absorption test measurements**, Ashot S. Markosyan, Roger Route, Martin M. Fejer, Stanford Univ. (USA) . . . . [8530-33]

9:00: **Light scattering to detect imperfections relevant for laser-induced damage**, Sven Schröder, Tobias Herffurth, Marcus Trost, Angela Duparré, Fraunhofer-Institut für Angewandte Optik und Feinmechanik (Germany) . . . . [8530-34]

9:20: **Multichannel laser-induced contamination test bench**, Helmut B. Schröder, Deutsches Zentrum für Luft- und Raumfahrt e.V. (Germany); Gintare Bataviciute, Vilnius Univ. (Lithuania); Karl Cichon, Deutsches Zentrum für Luft- und Raumfahrt e.V. (Germany); Istvan Balasa, Lars O. Jensen, Laser Zentrum Hannover e.V. (Germany); Wolfgang Riede, Deutsches Zentrum für Luft- und Raumfahrt e.V. (Germany); Adrian P. Tighe, European Space Research and Technology Ctr. (Netherlands). . . . . [8530-35]

9:40: **Advanced LIDT testing station in the frame of the HiLASE Project**, Jan Vanda, Laura Gemini, Roman Svabek, Tomas Mocek, Institute of Physics of the ASCR, v.v.i. (Czech Republic); Gilles Cheriaux, Ecole Nationale Supérieure de Techniques Avancées (France) . . . . [8530-36]

10:00 to 10:30 • Coffee Break

10:30 to 11:50 • SESSION 10

Materials and Measurements IV

Session Chairs: **Amy L. Rigatti,** Univ. of Rochester (USA); **Takahisa Jitsuno,** Osaka Univ. (Japan)

10:30: **Pulse-width dependent femtosecond damage threshold measurements for pulse compression gratings**, Enam Chowdhury, Patrick Poole, Richard Freeman, The Ohio State Univ. (USA); Douglas J. Smith, Plymouth Grating Lab. (USA) . . . . [8530-37]

10:50: **Laser-induced surface damage density measurements with small and large beams: the representativeness light**, Laurent Lamaignère, Thierry Donval, Gabriel Dupuy, Commissariat à l'Énergie Atomique (France) . . . . [8530-38]

11:10: **Electric field dependant decay and recovery of anthraquinones doped into PMMA thin films: beyond 100% recovery**, Benjamin R. Anderson, Mark G. Kuzyk, Washington State Univ. (USA) . . . . [8530-25]

11:30: **355nm absorption in HfO_2 and SiO_2 monolayers with embedded Hf nanoclusters studied using photothermal heterodyne imaging**, Semyon Papernov, Univ. of Rochester (USA); Eunsung Shin, Paul T. Murray, Univ. of Dayton Research Institute (USA); Ansgar W. Schmid, James B. Oliver, Univ. of Rochester (USA). . . . . [8530-31]

11:50 to 13:30 • Lunch Break

11:50 to 12:50 · 2 tours offered • NIST Facility Tours

NIST has generously offered to provide 2 limited tours of the facility, including the NIST-F1 and NIST-F2 Atomic Clocks. Space is limited. Sign up onsite by 14:00 on Tuesday to reserve your place. First come, first served for Laser Damage Attendees only. A sign-up sheet will be at the registration desk.

Analysis of residual absorptions in optical materials using OPO-based pulsed photoacoustic spectroscopy with ppm/cm sensitivity

Niklas Waasem, Fraunhofer-Institut für Physikalische Messtechnik (Germany) and Albert-Ludwigs-Univ. Freiburg (Germany); **Stephan Fieberg, Frank Kuehnemann,** Fraunhofer-Institut für Physikalische Messtechnik (Germany); **Karsten Buse,** Fraunhofer-Institut für Physikalische Messtechnik (Germany) and Albert-Ludwigs-Univ. Freiburg (Germany)

ABSTRACT TEXT: The spectroscopic analysis of residual absorption in transparent optical materials allows the quantification of the absorption level (which can be highly relevant for high power laser and non-linear optical applications) as well as a characterization of the materials in terms of optically relevant impurities and imperfections.

