2013 Laser Damage

XLV Annual Symposium on

Optical Materials for High Power Lasers

Abstract Book

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Conference
22–25 September 2013

Location
National Institute of Standards and Technology
Boulder, Colorado, USA

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SPIE Laser Damage

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Special Events

Sunday 22 September

5:30 to 8:30 pm **Registration Material Pick-up and Mixer at the Boulder Marriott** (2660 Canyon Blvd., Boulder)

6:00 to 7:00 pm **Roundtable Discussion at the Boulder Marriott**
Effects of Laser Field Enhancement in Laser-induced Damage

Panel Moderators: **MJ Soileau,** CREOL, College of Optics and Photonics, Univ. of Central Florida (USA); **Vitaly Gruzdev,** Dept. of Mechanical and Aerospace Engineering, Univ. of Missouri (USA)

The Round-Table discussion is a pre-symposium event that takes place during the registration on Sunday evening. 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 discussion is on the propagation of laser radiation through materials results in several fundamental effects of field enhancement. Those effects are capable of producing local high electrical fields that enforce laser-material interactions and initiate them at the locations of enhanced field (e. g, Fresnel reflection at rear surface of optical windows, interference in multilayer coatings, local field enhancement at surface scratches). This Round Table Discussion is focused on the enhancement effects with the major objective to study relations between the field enhancements and amount of laser fluence calculated from measured pulse energy divided by laser-spot area. Of special attention is the correct evaluation of laser fluence and local electric field at front and rear surfaces of thin transparent slabs in view of the well-established low damage threshold of the rear surfaces compared to the front surface.

7:00 to 8:30 pm **Welcome and Social Mixer at the Boulder Marriott**
Registration Material Pick-up continues until 8:30 pm

Monday 23 September

6:30 to 8:00 pm **ATFilms and Precision Photonics Open House and Reception**

Tuesday 24 September

6:30 to 8:00 pm **Wine and Cheese Tasting Reception at NCAR**

Wednesday 25 September

1:45 to 2:40 pm **NIST Facility Tours**

Monday AM • 23 September

7:30 am to 4:00 pm **Registration Material Pick-up,** NIST Lobby Area

7:50 to 8:30 am **Poster Placement at NIST**
Poster authors for the Monday poster session are to set up their posters at this time.

8:30 to 9:00 am **Opening Remarks and 2012 Awards Presentation**

9:00 AM TO 10:00 AM • SESSION I

Thin Films I

Session Chairs: **Joseph A. Menapace,** Lawrence Livermore National Lab. (USA);
MJ Soileau, Univ. of Central Florida Office of Research & Commercialization (USA)

9:00 am: **Defect insensitive 100 J/cm$_2$ multilayer mirror coating process** *(Plenary)*, Christopher J. Stolz, Justin E. Wolfe, Paul B. Mirkarimi, James A. Folta, John J. Adams, Marlon G. Menor, Nick E. Teslich, Regina Soufli, Lawrence Livermore National Lab. (USA); Carmen S. Menoni, Dinesh Patel, Colorado State Univ. (USA) . . . . [8885-1]

9:40 am: **Investigation of multiple pulse laser-induced damage on high-reflection coatings**, Zhichao Liu, Chengdu Fine Optical Engineering Research Ctr. (China) . . . . [8885-2]

10:00 am to 10:40 am • 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 am • Poster Session and Coffee/Refreshment Break

Mon. 11:30 am to 12:50 pm • Session 2

Thin Films II

Session Chairs: **James E. Andrew,** AWE plc (United Kingdom);
Mireille Commandré, Institut Fresnel (France)

11:30 am **Near-ultraviolet absorption annealing effects in HfO_2 thin films subjected to continuous-wave laser irradiation at 355 nm**, Semyon Papernov, Alexei A. Kozlov, James B. Oliver, Terrance J. Kessler, Univ. of Rochester (USA); Brendan T. Marozas, Cornell Univ. (USA) . . . . [8885-3]

11:50 am: **Nanosecond laser-induced damage study of Ta_2O_5/SiO_2 delectric multilayers**, Xinbin Cheng, Ganghua Bao, Hongfei Jiao, Zhanshan Wang, Tongji Univ. (China) . . . [8885-4]

12:10 pm: **Investigation of non-quarter wave design on multilayer optical thin film coatings from a heat transfer point of view**, Mustafa Ocak, ASELSAN Inc. (Turkey); Cüneyt Sert, Tuba O. Özyurt, Middle East Technical Univ. (Turkey) . . . . [8885-5]

12:30 pm: **High-power laser mirror coating for laser beam welding in hot high-pressure water**, Masataka Murahara, Tokai Univ. (Japan) and Toyko Institute of Technology (Japan); Yuji Sato, Takahisa Jitsuno, Osaka Univ. (Japan); Yoshiaki Okamoto, Okamoto Optics Works (Japan) . . . . [8885-6]

Mon 12:50 pm to 2:30 pm • Lunch Break

8885-1, Session 1

Defect insensitive 100 J/cm^2 multilayer mirror coating process

Christopher J. Stolz, Justin E. Wolfe, Paul B. Mirkarimi, James A. Folta, John J. Adams, Marlon G. Menor, Nick E. Teslich, Regina Soufli, Lawrence Livermore National Lab. (USA); **Carmen S. Menoni, Dinesh Patel,** Colorado State Univ. (USA)

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: Multilayer mirrors are typically fluence-limited by nodular defects. The inclusions can originate from the coating source (e-beam or ion beam) or can occur from inadequate cleaning, transport, pump down, heating, shedding from rotating hardware, etc. These overcoated inclusions behave as micro-lenses in the multilayer structure, resulting in light intensification within or surrounding the nodule. To minimize the impact of these defects, a planarization process has been developed to reduce the geometric-induced light intensification. By exploiting the angular dependent etching rate of oxide materials, a deposit and etch process can reduce the height and diameter of nodular defects. In order to demonstrate the efficiency of this process, contact lithography was used to create an array of engineered defects ranging from 1-5 microns in diameter. Through the planarization process, these defects were effectively smoothed resulting in a >20× increase in laser resistance at a wavelength of 1064 nm and pulse length of 10 ns.

This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344. [LLNL-ABS-635244]

Investigation of multiple pulse laser-induced damage on high-reflection coatings

Zhichao Liu, Chengdu Fine Optical Engineering Research Ctr. (China)

ABSTRACT TEXT: The behaviors of damage grown and morphological transformation process of HR coatings under multiple pulse irradiation has been discussed fully in this work. The results show that there are two typical kinds of damage morphologies on coatings surface under multi-shots: scalds and delaminates. The scalds will change to delaminate in a certain condition and the morphological transformation threshold is depended on both initial fluence and shot number. Test results indicate that delaminate damage will cause reflectivity collapse obviously. Further investigation shows that the lateral size of delaminate increases exponential with shot number to match the beam size. By use of finite element analysis method, the thermal accumulation effect under multi-shots is simulated on single film. The simulation result shows that the temperature of film surface grows rapidly with shot number in the beginning and then tends to steady. By assuming that damage happens while the surface temperature achieves the melting point, we get the relationship between LIDT and shot number theoretically. Actually, the measured LIDT indeed decreases exponential with shot number, which is consistent with simulation result. Finally, a simple empirical equation with five fitting parameters is used to predict coatings life-time.

Keywords: *laser-induced damage, damage morphology, morphological transformation*

Near-ultraviolet absorption annealing effects in HfO_2 thin films subjected to continuous-wave laser irradiation at 355 nm

Semyon Papernov, Alexei A. Kozlov, James B. Oliver, Terrance J. Kessler,
Univ. of Rochester (USA); **Brendan T. Marozas, Cornell Univ.** (USA)

SPEAKER BIOGRAPHY: Scientist at the Laboratory for Laser Energetics, University of Rochester, USA. Received PhD degree in Physics from Latvian University, Riga, Latvia. Conducts research and development in the area of optical materials for high-power-laser applications, specifically - laser induced damage in optical materials.

ABSTRACT TEXT: Hafnium oxide is the most frequently used high-index material in multilayer thin-film coatings for high-power laser applications ranging from near-infrared to near-ultraviolet. Ultraviolet absorption in this high-index material is also known to be responsible for nanosecond-pulse laser-damage initiation. In this work, we study modification of the near-ultraviolet absorption of HfO_2 monolayer films subjected to irradiation by continuous-wave (cw) 355-nm laser light focused into submicrometer spots to produce power densities of the order of ~100 KW/cm^2. Up to a 70% reduction in absorption is found in the areas subjected to irradiation. Temporal behavior of absorption is characterized by a rapid initial drop on the subsecond time scale, followed by a longer-term decline to a steady-state level. Absorption maps generated by photothermal heterodyne imaging confirm the permanent character of the observed effect. Nanosecond-pulse, 351-nm laser-damage tests performed on these cw-laser irradiated areas confirm reduction of absorption by measuring up to 30% higher damage thresholds. We discuss possible physical mechanisms responsible for near-ultraviolet absorption annealing and damage threshold improvement resulting from irradiation by 355-nm cw laser light.

Keywords: Absorption annealing, HfO_2 thin films, laser damage.

8885-4, Session 2

Nanosecond laser-induced damage study of Ta_2O_5/SiO_2 delectric multilayers

Xinbin Cheng, Ganghua Bao, Hongfei Jiao, Zhanshan Wang, Tongji Univ. (China)

ABSTRACT TEXT: Tantala is the high index material that is widely used in optical coatings for VIS-NIR region. Using energetic deposition processes, tantala coatings exhibit fine amorphous microstructure with high packing density, which results in very low optical loss and good environmental stability. The above merits make tantala an optimal material to fulfill high optical quality requirement or challenging spectral performance, for example, high reflection coatings with reflectivity higher than 99.99%, narrow band pass filters, et al. High laser damage resistant tantala coatings can be prepared if the substoichiometry issue could be solved. However, the process producing fully stoichiometric tantala coatings is not easy to develop. In this work, tantala coatings were prepared using ion assisted deposition process. We investigated the influence of process parameters, annealing and laser conditioning on the absorption and laser induced damage threshold (LIDT) of tantala coatings. The absorption at 1.064 μm was measured using a photothermal common path interferometry. And the LIDT was measured by 1.064 μm, 10 ns pulses from a Nd:YAG laser having a TEM00 mode and a beam diameter of 1mm. After optimizing the process to increase the LIDT of tantala coatings, interfacial damage characteristics of Ta_2O_5/SiO_2 delectric multilayers such as high reflection coatings and narrow band pass filters was investigated. Focus ion beam (FIB) technology, optical surface-profiler, scanning electron microscopy (SEM) and Nomarski optical microscopy were used to study the flat bottom pits damage morphologies in details. The depth of flat bottom pits exposed by FIB and optical surface-profiler showed that the damage originated at Ta_2O_5-on-SiO_2 interface. However, SEM micrographs showed that the mechanical delaminations at the border of flat bottom pits started from SiO_2-on-Ta_2O_5 interface. These results suggest that the mechanical strength of Ta_2O_5-on-SiO_2 interface is higher than SiO_2-on-Ta_2O_5 interface but Ta_2O_5-on-SiO_2 interface is more vulnerable to laser damage compared to SiO_2-on-Ta_2O_5 interface. Possible mechanisms were discussed.