To combine broad spectral coverage with high detection sensitivity, a photoacoustic spectrometer has been built which is based on a pulsed optical parametric oscillator (OPO) and a piezoelectric detector. The OPO (10 ns pulses at 10 Hz repetition rate) covers the wavelength range between 215 and 2600 nm. With pulse energies up to 100 mJ, absorption spectra can be measured down to 10 ppm/cm. Tuning the OPO wavelength does allow one to identify impurities responsible for the residual absorptions, which, in turn, can give important feedback for the fabrication and treatment of the materials.

The new spectrometer has been used to study the absorption properties of a range of materials relevant for nonlinear optics, where residual absorption may lead to thermal distortions as well as severe damage effects. As a case study, optically relevant impurities in lithium niobate were identified and quantified in samples of different origin. Using an additional continuous-wave pump beam at 532 nm did allow us to measure the light-induced changes in the absorption spectrum of lithium niobate.

Keywords: Photoacoustic spectroscopy, optical materials, impurities, residual absoprtion

8530-33, Session 9

Photothermal common-path interferometry: capabilities beyond the absorption test measurements

Ashot S. Markosyan, Roger Route, Martin M. Fejer, Stanford Univ. (United States)

ABSTRACT TEXT: The photothermal common-path interferometric (PCI) technique is a powerful tool for ultra-low loss optical absorption measurements. The technique exploits the thermal lensing effect produced in the material under investigation by a high-power pump beam and detected by a low-power probe beam. Absorption losses as low as 0.02 ppm in HR mirrors and bulk absorptions under 0.3 ppm/cm in solid materials can be measured with an incident pump power as low as 3 W.

The capabilities of the method extend well beyond the simple optical absorption test measurements. Due to the frequency modulation of the pump power, the thermalized AC signal sensed by the probe is also modulated with the same frequency but it has a delay in its phase. This makes it possible to study the thermal diffusivity of a material as well as providing a number of opportunities for thorough control of the measurement itself. The frequency dependence of the AC signal and the phase delay allows one to detect and, in some cases, isolate non-thermal contributions to the PCI signal, such as might arise from photorefraction or the presence of free carriers.

At Stanford University the PCI setup is equipped with high- and low-temperature units for data collection in the range from 15 to 650 K, and it allows measurement both in vacuum and air.

Keywords: Optical properties, Optical absorption measurements

8530-34, Session 9

Light scattering to detect imperfections relevant for laser-induced damage

Sven Schröder, Tobias Herffurth, Marcus Trost, Angela Duparré,
Fraunhofer-Institut für Angewandte Optik und Feinmechanik (Germany)

SPEAKER BIOGRAPHY: Sven Schroeder graduated in Physics from the Friedrich Schiller University (FSU) in Jena, Germany, in 2004. He received his PhD degree (Dr. rer. nat.) from the FSU in 2008. Since 2001, he is with the Surface and Thin Film Characterization group at the Fraunhofer IOF in Jena. In 2010, he spent one year at CREOL/UCF in Orlando, FL, USA. His interests are directed to the study of the roughness and light scattering of surfaces and thin film coatings.

ABSTRACT TEXT: Laser-induced damage of optical surfaces, thin film coatings, and materials is greatly influenced by imperfections such as surface and interface roughness, or surface or subsurface defects. All these imperfections give also rise to light scattering. Light scattering techniques are non-contact, highly sensitive, and enable even large sample areas to be investigated. They are thus well suited to identify and characterize damage-relevant features.

Surface roughness, polishing homogeneity and contaminations are known to be critical with respect to laser stability. Conventional characterization techniques are usually confined to small sample areas. A light scattering method will be presented that provides roughness and defect maps even of large and curved surface. Subsurface defects also play a critical role as damage precursors. Many detection methods are still based on wedging and/or etching the sample surface. A new non-contact approach to detect subsurface damage using polarized light scattering will be presented.

In addition, a method will be discussed that provides information about the structural and optical properties of multilayer coatings by analyzing the scattered light distribution. Even small deviations of the illumination and the design wavelengths or angles can lead to substantial field enhancements inside the coating which can be clearly observed as resonant scattering wings.