Keywords: *Tantala coatings, absorption, laser induced damage, interfacial properties*

Investigation of non-quarter wave design on multilayer optical thin film coatings from a heat transfer point of view

Mustafa Ocak, ASELSAN Inc. (Turkey);
Cüneyt Sert, Tuba O. Özyurt, Middle East Technical Univ. (Turkey)

ABSTRACT TEXT: In this study multilayer thin film optical coatings, which are indispensible parts of optical systems are investigated from a heat transfer point of view. Laser irradiation induced temperature distribution on multilayer coating stack is obtained by discretizing the heat diffusion equation using the finite volume method. In order to obtain mathematical representation of the energy flow and Electric Field Intensity (EFI) through the multilayer coating stack, Maxwell equations are solved by using the commercial software MacLeod®. Laser energy, which is absorbed by the multilayer coating stack in terms of heat, is calculated as a function of space and time by using the computed EFI, coating materials' optical properties and Gaussian laser beam parameters. Computed heat load is used in the finite volume solver ANSYS FLUENT® through a user defined function. Temperature distributions on 19 layer HR multilayer coating stacks irradiated by 1064 nm laser beam are obtained for both quarter wave and non-quarter wave designed configurations. Results of numerical simulations show that maximum temperature rise is seen in the first film-film interface for quarter wave design (QWD). The result of high temperatures at interfaces is associated to both EFI distribution on stack and wide differences in material properties between high and low index film layers. Non-quarter wave design (NQWD) is seen to be successful in decreasing temperatures at film-film interfaces. But it also changes the EFI distribution inside the multilayer stack, increasing absorbed laser energy and resulting in higher temperatures at modified low index layers.

Keywords: *Non-quarter wave design, Laser induced heating, Multilayer Thin film design, Heat transfer, Finite Volume Method*

High-power laser mirror coating for laser beam welding in hot high-pressure water

Masataka Murahara, Tokai Univ. (Japan) and Toyko Institute of Technology (Japan);
Yuji Sato, Takahisa Jitsuno, Osaka Univ. (Japan);
Yoshiaki Okamoto, Okamoto Optics Works (Japan)

ABSTRACT TEXT: We have reported that silicone oil was placed on the mirror surface and irradiated with vacuum ultraviolet in the air, which was solidified to become hard fused silica coating. This mirror and the concave mirror have excellent water and heat-resisting qualities and show a high laser tolerance in high temperature water. It is, therefore, considered as possible to weld cracks of thin piping in a cooling condenser of a nuclear reactor under hot high-pressure light-water.

The condenser of a boiling or pressurized light-water reactor and the steam generator of a pressurized water reactor require a heat exchanger where thin piping is bundled over and over. The light-water that is used to control the runaway of a fuel rod's heat comes in contact with the fuel rod undergoing fission; which is heated and pressurized at about 300ºC to become steam of 70 atmospheres, and the steam is, then, cooled down to around 50ºC to reduce pressure to an almost vacuum in the condenser, and it is returned to the nuclear reactor. .

As a high hydraulic pressure is applied inside this thin piping especially, the welded and bended parts in piping are frequently cracked by the inside pressure. It is necessary to drain the secondary cooling water and repair the weld in order to prevent accidents caused by such cracking. It is, however, waste of time to drain the water each time for welding. Thus, it is considered to weld in the hot high-pressure light-water by using YAG laser beam and a mirror produced by photo-oxidized silicone oil.

Keywords: laser mirror coating, laser welding, hot high-pressure water, photo-oxidized silicone oil, condenser of a nuclear reactor, YAG laser beam

Notes

Monday PM • 24 September

2:30 pm to 3:10 pm • SESSION 3

Thin Films III

Session Chairs: **Carmen S. Menoni,** Colorado State Univ. (USA);
Detlev Ristau, Laser Zentrum Hannover e.V. (Germany)

2:30 pm: **Study on the laser-induced damage performance of HfO_2, Al_2O_3, Y_2O_3, Sc_2O_3 and SiO_2 monolayer coatings**, Meiping Zhu, Kui Yi, Dawei Li, Hongji Qi, Yuanan Zhao, Xiaofeng Liu, Guohang Hu, Jianda Shao, Shanghai Institute of Optics and Fine Mechanics (China). . . . . [8885-8]

2:50 pm: **Brewster angle polarizing beamsplitter laser-damage competition: "S" polarization**, Christopher J. Stolz, Lawrence Livermore National Lab. (USA); Jeff Runkel, Quantel USA (USA) . . . . [8885-9]

3:10 pm to 4:00 pm • Poster Session and Refreshment Break

Mon 4:00 pm to 5:40 pm • SESSION 4

Materials and Measurements I

Session Chairs: **Stavros G. Demos,** Lawrence Livermore National Lab. (USA);
Takahisa Jitsuno, Osaka Univ. (Japan)

4:00 pm: **National Ignition Facility laser performance: status and thoughts on future capabilities** *(Plenary)*, Paul J. Wegner, Lawrence Livermore National Lab. (USA) . . . [8885-10]

4:40 pm: **The pressure dependence of laser-induced damage in high-power laser facility**, Ping Li, Runchang Zhao, Wei Wang, Jingqin Su, China Academy of Engineering Physics (China) . . . . [8885-11]

5:00 pm: **From ground to space: How to increase the confidence level in your flight optics**, Wolfgang Riede, Paul Allenspacher, Deutsches Zentrum für Luft- und Raumfahrt e.V. (Germany); Denny Wernham, Alessandra Ciapponi, Clemens Heese, European Space Research and Technology Ctr. (Netherlands); Lars O. Jensen, Heinrich Maedebach, Stefan Schrameyer, Detlev Ristau, Laser Zentrum Hannover e.V. (Germany). . . . . . . [8885-12]

5:20 pm: **Qualification testing of optical components with 1 trillion shot lifetime requirement for ICESAT-II space flight project**, Oleg A. Konoplev, Aleksey A. Vasilyev, Furqan L. Chriaqh, Sigma Space Corp. (USA); Demetrios Poulios, American Univ. (USA); Mark A. Stephen, NASA Goddard Space Flight Ctr. (USA); Kathy Strickler, ASRC Federal Space and Defense (USA); Michael A. Krainak, NASA Goddard Space Flight Ctr. (USA) . . . . [8885-13]

5:40 pm to 5:55 pm • Closing Remarks

6:30 pm to 8:00 pm • Open House and Reception

Study on the laser-induced damage performance of HfO_2, Al_2O_3, Y_2O_3, Sc_2O^3 and SiO_2 monolayer coatings

Meiping Zhu, Kui Yi, Dawei Li, Hongji Qi, Yuanan Zhao, Xiaofeng Liu, Guohang Hu, Jianda Shao, Shanghai Institute of Optics and Fine Mechanics (China)

SPEAKER BIOGRAPHY: Meiping Zhu received PhD degree at Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Sciences. Her current research interests include the preparation of high performance laser coatings and thickness monitoring of optical coatings.

ABSTRACT TEXT: Many studies have shown that the laser induced damage threshold (LIDT) and damage morphology of the monolayer coatings are easily influenced by the finish conditions of the substrates, which makes it difficult to compare the LIDT of different coating materials. In order to eliminate the influence of defect and sub-defect on the substrate, HfO_2, Al_2O_3, Y_2O_3, Sc_2O_3 and SiO_2 layer were prepared on HfO_2/SiO_2 mirror coatings, which are respectively high reflective at 1064 nm, 532 nm and 355 nm, using conventional e-beam deposition. The LIDT, as well as the damage morphology after laser irradiation at wavelength of 1064 nm, 532 nm and 355 nm was measured, and compared with that of the coating deposited on BK7 glass substrate. The detailed results will be shown in the report.

Keywords: Monolayer coating, Laser induced damage threshold, Damage morphology

Brewster angle polarizing beamsplitter laser-damage competition: "S" polarization

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

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: Last year's damage competition was tested only at "P" polarization due to the large number of submitted samples. This year, the samples will be damage tested at "S" polarization and compared against the "P" polarization results. This damage competition allows 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. In addition to the laser resistance results, details of deposition processes, coating materials and layer count, and spectral results will be shared. This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344. [LLNL-ABS-635214]

8885-10, Session 4

National Ignition Facility laser performance: status and thoughts on future capabilities

Paul J. Wegner, Lawrence Livermore National Lab. (USA)

SPEAKER BIOGRAPHY: Dr. Paul Wegner has over 25 years of experience developing solid-state inertial confinement fusion laser systems beginning with the Nova laser at LLNL in 1984. He received his B.S. in Physics and Mathematics from Portland State University in 1984 and his Ph.D. in Applied Science from the University of California, Davis, in 1995. In 1998, Dr. Wegner joined the National Ignition Facility project to work on the physics basis and systems engineering of the ultraviolet laser section. He currently manages the Lasers, Optics and Targets organization in the NIF and Photon Science directorate.

ABSTRACT TEXT: The National Ignition Facility (NIF) is a MJ-class solid-state laser driver and target experiments facility built by the Department of Energy for Stockpile Stewardship and High Energy Density Science Research. The NIF construction project was completed in March of 2009, followed immediately thereafter by a three year National Ignition Campaign, during which the laser and experimental facility were brought up to full design capability for the fielding of cryogenic implosion experiments. In this time period the laser energy and power available on target increased from 1 MJ, 350 TW to over 1.8 MJ, 500 TW, or roughly 300 kJ and 50 TW per year. Continued progress along this trajectory is possible. Areas under development to enable this progress will be discussed.

This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344. [LLNL-ABS-635656]

The pressure dependence of laser-induced damage in high-power laser facility

Ping Li, Runchang Zhao, Wei Wang, Jingqin Su,
China Academy of Engineering Physics (China)

SPEAKER BIOGRAPHY: Mr. Ping Li graduated from Tsinghua University and obtained the master degree in 2008. He is engaged in Chinese Academy of Engineering Physics and worked on reseresearch of high-power laser facility. Now he has worked as the director of the prototype of SG-III laser facility for 3 years.

ABSTRACT TEXT: To improve the performance of the prototype of SG-III laser facility, Final optics assembly (FOA) is redesigned. The design represents an integrated solution to a large number of performances, operational, and environmental requirements, one improvement is that the components inside the integrated optics module are designed to operate at atmosphere other than 10 torr low-pressure air. An ultraviolet vacuum window is needed to separate the atmosphere environment from the hard vacuum of target chamber; in addition, the vacuum window is also designed as beam sampling grating (BSG) that the rear surface is etched to reduce the total thickness of ultraviolet optics. The ultraviolet vacuum window could be broken induced by damage with atmospheric pressure, so the damage performances of the ultraviolet vacuum window should be emphasized.

The ultraviolet vacuum window in the redesigned FOA is more likely to be damaged for it supporting atmospheric pressure and being located in ultraviolet portion. So the thickness of ultraviolet vacuum window is a key parameter. There are two aspects to limit the thickness: one is the pressure resistance, the other is the threshold of intensity-length product of ultraviolet optics, and the two aspects are opposed each other. Some pressure resistance experiments with small-aperture optics are implemented to optimize the thickness:

i) Some small-aperture optics that has the same ratio of diameter-to-thickness to the large-aperture one is first irradiated by high-power laser to obtain the different damage deepness and position.

ii) The pressure resistance of these optics is tested on the stress test platform to obtain the broken threshed.

These experiments show that the laser-induced damages affect the pressure resistance sharply that any optical damage may degrade the pressure resistance half or more; the damage deepness and position is also closely correlated to the pressure resistance. So the optimum object is to avoid damage occurring other than increase the pressure resistance of optics. With the safety factor (5 times), the thickness of the window is mostly reduced. Finally the ultraviolet vacuum window is chosen as 20 mm thickness and at the same time integrated as BSG.

We investigated the atmospheric pressure dependence of laser-induced damage with almost 300 shots at full aperture over a wide range of fluence and intensity on the prototype of SG-III laser facility. The fluence and intensity is distributed in space by the modulation of near field to observe the damage initiation and growth. The result shows that damage initiation of vacuum window is common to other fused silica optics, but damage growth is more rapidly. The growth rates in space distribution are coupled with stress distribution by atmospheric pressure. That is consistent to the small-aperture optics experiments.

In summary, to improve the performance of the FOA on the prototype of SG-III laser facility, we studied the pressure dependence of laser-induced damage and some rules are obtained. The results may provide a valuable tool for the safe rule for ultraviolet vacuum window in high-power laser facility.

Keywords: pressure dependence, damage growth, space distribution, ultraviolet vacuum window, laser-induced damage, high-power laser facility, Final optics assembly, pressure resistance

From ground to space: How to increase the confidence level in your flight optics

Wolfgang Riede, Paul Allenspacher, Deutsches Zentrum für Luft- und Raumfahrt e.V. (Germany); **Denny Wernham, Alessandra Ciapponi, Clemens Heese,** European Space Research and Technology Ctr. (Netherlands); **Lars O. Jensen, Heinrich Maedebach, Stefan Schrameyer, Detlev Ristau,** Laser Zentrum Hannover e.V. (Germany)

ABSTRACT TEXT: Space environment presents unique challenges for operation of optics and optical coatings as part of laser systems. Besides testing components and sub-systems, the extended testing of complete laser systems like flight modules is an effective way to determine the reliability and long term stability of laser systems, and to mitigate the mission risk.

An important outcome for single component testing is the characteristic damage curve, which can be evaluated according to the S-on-1 test procedure detailed in ISO 21254-2. It allows for the prediction of the LIDT of a sample for large pulse numbers, i. e., higher than the one applied in the test itself. Hence, it is a means to estimate the real lifetime of the optical component. The drawback of this test is the small area coverage. For further operational risk mitigation, which is very stringent for space laser operation, the sample should be subjected to a test which is representative in terms of the tested area. Such a test is considered to be nondestructive by itself.

To cover the preparatory test issues of upcoming ESA space laser missions, in joined effort, an adaptation of existing laser damage test benches has been performed. Conventional S-on-1 tests are combined with raster scanning procedures. Various aspects of characteristic damage curve issues are discussed. Furthermore, the issues of raster scan fluence selection are detailed. Sensitive surface analysis like Time-of-flight SIMS is used to identify potential low density low damage threshold precursors. The inter-correlation of flight module testing and preceding single component testing is demonstrated.

Keywords: LIDT, High power laser system, Vacuum environment, Raster scan

Qualification testing of optical components with 1 trillion shot lifetime requirement for ICESAT-II space flight project

Oleg A. Konoplev, Aleksey A. Vasilyev, Furqan L. Chriaqh, Sigma Space Corp. (USA); **Demetrios Poulios,** American Univ. (USA); **Mark A. Stephen,** NASA Goddard Space Flight Ctr. (USA); **Kathy Strickler,** ASRC Federal Space and Defense (USA); **Michael A. Krainak,** NASA Goddard Space Flight Ctr. (USA)

SPEAKER BIOGRAPHY: Dr. Konoplev received MS from Moscow Institute of Physics and Technology and MS and PhD from University of Rochester, Rochester, NY. He spent more than 25 years working toward development and qualification of various laser based devices and systems for Bio-Medical, Telecom, Datacom and Space applications.

ABSTRACT TEXT: We report on the laser induced damage study of optical components with 1 nanosecond pulses at multi-kHz rate at 1064 nm and 532 nm in air. Laser induced damage threshold fatigue with increasing number of shots per site showed degradation of 2X from e-beam coated surfaces when number of shots increased from 100 to millions. The extrapolation analysis showed that the minimum safety margin of 4.5X-to-5X is required from the standard damage S-200 test value to nominal level for 1Trillion shots operation with 95% confidence. A complimentary testing of optical components with the level 4-5X below damage threshold with up to 1Trillion shot per site was done to corroborate the validity of damage tests and extrapolation. The high damage threshold IBS coatings showed less predictable trend in threshold fatigue. This article discusses methodology of reliability testing of optical components under prolonged pulsed laser radaition exposure.

Keywords: Lasers, Lidar, Laser Induced Damage Testing, Laser Damage Fatigue

Notes

Monday Poster Session • Rooms 1 & 2

Materials and Measurements

10:40 to 11:30 am and 3:10 to 4:00 pm

Suppression of transverse stimulated Raman scattering with laser-induced damage pinpoints in large-aperture KDP crystals, Fuquan Li, Wei Han, Fang Wang, Bing Feng, China Academy of Engineering Physics (China) . . . . [8885-18]

Commissioning and first results of the ELI-beamlines LIDT test station, Daniel Kramer, Rui Barros, Michaela Kozlova, Bedrich Rus, Tomas Medrik, Institute of Physics of the ASCR, v.v.i. (Czech Republic) . . . . [8885-50]

New tools for the description of the dynamics of high-power phased lasers and complex interacting systems, Erik J. Bochove, Air Force Research Lab. (USA); Alejandro B. Aceves, Southern Methodist Univ. (USA) . . . . [8885-53]

Correlating defects and damage initiation in CVD silica films produced under different chemical environment using vibrational spectroscopy, Nan Shen, Manyalibo J. Matthews, Selim Elhadj, Rajesh N. Raman, Arun K. Sridharan, Lawrence Livermore National Lab. (USA) . . . . [8885-55]

Algorithm for cumulative damage probability calculations in S-on-1 laser damage testing, Stefan Schrameyer, Laser Zentrum Hannover e.V. (Germany) and Cutting Edge Coatings GmbH (Germany); Marco Jupé, Lars O. Jensen, Detlev Ristau, Laser Zentrum Hannover e.V. (Germany) . . . . [8885-56]

Measuring residual bulk absorption in highly-transparent optical materials: a comparison between photoacoustic spectroscopy and photothermal common-path interferometry, Stephan Fieberg, Niklas Waasem, Frank Kühnemann, Fraunhofer-Institut für Physikalische Messtechnik (Germany); Karsten Buse, Fraunhofer-Institut für Physikalische Messtechnik (Germany) and Freiburg Univ. (Germany) . . . . [8885-60]

Laser calorimetric absorptance testing of samples with varying geometry, Istvan Balasa, Lars O. Jensen, Detlev Ristau, Laser Zentrum Hannover e.V. (Germany) . . . . [8885-61]

Effect of longitudinal laser mode beating in damage probability measurements, Gintare Bataviciute, Egidijus Pupka, Linas Smalakys, Viktorija Pyragaite, Andrius Melninkaitis, Vilnius Univ. (Lithuania) . . . . [8885-62]

Laser-induced damage threshold (LIDT) measurements of photopolymers used in 3D ultrafast laser micro/nano-lithography, Albertas Žukauskas, Gintare Bataviciute, Mindaugas Šciuka, Egidijus Pupka, Linas Smalakys, Roaldas Gadonas, Andrius Melninkaitis, Mangirdas Malinauskas, Valdas Sirutkaitis, Vilnius Univ. (Lithuania) . . . . [8885-63]

Accelerated life time testing of fused silica for DUV laser applications revised, Christian Mühlig, Simon Bublitz, Institut für Photonische Technologien e.V. (Germany) . . . . [8885-64]

An empirical investigation of the laser survivability curve: IV, Jonathan W. Arenberg, Northrop Grumman Aerospace Systems (USA); Wolfgang Riede, Alessandra Ciapponi, Paul Allenspacher, Deutsches Zentrum für Luft- und Raumfahrt e.V. (Germany); Jonathan H. Herringer, Arrow Thin Films, Inc. (USA); Denny Wernham, European Space Research and Technology Ctr. (Netherlands) . . . . [8885-65]

Laser damage of thick components, Laurent Lamaignère, Romain Diaz, Thierry Donval, Roger Courchinoux, Commissariat à l'Énergie Atomique (France) . . . . [8885-66]

Photothermal absorption measurements for improved thermal stability of high-power laser optics, Martin Stubenvoll, Bernd Schäfer, Klaus Mann, Laser-Lab. Göttingen e.V. (Germany); Annette Walter, Ludmilla Zittel, Sill Optics GmbH & Co. KG (Germany) . . . . [8885-67]

Fundamental Mechanisms

10:40 to 11:30 am and 3:10 to 4:00 pm

Suppression of ultrafast laser-induced ionization in transparent solids, Vitaly E. Gruzdev, Univ. of Missouri-Columbia (USA) . . . . [8885-51]

A theoretical analysis for temperature dependences of laser-induced damage threshold, Katsuhiro Mikami, Osaka Univ. (Japan) and JSPS (Japan); Shinji Motokoshi, Toshihiro Somekawa, Institute for Laser Technology (Japan); Takahisa Jitsuno, Osaka Univ. (Japan); Masayuki Fujita, Institute for Laser Technology (Japan); Kazuo A. Tanaka, Osaka Univ. (Japan) . . . . [8885-52]

Modeling femtosecond pulse laser damage on conductors and dielectrics using particle-in-cell (PIC) simulations, Robert Mitchell III, Douglass W. Schumacher, Enam Chowdhury, The Ohio State Univ. (USA) . . . . [8885-54]

Dependence of fs laser resistance of optical materials on wavelength, Laurent Gallais-During, Dam-Be L. Douti, Institut Fresnel (France); Gintare Bataviciute, Egidijus Pupka, Mindaugas Šciuka, Linas Smalakys, Andrius Melninkaitis, Vilnius Univ. (Lithuania); Fabien Lemarchand, Institut Fresnel (France); Valdas Sirutkaitis, Vilnius Univ. (Lithuania); Mireille Commandre, Institut Fresnel (France) . . . . [8885-57]

CW and pulsed laser-induced absorption changes in Titania films, Xuerong Zhang, Luke A. Emmert, Wolfgang Rudolph, The Univ. of New Mexico (USA) . . . . [8885-59]

Suppression of transverse stimulated Raman scattering with laser-induced damage pinpoints in large-aperture KDP crystals

Fuquan Li, Wei Han, Fang Wang, Bing Feng,
China Academy of Engineering Physics (China)

ABSTRACT TEXT: In the context of inertial confinement fusion (ICF) laser facilities, effective control of adverse non-linear effects such as self-focusing and stimulated Brillouin or Raman scattering during the propagation of high power laser pulses is a major concern. For instance, potassium dihydrogen phosphate (KDP) crystals which are widely used for frequency conversion and polarization smoothing are subject to stimulated Raman scattering (SRS) effect. As the large-aperture KDP crystals are exposed to high power laser pulses, spontaneously generated Raman light traveling orthogonal to the laser beam within the crystals can experience high gain via transverse SRS (TSRS). Consequently, amplified TSRS can lead to energy loss from the main beam and, more seriously, results in optical damage to the crystals in which this scattering occurs.

In this paper, we report a new method to suppress the TSRS effect in large-aperture KDP crystals. We use 5-ns (pulses width), 527-nm (pulses wavelength) laser pulses to generate laser-damage pinpoints in the KDP crystal. The damaged rectangular area is approximately centered on the width of the crystal and the long side of the rectangular is parallel to the extraordinary direction of the crystal which is also the polarization direction of pump beam. This damaged area is used to reduce the growth distance of TSRS. Then we carried out experiments to demonstrate the effect of this method. Experimental results show that this method can suppress the TSRS effect.