Keywords: Scattering, Roughness, Polishing, Subsurface-Damage, Coatings

Multichannel laser-induced contamination test bench

Helmut B. Schröder, Deutsches Zentrum für Luft- und Raumfahrt e.V. (Germany); **Gintare Bataviciute,** Vilnius Univ. (Lithuania); **Karl Cichon,** Deutsches Zentrum für Luft- und Raumfahrt e.V. (Germany); **Istvan Balasa, Lars O. Jensen,** Laser Zentrum Hannover e.V. (Germany); **Wolfgang Riede,** Deutsches Zentrum für Luft- und Raumfahrt e.V. (Germany); **Adrian P. Tighe,** European Space Research and Technology Ctr. (Netherlands)

SPEAKER BIOGRAPHY: Helmut Schroeder was born in 1955 in Bremen, Germany. He studied physics at the University of Goettingen and got his diploma degree in 1981 and his Ph.D. in 1985. In 1986 he joined the German Aerospace Center (DLR) in Stuttgart. There he was engaged in space and aircraft tribology and in epitaxy of group IV nitrides by Pulsed Laser Deposition. Since 2005 his main interests are laser induced contaminations of optics.

ABSTRACT TEXT: Lifetime enhancement of optical components is still one of the major topics in space based laser applications. In this paper a novel multichannel test setup for basic research of laser- induced contamination (LIC) phenomena is introduced. Main part of the setup is an ultra-high vacuum chamber with a contamination source similar to a Knudsen cell, which offers the possibility to apply constant partial pressure of pure contamination material throughout the whole time of testing. Up to three different optical samples can be tested simultaneously under identical experimental conditions. As laser source a diode pumped Nd:YAG system with frequency doubling and tripling is used. It provides 10 ns pulses with a repetition rate between 1 and 1000 Hz and 2.5 mJ pulse energy for 355 nm. Contamination growth is monitored online by transmission and fluorescence detection. LIC growth dynamic was analysed in dependence on laser fluence and repetition rate. Uncoated and HR and AR coated fused silica optics were investigated. The coatings were produced by different processes: e-beam, Ion Beam Sputtering, and Magnetron Sputtering. The influence of coating morphology and composition on LIC growth is discussed.

Keywords: Laser-induced contamination, Coating, Fluorescence

Advanced LIDT testing station in the frame of the HiLASE Project

Jan Vanda, Laura Gemini, Roman Svabek, Tomas Mocek,
Institute of Physics of the ASCR, v.v.i. (Czech Republic);
Gilles Cheriaux, Ecole Nationale Supérieure de Techniques Avancées (France)

ABSTRACT TEXT: Pulsed lasers operating in picosecond and femtosecond regime have evolved rapidly in the past years, mainly regarding the intensity and repetition rate. Purely scientific setups, designed for fundamental research, have extended into application in many fields, as metrology, machining or medical devices. Apparent achievements in laser physics and progress in engineering and material science gave a rise to cutting-edge projects, as Eli Beamlines or PETAL. Utilizing of gathered knowledge and state-of-the-art then allows construction of compact devices in applied research, which can reach substantial output powers and energy densities. Parallel application projects, as for example HiLASE, has important role in providing engineering background for the fundamental research as well as transfer scientific results into application level. For this purpose, HiLASE is developing three kW class thin-disk laser lines, delivering 1-2 picosecond pulses of energy 2-3 Joules with repetition rate up to 1 kHz and beam diameter 45 mm, and one multislab system delivering 1-2 nanosecond pulses of energy 100 Joules with repetition rate up to 100 Hz and beam diameter 15 mm.

Due to the fast evolution of lasers systems and consequent increase of the output powers, requirements on laser system components are now more demanding. Research and development of novel materials and novel measurement methods for optical coatings, mirrors, crystals and other components is highly desirable. Output parameters described above can be unattainable by common industrial lasers. Consequently, there is a significant demand for the beam time at the high power, high repetition rate devices, both from research laboratories and industrial companies. However, such lasers are in majority designed for scientific experiments, requiring complicated set-up to fit particular workplace, than for “test-and-go” approach.

One of the main goals of application program in HiLASE project will be to remove this deficit and provide valuable workplaces allowing fast set-up and exposure variety of samples. In particular, design of highly advanced station for measuring laser induced damage threshold, utilizing HiLASE lasers, will be described further. This station will be in compliance with series of ISO 21254 standards, fully computer controlled, offering beams with parameters described in previous paragraph. Station design will employ also online detecting devices, allowing precise control of damage threshold measurement as well as observation of non-damaging effects occurring under the high-energy beams. Further, particular measurements of mirrors intended for beam delivery system in HiLASE will be presented. These measurements are focused on LIDT and effects occurred after million and more incident pulses.