Commissioning and first results of the ELI-beamlines LIDT test station

Daniel Kramer, Rui Barros, Michaela Kozlova, Bedrich Rus, Tomas Medrik,
Institute of Physics of the ASCR, v.v.i. (Czech Republic)

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

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 or a kHz laser from the regenerative amplifier.

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. Samples are tested after different cleaning methods.

Most of the testing is done at central wavelength of 810nm but some of the testing will be also carried out at 1060 nm (required for the 10PW laser) when the front end lasers are ready.

Attempt is made to test unusual substrate material with ultrashort pulses.

Keywords: LIDT , ELI, contamination

New tools for the description of the dynamics of high-power phased lasers and complex interacting systems

Erik J. Bochove, Air Force Research Lab. (USA);
Alejandro B. Aceves, Southern Methodist Univ. (USA)

ABSTRACT TEXT: We propose new mathematical tools to describe the dynamics of laser arrays and complex systems such as neural assemblies that are based on the use of projection matrices, together with network and symmetry concepts. The methodology is based on the expansion of the system interconnect matrix in terms of Hebbian projection matrices, which is shown first to be a useful concept in describing and evaluating basic characteristics of phased laser arrays. Applications to external cavity passive beam combining using beam splitters, diffractive optical elements, self-Fourier optics, ring-cavity and multiplexed volume Bragg gratings (MVBG) are discussed as examples. An algorithm for the derivation of o.d.e's for application to the temporal dynamics of coupled laser systems will be presented next. It will be shown how the methodology can be extended to the description of other, potentially large and massively interconnected, self-organizing systems, such as to the dynamics of biological neural nets, in which non-linear self-organizing projection operations will be shown to describe memory, cognition, learning and association functions. The use of network graphics and symmetry properties are proposed as means of classification of the interaction dynamics.

*Funded by AFOSR (Dr. Arje Nachman)

Correlating defects and damage initiation in CVD silica films produced under different chemical environment using vibrational spectroscopy

Nan Shen, Manyalibo J. Matthews, Selim Elhadj, Rajesh N. Raman, Arun K. Sridharan, Lawrence Livermore National Lab. (USA)

SPEAKER BIOGRAPHY: Nan Shen received her Ph.D. in physics studying the interaction of ultrafast laser pulses with transparent materials. She joined the Lawrence Livermore National Laboratory in 2003 and investigated cellular response and organelle functions using ultrafast laser light. She continues to work on understanding the physics behind laser induced damage in optics. She is currently a member of the Target Systems and Optics Technology Group at the National Ignition Facility, and focuses her works on identifying damage precursors in fused silica optics and developing mitigation strategies.

ABSTRACT TEXT: In high energy laser systems, the peak power that can be achieved is often limited by the damage threshold of the optical components making up the system. For example, surface damage occurs in fused silica optics at a fluence well below the band gap (~9 eV) of the material. Both intrinsic defects (e.g. non-bridging oxygen hole centers and oxygen deficient centers) and extrinsic defects (e.g. impurity) can absorb laser energy and lead to damage. At the same time, macroscopic mechanical defects such as micro-fractures and scratches resulting from grinding, polishing, or handling processes also have a high propensity to damage. A better understanding of different types of light absorbing defect structures in silica and methods to mitigate them could shed light on the physics of laser damage processes and facilitate development of more effective damage mitigation strategies.

Vibrational spectroscopy has been proven to be a powerful tool to provide information on molecular composition, structure and interactions in a material. It is ideally suited to identify unique defect bonding signatures in SiO_2 which may lead to laser damage initiation. As a model system for defective silica, we use chemical vapor deposition (CVD) to prepare thin films of unannealed SiO_2 on fused silica substrate. In this study, we compare defect signatures and damage performance of SiO_2 films created with two chemical precursors, silane and tetra ethyl ortho-silicate (TEOS). Vibrational spectroscopy methods (FTIR, Raman and sum-frequency generation) are used to probe defects and surface chemical signatures of the films and correlate it to their damage performance before and after annealing. In particular, by using these two different precursor gases, we are able to probe different amounts of hydroxyl-related defects that are created during the CVD process. This allows us to directly examine the relationship between defects in SiO_2 and laser damage initiation.

Deposition of an overlayer of silica may also be applied to mitigate or passivate previously damaged optics. We have demonstrated that high damage threshold can be achieved in CO_2 laser annealed silica films produced using plasma-enhanced CVD method based on silane chemistry. Laser assisted CVD allows spatial control of SiO_2 deposition and annealing. A brief discussion on the application of using L-CVD of SiO_2 as a damage mitigation method will also be presented.

This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344. [LLNL-ABS-635259]

Keywords: chemical vapor deposition of SiO2, vibrational spectroscopy, hydroxyl-related defects, laser induced damage, TEOS, silane

8885-56, Session P1

Algorithm for cumulative damage probability calculations in S-on-1 laser damage testing

Stefan Schrameyer, Laser Zentrum Hannover e.V. (Germany) and Cutting Edge Coatings GmbH (Germany); **Marco Jupé, Lars O. Jensen, Detlev Ristau,** Laser Zentrum Hannover e.V. (Germany)

ABSTRACT TEXT: The calculation of damage probabilities as a function of the fluence is a key factor in the measurement of laser-induced damaged thresholds (LIDT) according to the ISO standard 21254-2. A typically linear regression of the damage probabilities p_(i)=n^(d)_(i)/(n^(d)_(i)+n^(nd)_(i)) reveals the threshold value for the tested optic by extrapolating the fit to a damage probability level of zero. Unfortunately, due to the limited sample surface and the resulting limited number of available test sites, the statistical confidence level is often not sufficient, and a big error bar σ_(i)=1/(n^(d)_(i)+n^(nd)_(i)) for the calculated p_(i) has to be considered. Therefore, the damage probabilities pi of the different fluence intervals i can scatter strongly, leading to a significant least square error in the linear regression of the survival curve. This inhibits a reliable extrapolation of the threshold and will result in an uncertainty in the estimation of the 0% LIDT.

In this publication, a simple procedure based on physical considerations is proposed to optimize the calculation of the damage probabilities by using a cumulative algorithm. The assumed behavior of damaged and undamaged test sites at higher and lower fluences respectively provides the basis for the data reduction. It is shown that the algorithm increases the statistically relevant amount of data per fluence interval i by using virtual test sites. Thus, the error ?i in the calculation of the damage probabilities is reduced significantly and the subsequent linear regression of the damage probabilities will have a reduced least square error. Non-linear regression of the damage probability according to defect-induced damage models as published numerous times in recent years can also be performed with a better confidence level and will be shown exemplarily.

Keywords: Cumulative algorithm, damage probabilities, error bars, statistics, non-linear damage probability curve

Measuring residual bulk absorption in highly-transparent optical materials: a comparison between photoacoustic spectroscopy and photothermal common-path interferometry

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

ABSTRACT TEXT: The current development of high-power lasers results in a growing importance of the quality assessment of optical materials. This applies to bulk materials for lenses and mirrors as well as to non-linear optical components. Several techniques have been developed to detect residual absorption in highly transparent optical materials down to 10 ppm/cm and below. At such high sensitivity levels all methods are indirect ones: They detect either the resulting temperature increase or secondary effects like the thermal expansion or the change in the refractive index. Due to the absence of standardized samples for such low absorption levels, challenges may arise for the individual methods from the need for an absolute absorption calibration or from the possible existence of non-thermal interfering effects.

Fraunhofer IPM has recently completed two complementary instruments for the spectroscopy of residual absorptions in highly transparent materials: While the photo-acoustic spectroscopy (PAS [1]) exploits the thermal expansion in the material to detect the absorption, the photo-thermal common-path interferometry (PCI [2]) measures residual absorptions through a thermal lens formed in the material upon absorption. Using optical parametric oscillators as pump sources, the two spectrometers cover a wide wavelength range from the UV to the mid-IR (PAS: 216 – 2500 nm, PCP: 1460 – 1900 and 2400 – 3900 nm). The spectral overlap in the NIR range does offer the possibility to study samples with both methods, allowing a direct comparison between the two complementary techniques.

Based on a comparison of the data, the paper will present an analysis of the issues of absorption calibration and of detection limits for both techniques. The work aims at contributing to a better comparability between the different techniques used in high-sensitivity absorption measurements.

[1] N. Waasem, S. Fieberg, J. Hauser, G. Gomes, D. Haertle, F. Kühnemann, and K. Buse "Photoacoustic absorption spectrometer for highly transparent dielectrics with parts-per-million sensitivity". Rev. Sci. Instr. 84, 23109/1-8 (2013)

[2] A. Alexandrovski, M. Fejer, A. Markosyan, and R. Route, "Photothermal common-path interferometry (PCI): new developments". Solid StateLasers XVIII: Technology and Devices, Vol. 7193, edited by W. A. Clarkson, N. Hodgson, and R. K. Shori (SPIE, Bellingham, 2009).

Keywords: residual absorption, photoacoustic spectroscopy, photo-thermal common-path interferometry, detection limits, impurities

Laser calorimetric absorptance testing of samples with varying geometry

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

ABSTRACT TEXT: During the 1990s the International Standard for absorptance testing of optical coatings was developed. Based on the method of laser calorimetry and after years of theoretical and empirical work, ISO 11551 was revised and published in its current version in 2003.

Laser calorimetry is based on the measurement and evaluation of the temperature increase caused by absorption in the sample exposed to laser radiation. As optical materials are usually of low heat conduction, a temperature distribution develops in the irradiated sample, and measuring a temperature increase becomes a complex task. This challenge was met by keeping the sample geometry to a standard size and simulating the thermal distribution for a number of optical materials. By this LZH developed a calorimetric test set-up that offers fully calibrated absorptance values of 25mm (or 1") sample with a total error of below 13% and a relative measurement error of below 3%. However, this technique is limited to the mentioned sample geometry.

This work presents a new approach to adjust the measurement configuration to numerous sample sizes of standard circular laser components. FEA calculations and experimental verification is presented for exemplary values of the samples diameters. Based on a new sample mount concept, this procedure allows to utilize all flexibility in test wavelength and angle of incidence, combined with the sensitivity level sufficient for current optical materials.

Keywords: laser calorimetry, absorption, metrology, high power laser, optical thin films, substrates, ultrafast laser optics, contamination

8885-62, Session P1

Effect of longitudinal laser mode beating in damage probability measurements

Gintare Bataviciute, Egidijus Pupka, Linas Smalakys, Viktorija Pyragaite, 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). My current research interest includes both theoretical and experimental laser-induced damage threshold studies under normal and extreme conditions.

ABSTRACT TEXT: Laser-Induced Damage Threshold (LIDT) and its probability have been shown to be sensitive to testing laser parameters including beam diameter, wavelength and pulse duration. Pulse to pulse fluctuations of these parameters causes systematic errors and limitations in LIDT measurement accuracy. On the other hand damage threshold of optical component needs to be characterized in the operation regime as close as possible to real application conditions. In this context more deep understanding about the role of longitudinal mode structure and temporal beating in damage threshold experiments is required. To gain more specific knowledge about these effects we directly compare damage probabilities measured with laser operating in single- and multi- longitudinal mode regimes. 1-on-1 LIDT testing has been performed on conventionally polished fused silica samples. One of the samples was uncoated while the other was deposited by single (SiO_2) layer. Both samples were exposed to UV (355nm, ~5ns) laser radiation featuring Gaussian like spatial beam profile. Qualitative differences in the damage morphology and damage probability curve have been observed. The transition in damage probability was rather steep with single-mode pulses while under multimode irradiation it resulted in “S shaped” transition. Analysis of these phenomena was performed by employing Monte Carlo simulations representing the statistical interaction between laser irradiation and randomly distributed damage precursors. Both idealized and realistic laser irradiation conditions were modeled by considering statistical differences in pulse duration. The results and findings of this study will be reported and discussed in detail.

Keywords: Laser-induced damage threshold, damage probability, longitudinal laser mode beating , systematic errors, Monte Carlo modelling, single- and multi- longitudinal mode regimes, 1-on-1 testing

Laser-induced damage threshold (LIDT) measurements of photopolymers used in 3D ultrafast laser micro/nano-lithography

Albertas Šukauskas, Gintare Bataviciute, Mindaugas Šciuka, Egidijus Pupka, Linas Smalakys, Roaldas Gadonas, Andrius Melninkaitis, Mangirdas Malinauskas, Valdas Sirutkaitis, 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). My current research interest includes both theoretical and experimental laser-induced damage threshold studies under normal and extreme conditions.

ABSTRACT TEXT: Ultrafast laser direct write lithography is already an established technique widely used for the rapid and flexible manufacturing of diverse three-dimensional (3D) micro/nano-objects. Currently, fields of micro-optics and nano-photonics are being actively explored and driven towards scientific and industrial applications. Though direct laser writing setups are commercially available, the optical damage threshold of vast photo-polymeric materials is not evaluated yet. However, this parameter is critical for the photonic applications such as integrated optical devices dedicated to operation under intense laser irradiation conditions. In our study we applied standardized S-on-1 laser induced damage threshold (LIDT) procedure in order to characterize optical resistance of common photopolymers and photoresists used in 3D laser micro/nano-lithography. Fundamental and second harmonic pulses of Nd:YAG (1064 nm, 532 nm, 10 ns, 50 Hz) and Yb:KGW (1030 nm, 515 nm, 300 fs, 50 kHz) lasers were applied at different repetition rates. Obtained results indicated that hybrid organic-inorganic photopolymers such as Ormocore b59 (ORMOCER) and SZ2080 (ORMOSIL) are more resistant if compared to pure organic SU-8 and PDMS materials. In addition, the role of photoinitiator was also assessed in case of SZ2080: it was measured with and without incorporation of photoinitiator Irgacure 369. All of the experimental LIDT values were directly compared to reference materials such as glass and spin-coated PMMA films. They were of the same order as conventional dielectric coatings used in laser systems. This determines the potential of the polymeric materials applications in high power laser systems as well as novel possibilities of direct laser written microoptical and nanophotonic devices.

Keywords: direct laser writing, nanolithography, 3D microstructures, microoptics, SZ2080, ORMOCER, SU-8, laser induced damage threshold

8885-64, Session P1

Accelerated life time testing of fused silica for DUV laser applications revised

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

ABSTRACT TEXT: We report on the continuation of a comparative study of different fused silica materials for ArF laser applications. After selecting potentially suited fused silica materials from their laser induced absorption and compaction obtained by a short time testing procedure, accelerated life time tests have been undertaken by sample irradiating at liquid nitrogen temperature and subsequent direct absorption measurements using the laser induced deflection (LID) technique. The obtained degradation acceleration strongly differs between fused silica materials showing high and low OH contents, respectively. As a result, a difference in the absorption degradation mechanism between high and low OH containing fused silica is proposed. Consequently two different scenarios for an acceleration of the absorption degradation are derived.

Keywords: Fused silica, ArF laser, Absorption, Laser induced degradation

An empirical investigation of the laser survivability curve: IV

Jonathan W. Arenberg, Northrop Grumman Aerospace Systems (USA); **Wolfgang Riede, Alessandra Ciapponi, Paul Allenspacher,** Deutsches Zentrum für Luft- und Raumfahrt e.V. (Germany); **Jonathan H. Herringer,** Arrow Thin Films, Inc. (USA); **Denny Wernham,** European Space Research and Technology Ctr. (Netherlands)

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. This year's report introduces an algorithm for the analysis of life-test data. The algorithm is applied to data from our measurements on 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. The performance of the algorithm is reported and evaluated a candidate process for the automation of S on 1 testing data processing.

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

Laser damage of thick components

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Commissariat à l'Énergie Atomique (France)

ABSTRACT TEXT: The determination of damage densities of thick optical components is tricky due to the occurrence of non-linear effects (Brillouin and Kerr) that affect the beam propagation through the optics. It is then compulsory to record the beam parameters, mainly the temporal profile, in order to predict and calculate fluence and/or intensity on the rear surface taking into account the non-linear beam propagation.

Experiments have been realized with the use of large beams and several phase modulations were activated, leading to numerous peak intensities due to the occurrence of amplitude modulations. Results are first compared in the case of thin optics in order to separate the intrinsic absorptions by the defects which are the weak points of the optics to the effect of the non-linear propagation.

Experiments have been realized by means of small beams too, where beam parameters were more easily controlled and measured. For the two configurations (large and small beams), the correspondence between the length of the filaments and the beam parameters has been realised too in order to highlight the relevant beam parameters that have to be considered for the damage of thick optics.

The whole of measurements and modeling permit us to measure more accurately the rear surface damage of thick optics due to intrinsic defects.

Keywords: non linear propagation, filamentation, kerr effect, brillouin effect, amplitude modulation, phase modulation

Photothermal absorption measurements for improved thermal stability of high-power laser optics

Martin Stubenvoll, Bernd Schäfer, Klaus Mann, Laser-Lab. Göttingen e.V. (Germany);
Annette Walter, Ludmilla Zittel, Sill Optics GmbH & Co. KG (Germany)

ABSTRACT TEXT: Thermal effects within optical elements represent a major challenge for industrial high power laser applications. In order to reduce focal shifts due to thermal lensing, absorption losses have to be kept as low as possible by appropriately selecting and matching glass substrates and AR coatings. However, in order to compensate for the remaining heat dissipation, passive compensation schemes can be considered by combining suitable materials and layer systems with specifically matched dn/dT behavior. In order to design a thermally stabilized F-Theta lens for NIR wavelengths, eligible optical materials were characterized, compared, and assessed in collaboration between Laser Laboratorium Göttingen and Sill Optics GmbH.

An absorption measurement system was set up deploying 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 photo-thermal technique can be employed for a rapid assessment of the material characteristics. Photothermal absorption measurements in the near-infrared range were performed for both the characterization of materials and the optimization of the complete optical system, utilizing a 500 W Ytterbium fiber laser (λ = 1070 nm) to induce thermal load. As a first step, different combinations of bulk materials and AR coatings were examined to minimize absorption and to evaluate potential approaches for thermal compensation. Additionally, an attempt to separate bulk and surface / coating absorption was carried out. Furthermore, complete F-Theta lenses were tested to gain understanding of the thermal behavior of the entire optical system.

Along with a description of the measurement setup and the applied technique, we present selected results on the properties of optical materials, and their applicability to realize passive compensation within an F-Theta objective.

Keywords: thermal lens, near-infrared, absorption, thermal compensation, F-Theta

8885-51, Session P2

Suppression of ultrafast laser-induced ionization in transparent solids

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

SPEAKER BIOGRAPHY: Dr. Gruzdev graduated from the St. Petersburg Institute of Fine Mechanics and Optics, St. Petersburg, Russia in 1994. In 2000 he received Ph.D. in optics from S. I. Vavilov State Optical Institute in St. Petersburg, Russia. He has spent 2 years as a visiting researcher with the group of Dr. D. von der Linde (University of Essen, Essen, Germany). Since 2005 he is with the Department of Mechanical and Aerospace Engineering of University of Missouri, USA. He is a co-chair of SPIE Laser Damage Symposium since 2009.

ABSTRACT TEXT: Laser-induced ionization of wide-band-gap solids (i.e., promotion of valence electrons to conduction band by laser radiation) is the fundamental effect that underlies the laser-induced damage (LID). It is frequently assumed that the ionization determines threshold of intrinsic LID and its dependence on laser and material parameters. In this presentation, results of numerical simulations demonstrate that the ionization can be suppressed (and correspondingly, LID threshold can be increased) by proper choice of laser parameters for materials with certain band structure. For simulations, we apply 2 formulations for the photo-ionization rate: the original Keldysh formula and its modification for wide-band-gap crystals with volume-centered crystal lattice. Avalanche ionization is simulated using the Drude model recently applied for studies of LID by femtosecond pulses. Dynamics of conduction-band electron density is described by a single rate equation. Maximum value of the conduction-band electron density is calculated as a function of peak intensity of femtosecond laser pulses for alkali halide crystals. It is shown that the conduction-electron density increases according to the multiphoton power law at low intensity. As soon as intensity approaches the first Keldysh singularity, the rate of the electron-density increase comes to saturation due to suppression of the photo-ionization. In case of the Keldysh formula, the electron density exhibits monotonous increase after each range of saturation and makes a ladder-type pattern on the intensity dependence. In case of the volume-centered crystals, the electron density can come to the saturation followed by decrease with intensity approaching the strong Gruzdev-type singularity. Those trends are explained based on the specific modifications of material band structure by electric field of laser pulses. In this connection, parametric dependence of intrinsic-LID threshold on laser wavelength is discussed under the monochromatic-light approximation.

Keywords: laser-induced damage, ultrashort laser pulses, wide-band-gap solids, laser-induced ionization, the Keldysh formula, avalanche ionization, photo-ionization

8885-52, Session P2

A theoretical analysis for temperature dependences of laser-induced damage threshold

Katsuhiro Mikami, Osaka Univ. (Japan) and JSPS (Japan);
Shinji Motokoshi, Toshihiro Somekawa, Institute for Laser Technology (Japan);
Takahisa Jitsuno, Osaka Univ. (Japan); **Masayuki Fujita,** Institute for Laser Technology (Japan); **Kazuo A. Tanaka,** Osaka Univ. (Japan)

SPEAKER BIOGRAPHY: Katsuhiro MIKAMI was born in 1986. He received Engineering Ph.D. degree from Osaka University, Japan. He is currently a research fellow at Japan society for the promotion of science. His present research area are temperature dependence of damage threshold and non-destruction testing for damage threshold.

ABSTRACT TEXT: Temperature dependences of laser-induced damage thresholds for dielectric optical coatings were reported at this symposium last year. The temperature dependence by nanosecond pulse was inversed to that by femtosecond pulse. The temperature dependences were irregular in 2-picosecond pulse. These laser-induced damage thresholds were measured with Nd:YAG laser (wavelength 1064 nm, pulse width 4 ns) and Ti:Sapphire laser (wavelength 800 nm, pulse width 200 ps, 2 ps, and 100 fs). In this study, we constructed a logical model to elucidate the temperature dependence. The model consisted of several physical mechanisms (photoionization, electron-phonon interaction, multiphoton ionization, electron avalanche, and critical density). The calculated results with the model agreed the laser-induced damage thresholds by femtosecond and nanosecond pulses. The calculation model would give an answer about the cause of the dependence. The irregular dependence in 2-ps pulse would also be explained when a variable expressing an influence from nonlinear phenomena was applied. The electron resistivity of optical materials is key-parameters through the modeling and discussion in this study.