Keywords: LIDT, ISO 11254, high power laser

8530-37, Session 10

Pulse-width dependent femtosecond damage threshold measurements for pulse compression gratings

Enam Chowdhury, Patrick Poole, Richard Freeman,
The Ohio State Univ. (United States);
Douglas J. Smith, Plymouth Grating Lab. (United States)

SPEAKER BIOGRAPHY: Dr. Enam Chowdhury is an expert in ultra-intense peta-watt class lasers and laser matter interactions at relativistic intensities (10^{20} W/cm^2 and beyond). His main interests are in laser plasma/solid interaction, laser damage, MeV ion acceleration, laser neutron generation, ultra-fast laser technology. He leads the SCARLET Peta-watt Laser team at the Ohio State University, where the 0.5 PW laser construction is being completed by May 2012.

ABSTRACT TEXT: Gratings used in high power ultra-intense laser systems are required to have broad bandwidth and high damage fluence, though they are often the weakest link in such a laser system. Here we use new types of gratings for in vacuum short pulse laser damage testing, where the grating grooves are etched into the substrate (fused silica), rather than a thin coating of photoresist (organic polymer) holding the pattern.

The SCARLET laser system front end at the Ohio State University used in this experiment delivers a kHz repetition rate 25-200 fs 800 nm high quality beam, with up to 400 µJ/pulse on target. The experiment was performed under vacuum (<10^{-1} Torr) at 45 degree AOI.

Damage probability vs. fluence at different pulsewidths for different types of gratings (1500 l/mm) is discussed, with some gold and silver gratings having Au and Ag coating with normal sputtering process, whereas, the conformal Au grating coating was deposited under energetic sputtering conditions, resulting in a much smoother coating, yielding a single shot damage threshold of 400 mJ/cm^2. Unlike in nanosecond laser damage regimes, femtosecond laser damage threshold in metal coated gratings do not seem to exhibit a strong dependence on laser pulse width. SEM analysis of laser damage spot on these grating show that only gold overcoat damage, whereas the grating pattern on fused silica substrate remain undamaged. These gratings have been successfully stripped off damaged gold coating and fully re-coated at fraction of the cost of a new grating.

Keywords: laser damage, pulse compression, femtosecond laser, short pulse laser, pulse compression grating, femtosecond laser matter interaction

Laser-induced surface damage density measurements with small and large beams: the representativeness light

Laurent Lamaignère, Thierry Donval, Gabriel Dupuy,
Commissariat à l'Énergie Atomique (France)

ABSTRACT TEXT: The comparison of laser-damage-densities (LDD) measurements performed with pulsed laser radiation at different facilities is tricky due to numerous parameters involved. These parameters, namely pulse length, profile, and frequency, beam size, as well as method of damage detection have significant impact on final result. Previous methods and suitable data processing developed to determine with accuracy and repeatability the LDD allow us to achieve this comparison, e.g. the reproducibility.

Since such studies are related to the life-time predictions for large aperture optical materials used in high-power lasers, the question that is addressed in this presentation concerns the representativeness of such results as regards of laser damage with large and real beams. Tests with large beams of centimetric size on a high power laser facility have beam performed according to a parametric study and are compared to small beam laboratory tests. More the emphasis is on the optical component thickness that may affect both damage initiation and damage growth due to the occurrence of non-linear effects that intensify damage issue.

Keywords: laser damage, inititiation, growth, fused silica

Electric field dependent decay and recovery of anthraquinones doped into PMMA thin films: beyond 100% recovery?

Benjamin R. Anderson, Mark G. Kuzyk, Washington State Univ. (United States)

SPEAKER BIOGRAPHY: Mr. Benjamin R. Anderson is a doctoral candidate of physics at Washington State University. His research interests are primarily in nonlinear optics and laser physics. He is originally from Detroit, MI.

ABSTRACT TEXT: Anthraquinones are a class of organic dyes with a wide range of uses in optical devices that require intensities above the damage threshold for operation. It has been demonstrated that some anthraquinones doped into (poly)methyl methacrylate (PMMA) demonstrate the novel effect of self healing. Understanding the physics underlying this effect could help lead to more photoresistant materials. One theory of decay and self healing is photocharge ejection and recombination. Using photoconductivity measurements we test this hypothesis and report our results comparing them to theory.