Keywords: Laser-induced damage, Temperature dependence, Pulse width dependence, Cryogenic cooled laser, Theoretical analysis

8885-54, Session P2

Modeling femtosecond pulse laser damage on conductors and dielectrics using particle-in-cell (PIC) simulations

Robert Mitchell III, Douglass W. Schumacher, Enam Chowdhury,
The Ohio State Univ. (USA)

SPEAKER BIOGRAPHY: Douglass Schumacher received his B.S. degree in physics from the University of Illinois in 1983, worked at AT&T Bell Laboratories until 1990, and received his Ph.D. degree in physics from the University of Michigan in 1994. After a post-doctoral position at the University of Virginia, he has been with The Ohio State University Department of Physics since 1996. He has studied intense laser driven atomic and molecular ionization, atomic wavepacket excitation and evolution, and the nonlinear propagation of intense lasers in dielectrics. His current research interests include laser damage and the interaction of lasers and dense plasmas at relativistic intensities, including particle acceleration and the analysis of experimental diagnostics under these conditions. He uses particle-in-cell and hydrodynamic modeling to plan and analyze the results of experiments.

ABSTRACT TEXT: We present the first particle-in-cell (PIC) simulations of laser damage and the resulting damage spot morphology. We model the effect of an ultra-short pulse laser on conducting and dielectric targets near and above the damage threshold and compare to recent experimental results.

Femtosecond laser pulses cause damage that is highly deterministic, and thus ideal for materials processing. Although short pulse laser damage is already being applied, current understanding is still limited and no broadly applicable, fundamental model exists. Two approaches that have been successful and are widely used are semi-empirical models requiring many fitting parameters and molecular dynamics (MD) simulations.[1,2] The former can describe a range of experimental conditions and are straightforward to implement, but are neither general nor fully informative of the underlying physical processes. MD simulations are fundamental, but are generally computationally limited to be able to treat only a small portion of the target area and thus cannot address damage morphology. Both approaches generally forgo a realistic treatment of the laser-target interaction.

We show that PIC simulations provide a new and complementary approach. PIC simulations integrate the Maxwell and Lorentz equations of motion for “macroparticles”, representing a collection of electrons or ions, with continuously varying positions and momenta that interact with electromagnetic fields on a discretized grid. PIC simulations are ideal for treating intense interactions between lasers and matter and the flow of material after heating. The bare PIC approach does not treat particle-particle interactions within a grid cell correctly, but the effect of such interactions can be added to the PIC integration cycle.

To demonstrate the technique, we use the PIC code LSP [3] in 1D(3V) geometry to simulate the laser-target interaction and in 2D(3V) geometry to treat the subsequent target evolution. The 1D simulations run for 1 ps and are performed implicitly using ~ 2 nm cells and initially 1000 particles per cell for a range of peak intensities sampled from a Gaussian laser profile. These results are then used to initialize a 2D simulation with ~4-16 nm cells that is run for ~100 ps using an implicit algorithm optimized for large time steps that can stably exceed the Courant limit. Conducting targets were modeled using copper or gold ions and electrons at room temperature and dielectric targets were modeled using silicon and oxygen particles. We model, for example, 300 fs laser pulses with 2 micrometer spot sizes on ~5-10 micrometer scale targets over a range of intensities near the damage threshold. A binary collision operator is used and ionization is modeled in both cases. Using this approach, we observe laser absorption, target heating profiles, and damage evolution consistent with other approaches and experiment. We discuss extension of this approach to 2D/3D geometries.

This work was supported by the Ohio Supercomputer Center and performed under the auspices of the AFOSR under contract FA9550-12-1-0454.

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Keywords: femtosecond laser damage, femtosecond laser ablation, laser damage threshold, simulation of ultrafast dynamics, Particle in Cell simulation, Laser damage fundamental mechanism, Laser solid interaction, femtosecond dynamics

Dependence of fs laser resistance of optical materials on wavelength

Laurent Gallais-During, Dam-Be L. Douti, Institut Fresnel (France); **Gintare Bataviciute, Egidijus Pupka, Mindaugas Šciuka, Linas Smalakys, Andrius Melninkaitis,** Vilnius Univ. (Lithuania); **Fabien Lemarchand,** Institut Fresnel (France); **Valdas Sirutkaitis,** Vilnius Univ. (Lithuania); **Mireille Commandre,** Institut Fresnel (France)

ABSTRACT TEXT: Experimental data for the damage threshold as a function of the material properties or irradiation conditions (wavelength, pulse duration) are of practical importance for the design and choice of materials in high power laser systems but also for fundamental aspects for comparison with models.

In the present work a particular point that we have tried to analyze is the dependence of the laser damage threshold with the band-gap of the material in the femtosecond regime. Indeed for damage to occur in this regime excitation of electrons to the conduction band have to occur and the required energy for this to happen is directly dependent on the band-gap.

Particularly a linear scaling of the breakdown fluence with band-gap energy is experimentally observed in the near-infrared region and can be explained by invoking the band-gap dependence of the multi-photon absorption coefficient from the Keldysh photoionization theory. To expand the available data in the litterature (mainly for oxides between 4 and 9eV) to higher and lower band-gaps and materials of different nature (fluorides, oxides, semi-conductors...), a large number of high quality samples were gathered. All the samples were optically characterized by spectrophotometry in order to determine their absorption gap and later damage-tested in the same conditions at 500fs, 1030nm, 1on1 mode. The dependence of the LIDT in the S-on-1 mode has also been studied for several samples, with different repetition rate of the laser.

Furthermore an optical parametric amplifier pumped by a 100fs, 800nm Ti:Sapphire laser was used in an original experiment to measure the LIDT dependence on band-gap at different photon energies (8 wavelengths from 260 to 1200nm). A linear dependence of LIDT versus band-gap was observed from the IR to the UV.

These data are then compared to different published models that describe the free electron generation and heating in solids irradiated by ultra-short pulse laser, in order to test the validity or range of validity of these models.

CW and pulsed laser-induced absorption changes in Titania films

Xuerong Zhang, Luke A. Emmert, Wolfgang Rudolph,
The Univ. of New Mexico (USA)

ABSTRACT TEXT: The time-dependence of absorption at 800 nm in TiO_2 films was measured by photo-thermal detection [1]. The pump laser was a Ti:sapphire oscillator that could be operated in either CW or pulsed mode, delivering a train of 100 fs pulses at 113 MHz repetition rate. The time dependent absorption was measured for two films (ion-beam sputter (IBS) and electron-beam (EB) deposition) for both CW and pulsed illumination intensities from (40 kW/ cm^2 to 360kW/cm^2). Under CW illumination, the absorption coefficient of the IBS sample was constant (~8.5 cm^{-1}) for all powers. But under pulsed excitation, the absorption of the IBS sample increased for all intensities and reached nearly 10 times its initial value after 5 hours at the highest intensity. By contrast the absorption coefficient of the EB sample increased for both pulsed and CW illumination, ranging from an initial value of 25 cm^{-1} to values as high as 450 cm-1. The relaxation of these laser-induced modifications was studied as well. The implications of these results will be discussed in terms of a level scheme that includes a ladder of states between the conduction and valence bands.

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Keywords: time-dependent absorption, TiO_2, 800 nm, CW and pulsed excitation, electron-beam evaporation, ion-beam sputtering

Notes

Tuesday AM • 24 September

7:30 am to 4:00 pm **Registration Material Pick-up,** NIST Lobby Area

7:50 am to 8:30 am **Poster Placement at NIST**
Poster authors for the Tuesday poster session are to set up their posters at this time.

8:30 am to 9:50 am • SESSION 5

Materials and Measurements II

Session Chairs: **Gregory J. Exarhos,** Pacific Northwest National Lab. (USA);
Vitaly E. Gruzdev, Univ. of Missouri-Columbia (USA)

8:30 am: **Round Robin experiment on LIDT measurements at 1064nm in vacuum for space qualification of optics**, Stefan Schrameyer, Heinrich Maedebach, Lars O. Jensen, Detlev Ristau, Laser Zentrum Hannover e.V. (Germany); Clemens Heese, Jorge Piris, Alessandra Ciapponi, Bruno Sarti, European Space Research and Technology Ctr. (Netherlands); Andrius Melninkaitis, Gintare Bataviciute, Linas Smalakys, Valdas Sirutkaitis, Vilnius Univ. (Lithuania); Paul Allenspacher, Wolfgang Riede, Deutsches Zentrum für Luft- und Raumfahrt e.V. (Germany) . . . . [8885-14]

8:50 am: **1-on-1 pulse nanosecond laser-damage studies of thin films using time-resolved transmission**, Yejia Xu, Luke A. Emmert, The Univ. of New Mexico (USA); Dinesh Patel, Carmen S. Menoni, Colorado State Univ. (USA); Wolfgang Rudolph, The Univ. of New Mexico (USA) . . . . [8885-15]

9:10 am: **Method for studying laser-induced damage from sparse defects**, Sam Richman, Alexander R. Martin, Quentin Turchette, Trey Turner, Research Electro-Optics, Inc. (USA). . . . . [8885-16]

9:30 am: **Influence of growth behavior on laser-induced bulk damage in deuterated potassium di-hydrogen phosphate (DKDP) crystals**, Zhi M. Liao, Lawrence Livermore National Lab. (USA); Roshea Roussell, Southern Univ. and A&M College (USA); John J. Adams, Michael J. Runkel, Lawrence Livermore National Lab. (USA); W. T. Frenk, Jeffrey Luken, Gooch & Housego, Cleveland (USA); Christopher W. Carr, Lawrence Livermore National Lab. (USA) . . . . [8885-17]

9:50 am to 10:30 am • 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 am to 11:20 am • Poster Session and Refreshment Break

11:20 am to 12:40 pm • SESSION 6

Materials and Measurements III

Session Chairs: **Semyon Papernov,** Univ. of Rochester (USA);
Jianda Shao, Shanghai Institute of Optics and Fine Mechanics (China)

11:20 am: **Contamination resistant antireflection nano-textures in fused silica for laser optics**, Douglas S. Hobbs, Bruce D. MacLeod, Ernest Sabatino III, TelAztec LLC (USA); Jerald A. Britten, Lawrence Livermore National Lab. (USA). . . . [8885-87]

11:40 am: **High-power laser testing of 3D meta-optics**, Aaron J. Pung, Indumathi Raghu, Yuan Li, Eric G. Johnson, Clemson Univ. (USA); Michelle D. Shinn, Thomas Jefferson National Accelerator Facility (USA); Robert Magnusson, The Univ. of Texas at Arlington (USA); Joseph J. Talghader, Luke Taylor, Univ. of Minnesota, Twin Cities (USA); Lawrence Shah, Martin C. Richardson, CREOL, The College of Optics and Photonics, Univ. of Central Florida (USA) . . . . [8885-19]

12:00 pm: **Damage threshold studies for ceramic Yb:YAG at cryogenic and room temperatures**, Paul J. Phillips, Klaus Ertel, Paul Mason, Saumyabrata Banerjee, Justin Greenhalgh, Rutherford Appleton Lab. (United Kingdom); Joachim Hein, Jorg Koerner, Friedrich-Schiller-Univ. Jena (Germany); John L. Collier, Rutherford Appleton Lab. (United Kingdom). . . . . [8885-20]

12:20 pm: **Compositional dependent response of silica-based glasses after femtosecond laser pulse irradiation**, Thomas Seuthe, Fraunhofer-Institut für Keramische Technologien und Systeme (Germany); Moritz Grehn, Technische Univ. Berlin (Germany); Alexandre Mermillod-Blondin, Max-Born-Institut für Nichtlineare Optik und Kurzzeitspektroskopie (Germany); Jörn Bonse, Bundesanstalt für Materialforschung und -prüfung (Germany); Markus Eberstein, Fraunhofer-Institut für Keramische Technologien und Systeme (Germany) . . . . [8885-21]

12:40 pm to 2:00 pm • Lunch Break

Round Robin experiment on LIDT measurements at 1064nm in vacuum for space qualification of optics

Stefan Schrameyer, Heinrich Maedebach, Lars O. Jensen, Detlev Ristau, Laser Zentrum Hannover e.V. (Germany); **Clemens Heese, Jorge Piris, Alessandra Ciapponi, Bruno Sarti,** European Space Research and Technology Ctr. (Netherlands); **Andrius Melninkaitis, Gintare Bataviciute, Linas Smalakys, Valdas Sirutkaitis,** Vilnius Univ. (Lithuania); **Paul Allenspacher, Wolfgang Riede,** Deutsches Zentrum für Luft- und Raumfahrt e.V. (Germany)

ABSTRACT TEXT: In the determination of the laser-induced damage threshold (LIDT) of optical coatings former Round Robin (RR) experiments stand as the empirical foundation for the development of the international standard as it is known today. In 1983 and 1997 such experiments were conducted at the fundamental wavelength of the Nd:YAG laser under atmospheric conditions settling the international standard as it is known today.

To cope with the growing demand of LIDT testing for satellite missions, existing test methods have to be extended to deal with operation in space-like environments. This requires LIDT measurements performed under customized vacuum conditions to validate the laser resistance capability and estimate the life time of optical components. To foster the quality of measurements in such environments the need for an inter-laboratory comparison in vacuum conditions emerged.

Four institutes in three different countries have performed measurements on the damage threshold of optics under almost identical conditions, following a strict procedure, complementing the ISO 21254-2 standard. Each facility has tested two identical anti-reflective (AR) and high-reflective (HR) samples. Each test site was irradiated with a maximum of 10.000 laser pulses (10.000-on-1) at a wavelength of 1064 nm. The pulse duration was a few ns at a repetition frequency of 50 Hz and 100 Hz, respectively. All samples were produced in two coating runs using ion beam sputtering (IBS) to deposit multilayer systems of SiO_2/Ta_2O_5 on super-polished fused silica substrates. IBS technology enables the manufacturing of dense coatings without wavelength shifts known from porous coatings. This makes IBS coatings ideally suited for low pressure applications like high-power optical components in harsh space environment.

Within the scope of this work a detailed analysis of the acquired data has been performed. The data was evaluated by each participating laboratory followed by an evaluation of the coordinator LZH. In this way differences in the treatment of the raw-data become visible. In conclusion this Round Robin experiment sensitized all laboratories to critical points in their procedures and the application of the ISO standard to LIDT measurements in vacuum could be confirmed.

Keywords: Round Robin, Inter-Laboratory Comparison, 1064nm, Vacuum Conditions, LIDT-Measurements, Space qualification

1-on-1 pulse nanosecond laser-damage studies of thin films using time-resolved transmission

Yejia Xu, Luke A. Emmert, The Univ. of New Mexico (USA);
Dinesh Patel, Carmen S. Menoni, Colorado State Univ. (USA);
Wolfgang Rudolph, The Univ. of New Mexico (USA)

ABSTRACT TEXT: The shape of the characteristic damage curve (damage probability vs. incident pulse fluence) contains information about extrinsic damage centers (defects) in thin films[1]. However, the generation of these curves is tedious due to the number of tests required to extract the inherently statistical result from individual tests with only two outcomes: “damage” and “no damage”. Moreover, the sites with lowest damage fluence can be easily missed[2]. We present an alternative method, suitable for 1-on-1 studies, using time-resolved monitoring of the transmitted laser pulse with a fast photodetector[3]. This technique has been used to demonstrate the intrinsic bulk and surface damage threshold of fused silica[4]. The sample of interest is tested at multiple sites using a fixed fluence well above the damage threshold to ensure damage. In agreement with established damage models, the transmission signal suddenly drops at the onset of damage due to the rapidly expanding plasma following dielectric breakdown. By calibrating the photodetector, a damage intensity is measured for each site. Rare events are not missed, because damage occurs in every test, and weak sites are identified by their low damage intensity. The variance in the data reflects the probability of testing damage precursors in the film. The relationship between the measured intensity threshold and the fluence threshold as measured by the ISO method[5] will be discussed.

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Keywords: damage precursors, dielectric thin film, ns pulse, time-resolved transmission, 1064 nm

8885-16, Session 5

Method for studying laser-induced damage from sparse defects

Sam Richman, Alexander R. Martin, Quentin Turchette, Trey Turner,
Research Electro-Optics, Inc. (USA)

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

ABSTRACT TEXT: For standard high laser damage threshold (HLDT) optics at near-infrared wavelengths in the nano-second pulsewidth regime, the damage is largely governed by small absorbing defects at the surface and subsurface of the substrates and within the dielectric coatings. Because these defects are typically quite sparse (around 1/mm^2 or less), probing a large area with a large range of fluences is statistically necessary to make a meaningful statement of damage likelihood. We report the results of this type of characterization and attempt to develop a reliable way to accurately predict laser damage performance with a minimum of costly measurements. In such a study, it is useful to go beyond the ISO 11254 standard both in terms of the test procedure and the interpretation of the results.

Keywords: Laser damage threshold, HLDT, damage testing protocol, surface quality, inspection, defects

Influence of growth behavior on laser-induced bulk damage in deuterated potassium di-hydrogen phosphate (DKDP) crystals

Zhi M. Liao, Lawrence Livermore National Lab. (USA); **Roshea Roussell,** Southern Univ. and A&M College (USA); **John J. Adams, Michael J. Runkel,** Lawrence Livermore National Lab. (USA); **W. T. Frenk, Jeffrey Luken,** Gooch & Housego, Cleveland (USA); **Christopher W. Carr,** Lawrence Livermore National Lab. (USA)

SPEAKER BIOGRAPHY: Zhi M. Liao attended University of Rochester where he obtained his B.S., M.S. and PhD in optical engineering, working under Dr. Govind Agrawal on nonlinear fiber optics before joining Lawrence Livermore National Laboratory (LLNL) in 2001 as a laser physicist. Zhi's expertise is in nonlinear optics, adaptive optics, and laser-induced damage in optics. He has contributed to many of LLNL's successful laser projects over the years such as the Fiber Laser Guide Star, Alkali Laser, ARC, the Mercury Laser, and NIF (National Ignition Facility). Currently, Zhi is developing models to predict optic lifetime for optics on the National Ignition Facility (NIF) and has authored peer-reviewed scientific publications covering these topics. Zhi was also the co-PI for the team that won 2006 R&D award for high-average-power frequency conversion using YCOB crystals.

ABSTRACT TEXT: Bulk laser damage variability in deuterated potassium dihydrogen phosphate (DKDP) crystals is well known and makes online conditioning of multiple-beam laser systems difficult to optimize. By using an empirical model, Absorption Distribution Model (ADM), we are able to map the damage variability of the crystals (boule to boule as well as within same boule) in terms of defect populations using small beam damage probability tests. A relationship between defect density and the relative damage behavior of a boule had been found based on its late growth behavior, allowing potential laser damage and conditioning predictions based on damage probability tests alone.

Keywords: Laser Damage, DKDP, laser conditioning, Absorption Distribution Model (ADM), damage density, damage probability

8885-87, Session 6

Contamination resistant antireflection nano-textures in fused silica for laser optics

Douglas S. Hobbs, Bruce D. MacLeod, Ernest Sabatino III,
TelAztec LLC (United States); **Jerald A. Britten, Christopher J. Stolz,**
Lawrence Livermore National Lab. (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: Anti-reflecting (AR) surface relief nano-textures have been superimposed atop shallow diffraction grating structures to demonstrate the potential of stable diffractive 3? beam samplers with increased energy to target at the National Ignition Facility. TelAztec's plasma-based AR texturing process was used to superimpose Random-type AR microstructures onto existing 2000nm pitch, 20nm deep square profile diffraction gratings etched in prototype 50mm round fused silica windows. The superposition yielded the desired ~3.5% increase in transmission uniformly over the full aperture without compromising the grating function. The ratio of diffraction to 0-order transmission was preserved. A capillary condensation test was conducted to evaluate the resistance of the Random AR nano-texture to organic contamination. It was found that for a one day exposure time to a surrogate suite of organic contaminants, the Random AR textured fused silica surfaces adsorbed less than one fourth the amount of organic contaminants found on sol-gel AR coated fused silica surfaces. Transmission loss after exposure at a wavelength of 351nm for the Random AR textured window was <0.1%, whereas the sol-gel coated window showed 0.7% loss. A series of Random AR textured and sol-gel coated windows were then subjected to pulsed laser damage testing at LLNL and Quantel. The results will be presented.

Keywords: nano-textures, antireflection, AR, Motheye, Laser Damage Resistance, high power lasers, sol-gel coatings, grating beam samplers

High-power laser testing of 3D meta-optics

Aaron J. Pung, Indumathi Raghu, Yuan Li, Eric G. Johnson, Clemson Univ. (United States); **Michelle D. Shinn,** Thomas Jefferson National Accelerator Facility (United States); **Robert Magnusson,** The Univ. of Texas at Arlington (United States); **Joseph J. Talghader, Luke Taylor,** Univ. of Minnesota, Twin Cities (United States); **Lawrence Shah, Martin C. Richardson,** CREOL, The College of Optics and Photonics, Univ. of Central Florida (United States)

ABSTRACT TEXT: 3D Meta-Optics are optical components that are based on the engineering of the electromagnetic fields in 3D dielectric structures. The results of which will provide a class of transformational optical components that can be integrated at all levels throughout a High Energy Laser system. This paper will address a number of optical components based on 2D and 3D micro and nano-scale structures and their performance when exposed to high power lasers. Specifically, results will be presented for 1550 nm and 2000 nm spectral bands and power densities up to 100 kW/cm^2.

8885-20, Session 6

Damage threshold studies for ceramic Yb:YAG at cryogenic and room temperatures

Paul J. Phillips, Klaus Ertel, Paul Mason, Saumyabrata Banerjee, Justin Greenhalgh, Rutherford Appleton Lab. (United Kingdom); **Joachim Hein, Jorg Koerner,** Friedrich-Schiller-Univ. Jena (Germany); **John L. Collier,** Rutherford Appleton Lab. (United Kingdom)

ABSTRACT TEXT: The DiPOLE[1,2] project aims to develop high energy, high repetition rate diode-pumped lasers based on cryogenically gas-cooled ceramic Yb:YAG. Slabs of this material are easy to fabricate in large sizes, which are required for pulse energy levels of 1 kJ and beyond. To make the laser amplifiers compact and efficient, they need to be operated at high fluence levels. They will operate in the nanosecond regime in which damage arises from defects and imperfections on the surface of the material. It is therefore important to characterise the damage threshold of ceramic Yb:YAG under the proposed operating conditions. In this regard we embarked on a damage threshold study using eight ceramic 0.7% Yb-doped YAG samples measuring 24x24x7 mm^3. Two samples each were polished by four different companies, each using a different advanced polishing technique. Two companies employed a form of super polishing, one used magnetorheological finishing (MRF) and one used ion beam polishing. After polishing, the surface roughness of each sample was measured in three different locations. One sample from each company was then coated by IAD and one sample from each company was coated by IBS.