We also perform spatially resolved absorbance measurements using a white light interferometric microscope and compare the results to our previous measurements using normal absorption and digital imaging. We find consistent results showing an intensity dependent decay rate and a dose independent recovery rate. We also comment on the change in index of refraction due to decay and recovery.

Keywords: Organic dyes, Dye doped polymer thin films, self healing, photoconductivity, white light interferometry, anthraquinones

355nm absorption in HfO_2 and SiO_2 monolayers with embedded Hf nanoclusters studied using photothermal heterodyne imaging

Semyon Papernov, Univ. of Rochester (United States);
Eunsung Shin, Paul T. Murray, Univ. of Dayton Research Institute (United States);
Ansgar W. Schmid, James B. Oliver, Univ. of Rochester (United States)

ABSTRACT TEXT: The role of the Hf nanoclusters as UV, nanosecond-pulse laser-damage initiators in multilayer coatings remains speculative. Recent studies of near-UV localized absorption and nanosecond-pulse damage in HfO_2 monolayers using photothermal heterodyne imaging (PHI) and atomic force microscopy (AFM) provided an estimate for an average absorber separations at <100 nm. In this work we use the same techniques to investigate absorption in the HfO_2 and SiO_2 monolayers containing embedded nm-sized Hf clusters produced by backside-through-thin-film ablation. Hf cluster size and areal density distributions were characterized using transmission electron microscopy and AFM. PHI measurements for cluster-containing samples revealed different spatial structure of absorption signals as compared to similarly prepared HfO_2 and SiO_2 film samples of the same thickness not containing clusters. This data together with AFM analysis of the 351-nm, 0.5-ns-pulse damage morphology allowed us to evaluate a possible contribution from two hypothetical sources of the localized damage: Hf clusters and high-density areas of electronic defects.

Keywords: Hf nanoclusters, thin films, photothermal heterodyne imaging

Wednesday PM • 26 September

13:30 to 15:10 • SESSION 11

Mini-Symposium: Laser-Induced Plasma Interactions

Session Chairs: **Stavros G. Demos,** Lawrence Livermore National Lab. (USA);
Detlev Ristau, Laser Zentrum Hannover e.V. (Germany)

13:30: **Plasma-particle interactions in a laser-induced plasma** *(Invited Paper)*, David W. Hahn, Michael E. Asgill, Prasoon K. Diwakar, Univ. of Florida (USA) . . . . [8530-40]

14:10: **Laser ablation for chemical analysis: 50 years** *(Invited Paper)*, Richard E. Russo, Jhanis J. Gonzalez, Vassilia Zormpa, Inhee Choi, Lawrence Berkeley National Lab. (USA); Alexander A. Bolshakov, Applied Spectra, Inc. (USA); Javier Ruiz, Samuel S. Mao, Lawrence Berkeley National Lab. (USA); Jong H. Yoo, Applied Spectra, Inc. (USA). . . [8530-41]

14:50: **Laser-induced gas plasma etching of fused silica under ambient conditions**, Selim Elhadj, Gabe Guss, Isaac L. Bass, Manyalibo J. Matthews, Lawrence Livermore National Lab. (USA) . . . . [8530-42]

15:10 to 15:40 • Coffee Break

15:40 to 16:20 • SESSION 12

Surfaces, Mirrors, and Contamination

Session Chairs: **Joseph A. Menapace,** Lawrence Livermore National Lab. (USA);
Michelle D. Shinn, Thomas Jefferson National Accelerator Facility (USA)

15:40: **Measurement of debris and shrapnel plumes from cylindrical metal targets used in high-power laser systems**, James E. Andrew, Kathryn A. Wallace, AWE plc (United Kingdom) . . . . [8530-44]

16:00: **Influences of oil-contamination on LIDT and optical properties in dielectric coatings**, Takahisa Jitsuno, Hidetoshi Murakami, Shinji Motokoshi, Eiji Sato, Katsuhiro Mikami, Kota Kato, Tetsuji Kawasaki, Yoshiki Nakata, Nobuhiko Sarukura, Toshihiko Shimizu, Hiroyuki Shiraga, Noriaki Miyanaga, Hiroshi Azechi, Osaka Univ. (Japan) . . . .[8530-45]]

16:20 to 16:30 • Closing Remarks

Plasma-particle interactions in a laser-induced plasma *(Invited Paper)*

David W. Hahn, Michael E. Asgill, Prasoon K. Diwakar,
Univ. of Florida (United States)

SPEAKER BIOGRAPHY: David W. Hahn received his BSME (1986) and PhD (1992) degrees from LSU in Baton Rouge. Following graduation, he was a NRC Associate at the US FDA, Center for Devices and Radiological Health (1992-1994), and then a member of the technical staff at Sandia National Laboratories (1994-1998). David joined the University of Florida (Gainesville, FL) in 1998. He is currently Knox T. Millsaps Professor and Department Chair in the Department of Mechanical and Aerospace Engineering.

ABSTRACT TEXT: Laser-induced breakdown spectroscopy (LIBS) has gained in popularity as an analytical scheme for rapid materials analysis. In all of cases, the complex plasma-analyte interactions are directly related to the ultimate analyte response, and to the quality of the results provided by the techniques. Careful analysis of laser-induced plasmas and the resulting emission processes can play a vital role in understanding the many complex issues associated with the plasma-analyte interface, thereby providing an essential step forward in quantitative plasma-based and plasma-assisted analysis. pplications extend beyond LIBS to the larger analytical community, including ICP-AES and LA-ICP-MS, where plasma dissociation and ionization are also vital steps. This talk will give a brief history of the role of plasma-particle interactions within laser-induced plasmas, with emphasis on recent research focused on understanding the important issues of analyte transport, vaporization and ionization, and matrix effects within the analytical plasmas. The progress toward the current state of knowledge will be presented and discussed in the context of relevant physical processes that control the overall analyte response.

Keywords: LIBS, Laser-induced plasma, particle, Vaporization, Matrix effects

Laser ablation for chemical analysis: 50 years *(Invited Paper)*

Richard E. Russo, Jhanis J. Gonzalez, Vassilia Zormpa, Inhee Choi, Lawrence Berkeley National Lab. (United States); **Alexander A. Bolshakov,** Applied Spectra, Inc. (United States); **Javier Ruiz, Samuel S. Mao,** Lawrence Berkeley National Lab. (United States); **Jong H. Yoo,** Applied Spectra, Inc. (United States)

ABSTRACT TEXT: This lecture will provide an up-to-date status on advances and capabilities of laser ablation (LA) for chemical analysis at its half-century mark. Laser ablation direct solid sample chemical analysis is a value proposition. The benefits are well documented; little or no sample preparation, no consumables or waste, real-time measurements, excellent spatial and depth resolution, and laboratory and field measurements (1). The first papers on laser ablation chemical analysis were published in 1962 (2) and 1964 (3). In these manuscripts, the laser-induced plasma was interrogated for elemental spectral content. At the time, analysis was proposed strictly based on optical emission measurements in the laser-induced optical plasma. Much of the research shifted to hyphenated techniques in which the laser was used for sampling with secondary detection by flames, arcs/sparks, microwaves and then the ICP, which is used almost exclusively today. ICP with AES and MS has become the workhorse for direct solid sampling using laser ablation. A tremendous R&D effort has addressed the fundamental processes and utilized this knowledge to specify laser and detector parameters for optimum performance. Over the last 50 years, fundamental laser ablation mechanisms have defined optimum parameters for analysis. The 'optimal' laser conditions really depend on the sample, availability of calibration standards, and most importantly, the purpose of the analysis. Laser plasma spectrochemical analysis has experienced a revival in the past ten years, mainly due to the additional benefits of no gases (ICP) and simpler system components. The modern day term for this technology is LIBS (Laser Induced Breakdown Spectroscopy). Ideally, LIBS can address optimum sampling and analysis in one source, like the initial publications intended. There still remain tradeoffs in performance when sampling and excitation are combined in the LIBS approach. However, with new stable laser sources and intensified detectors, LIBS applications are increasing daily. Chemometric data processing is driving applications. LA-ICP continues to provide superior metrics in terms of sensitivity, accuracy and isotope measurements. LIBS is catching up with improvements in all analytical capabilities, including isotopes (4) - once thought impossible without painstaking large spectrometers and vacuum requirements, and the ability to achieve sub-micron spatial resolution with attogram absolute mass detection (5).

Laser-induced gas plasma etching of fused silica under ambient conditions

Selim Elhadj, Gabe Guss, Isaac L. Bass, Manylibo J. Matthews,
Lawrence Livermore National Lab. (United States)

SPEAKER BIOGRAPHY: Dr. Selim Elhadj is part of the advanced laser-based mitigation development effort at LLNL, CA, USA where the NIF fusion-class laser is being used. Thus most of my current work involves studies on laser-matter coupling, solid gas phase chemistry, and crystal growth. My formal background is Chemical Engineering (PhD).

ABSTRACT TEXT: Laser machining of optics for the purposes of damage mitigation has greatly enhanced the ability to process large optics such as those found in fusion-class lasers. Recently, the use of assist reactive gases has shown promise in enhancing manifold etching rates relative to ambient conditions for CW-laser exposures. However, these methods still require significant heating of the substrate that induce residual stress, redeposit coverage, material flow, and compromise the final surface finish and damage threshold. While very reactive gases such as HF are capable in principle to reduce treatment temperatures even further, they are also inherently toxic and not readily transferable to large processing facilities. Therefore, a short-lived gas plasma should in principle provide both a safe and effective etchant to reduce the amount of heating and thermal coupling needed for machining surfaces. We describe laser-based machining of fused silica that uses the formation of a YAG laser-induced gas plasma from ambient air brought close to the material surface to act as an etchant. The configuration and orientation of the beam and optical apparatus with respect to the surface was critical in preventing surface damage while etching the surface. Results of the etching are shown along with a description of the implementations attempted.

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8530-44, Session 12

Measurement of debris and shrapnel plumes from cylindrical metal targets used in high-power laser systems

James E. Andrew, Kathryn A. Wallace, AWE plc (United Kingdom)

SPEAKER BIOGRAPHY: Jim Andrew is a team leader in the plasma physics department at AWE plc.

ABSTRACT TEXT: All laser targets subjected to heating by focussed energetic lasers for the study of high temperature plasmas produce shrapnel, debris or radiation directly or indirectly that impact and coat the optics, instruments and surfaces used in the vacuum chambers employed for such studies. We describe the spatial distributions of the target ejecta arising from various configurations of thin walled metal cylinder targets and their mechanical mounting systems that have been deployed on the Helen and Zbeamlet lasers. We also demonstrate how this data can be used to evaluate threats to optical surfaces and ancillary instruments in high energy, high power laser systems. The methods used for characterising and quantifying material plumes will also be described.

Keywords: Debris, Shrapnel, Gold, Copper, Silica, Craters, Splats, X rays

8530-45, Session 12

Influences of oil-contamination on LIDT and optical properties in dielectric coatings

Takahisa Jitsuno, Hidetoshi Murakami, Shinji Motokoshi, Eiji Sato, Katsuhiro Mikami, Kota Kato, Tetsuji Kawasaki, Yoshiki Nakata, Nobuhiko Sarukura, Toshihiko Shimizu, Hiroyuki Shiraga, Noriaki Miyanaga, Hiroshi Azechi, Osaka Univ. (Japan)

SPEAKER BIOGRAPHY: Prof. Takahisa Jitsuno, High power CO_2 laser research (1973-1978); Large scale optics research for fusion laser (1982-2012); Currently; Specially Appointed Professor

ABSTRACT TEXT: Laser-induced damage threshold (LIDT) in optical coating is very sensitive to organic contaminations accumulated in coating layers during storage and using condition. The sources of contamination are commonly exists, and optical coatings are easily contaminated regardless to the environment pressure. LIDT at ns region decreased largely by contamination, but LIDT at ps seems insensitive.

We have investigated the influences of contamination of optical coatings on LIDT and other optical properties. We examined several kinds of coating to clarify the sensitivity to the contamination. Degradations of LIDT were commonly observed in e-beam deposition, IAD and IBS. Some coatings changed spectral characteristics by contamination, and other coatings did not change. Some samples were contaminated as received condition, and some were very clean. We are continuing efforts to clarify the mechanism of contamination and quantitative measurement of LIDT at the controlled contamination. We will present some other characteristics of contamination on the dielectric coatings.

Keywords: laser induced damage, dielectric coating, oil-contamination, LFEX, Silica-gel

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