In order to asses there damage threshold at different temperatures the samples were sent to IOQ for damage testing. In these experiments, a 1030 nm laser with 3 ns pulse duration and the samples were held in a vacuum of 1e-6mBar. The first sample tested so far (IBS coated and conventionally polished) showed a front surface damage threshold fluence of 31.4 J/cm^2 at 300K, with a back surface damage threshold probability of 29.4 J/cm^2. At a temperature of 105 K, the same surface showed a damage probability of 61.1 J/cm2 at the front surface and of 32.1 J /cm^2 at the back surface.

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Keywords: YAG, Laser ceramics, low temperature, AR Coating

Compositional dependent response of silica-based glasses after femtosecond laser pulse irradiation

Thomas Seuthe, Fraunhofer-Institut für Keramische Technologien und Systeme (Germany); **Moritz Grehn,** Technische Univ. Berlin (Germany); **Alexandre Mermillod-Blondin,** Max-Born-Institut für Nichtlineare Optik und Kurzzeitspektroskopie (Germany); **Jörn Bonse,** Bundesanstalt für Materialforschung und -prüfung (Germany); **Markus Eberstein,** Fraunhofer-Institut für Keramische Technologien und Systeme (Germany)

SPEAKER BIOGRAPHY: Thomas Seuthe is PhD student at the Fraunhofer Institute for Ceramic Technologies and Systems (IKTS) in Dresden, Germany since 2010. His fields of interest are mainly related to glass, as structural changes of glass upon femtosecond laser irradiation, glass structure and physical properties and the sintering behavior of glass powders.

ABSTRACT TEXT: Femtosecond laser pulse irradiation of inorganic glasses allows a selective modification of the optical properties with very high precision. This results in the possibility for the production of three-dimensional functional optical elements in the interior of glass materials, such as for optical data storage, waveguide writing, etc. However, very little literature exists on the subject of laser pulse-glass interaction, in which the influence of the chemical glass composition has been studied systematically. Simple silica-based model glasses composed of systematically varying alkaline- and earth-alkaline components were prepared, irradiated on the surface and in the volume with single fs laser pulses (~100 fs, 800 nm), and were subsequently analyzed by means of micro-Raman spectroscopy, X-ray absorption spectroscopy (XANES) and optical methods (phase contrast microscopy) for changes in the glass structure, and for alterations of the optical refractive index. Studies of the laser-irradiated spots revealed no change in the average binding ratio (the so called Q-structure), but local changes of bond-angles and bond-lengths. Those changes are explained by structural relaxation of the glass network due to densification caused by a transient laser-induced shock wave or by other thermal phenomena. Glasses with a low amount of network modifiers show changes in the Si-O network while glasses with a high amount of network modifiers react primarily via changes of the non-bridging oxygen ions. The laser-induced refractive index modifications are determined by measuring differences in the optical path length with a phase contrast optical microscope. The results are discussed in terms of possible mechanisms and conclusions are outlined regarding glass compositions with technical suitability for fs-laser modifications.

Keywords: Micro-Raman spectroscopy, glass, Femtosecond phenomena, Laser-induced damage threshold

Tuesday PM • 24 September

2:00 pm to 3:00 pm • SESSION 7

Materials and Measurements IV

Session Chairs: **Amy L. Rigatti,** Univ. of Rochester (USA);
Christopher J. Stolz, Lawrence Livermore National Lab. (USA)

2:00 pm: **Comparative measurements of laser damage thresholds at the nanosecond and femtosecond pulse duration domain**, Tamas Somoskoi, Csaba Vass, Univ. of Szeged (Hungary); Mark Mero, Univ. of Szeged (Hungary) and Max-Born-Institut (Germany); Robert Mingesz, Zoltan Bozoki, Univ. of Szeged (Hungary); Karoly Osvay, Univ. of Szeged (Hungary) and ELI-Hu Nkft (Hungary) . . . . [8885-22]

2:20 pm: **Laser damage threshold measurements via maximum likelihood estimation**, Jonathan W. Arenberg, Northrop Grumman Aerospace Systems (USA); Michael D. Thomas, Spica Technologies, Inc. (USA) . . . . [8885-58]

2:40 pm: **Examination of multi-shot laser-induced damage on uncoated fused-silica substrates at the surface and in the bulk material using P-polarized 1 ns 1.5 kHz laser pulses at 1064nm**, Furqan L. Chiragh, Oleg A. Konoplev, Alexey A. Vasilyev, Sigma Space Corp. (USA); Demetrios Poulios, American Univ. (USA); Mark A. Stephen, Michael A. Krainak, NASA Goddard Space Flight Ctr. (USA) . . . . [8885-24]

3:00 pm to 3:50 pm • Poster Session and Refreshment Break

3:50 pm to 5:50 pm • SESSION 8

Surfaces, Mirrors, and Contamination I

Session Chairs: **Stavros G. Demos,** Lawrence Livermore National Lab. (USA);
Wolfgang Rudolph, The Univ. of New Mexico (USA)

3:50 pm: **A review of laser target debris and shrapnel studies by AWE** *(Plenary)*, James E. Andrew, AWE plc (United Kingdom) . . . . [8885-25]

4:30 pm: **Laser-induced contamination and its impact on laser damage threshold**, Helmut B. Schröder, Deutsches Zentrum für Luft- und Raumfahrt e.V. (Germany); Dimitrios Kokkinos, Univ. de Liège (Belgium); Wolfgang Riede, Deutsches Zentrum für Luft- und Raumfahrt e.V. (Germany); Adrian P. Tighe, European Space Research and Technology Ctr. (Netherlands) . . . . [8885-26]

4:50 pm: **Quantitative study of effect of contaminations on the damage threshold in optical coating**, Hidetoshi Murakami, Osaka Univ. (Japan) and Promotion Ctr. for Laser Technology (Japan); Takahisa Jitsuno, Osaka Univ. (Japan); Kota Kato, Osaka Univ. (Japan) and Promotion Ctr. for Laser Technology (Japan); Katsuhiro Mikami, Osaka Univ. (Japan); Shinji Motokoshi, Institute for Laser Technology (Japan); Tetsuji Kawasaki, Noriaki Miyanaga, Hiroshi Azechi, Osaka Univ. (Japan) . . . . [8885-27]

3:50 pm to 5:50 pm • SESSION 8 (continued)

5:10 pm: **Phase modulation in high-power optical systems caused by pulsed laser-driven particle ablation events**, Manyalibo J. Matthews, Nan Shen, Alexander M. Rubenchik, John Honig, Jeffrey D. Bude, Lawrence Livermore National Lab. (USA) . . . . [8885-28]

5:30 pm: **Laser-induced damage and ripples on the surface of fused silica by nanosecond laser pulse**, OuYang Sheng, Chengdu Fine Optical Engineering Research Ctr. (China). . . . . [8885-29]

5:50 pm to 6:15 pm • Closing Remarks

6:30 pm to 8:00 pm • Wine and Cheese Tasting Reception at NCAR

Sponsored by SPIE and the Conference Co-chairs of Laser Damage XLV

FOOD AND DRINK SPONSORED BY:

Comparative measurements of laser damage thresholds at the nanosecond and femtosecond pulse duration domain

Tamas Somoskoi, Csaba Vass, Univ. of Szeged (Hungary);
Mark Mero, Univ. of Szeged (Hungary) and Max-Born-Institut (Germany);
Robert Mingesz, Zoltan Bozoki, Univ. of Szeged (Hungary);
Karoly Osvay, Univ. of Szeged (Hungary) and ELI-Hu Nkft (Hungary)

ABSTRACT TEXT: One of the fundamental requirements of safe laser operation is the knowledge of the laser-induced damage threshold (LIDT) of the applied optical components. The damage resistances of optical coatings have been gradually increased through the decades. This involved the development of different damage detection techniques as well as the introduction of strict testing procedures aiming increased sensitivity and reliability. The most advanced detection method is based on the inspection of the irradiated site with either an imaging detector or through the change in a given property of the test sample (e.g. scattering, transmission). Another approach relies on the detection of the emergent photoacoustic waves by a microphone, a piezoelectric transducer or through the deflection of an auxiliary laser beam. In this paper we introduce a comprehensive test of these techniques for both nanosecond and femtosecond laser pulses.

The laser damage threshold of laser mirrors have been simultaneously determined from visual inspection, measurement of scattered light, as well as from the detection of acoustic waves by a microphone and by a piezoelectric sensor. To ensure the reliability of our results, we repeated the experiment at different wavelengths (266 nm and 532 nm) in the ns pulse duration regime, while the ultra-short regime has been explored by 30 fs laser pulses at 800 nm.

Measurements were made according to the standard ISO 11254-1 testing procedure, which means that every laser pulse should irradiate an untreated spot of the sample. To establish the damage thresholds, we applied the kernel density estimation procedure, where a critical signal level for each detection technique was assigned. The damage probability curves were determined according to the ISO prescription.

In the long pulse case the determined LIDT values resulting from all the four methods have been found similar, ranging between 4.02 J/cm^2 to 4.85 J/cm^2 for 532 nm and 1.90 – 2.74 J/cm^2 for 266 nm laser pulses. Among the sensing methods, the one based on visual inspection was found to be the most sensitive for both wavelengths. In the ultra-short pulse domain the measured damage thresholds by visual inspection and light scattering methods concluded a LIDT of around of 200 mJ/cm^2. Slightly surprisingly, no acoustic signal has been detected so far, even with tuning the microphone and the piezo sensors to a rather sensitive regime. The lack of signal may presumably due to the different nature of the underlying damaging mechanisms in these distinct time regimes. Besides, similarly to the results of ns pulses, visual inspection utilizing an optical microscope proved to be more sensitive than the scattered light detection.

Keywords: Laser damage, Scattering measurements, Photoacoustics

8885-58, Session 7

Laser damage threshold measurements via maximum likelihood estimation

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

SPEAKER BIOGRAPHY: Jonathan Arenberg is currently the Chief Engineer for the James Webb Space Telescope and has been with Northrop Grumman Aerospace Systems since 1989 having started with Hughes Aircraft Company. His work experience includes optical, space and laser systems. Dr. Arenberg has worked on such astronomical programs as the Chandra X-ray Observatory, James Webb Space Telescope and helped develop the New Worlds Observer concept for the imaging of extra-solar planets. He has worked on major high-energy and tactical laser systems, laser component engineering and metrology issues. He is a member of the ISO sub-committee charged with writing standards for laser and electro-optic systems and components, SPIE, American Astronomical Society and AIAA. Dr. Arenberg holds a BS in physics and an MS and PhD in engineering, all from the University of California, Los Angeles. He is the author of over 100 conference presentations and publications, and holds 1 European and 11 U.S. Patents.

ABSTRACT TEXT: In a last year's proceedings we reported on the performance of a maximum likelihood estimate (MLE) based method for the determination of the laser damage threshold. This report showed that an MLE based technique has promise as a method for producing an unbiased estimate of the laser damage threshold. Further investigations of the performance of an MLE based method are the subject of this year's report. An MLE based threshold determination method is evaluated against both theoretical models and experimental data. The MLE based results are compared to those derived from other methods such as the damage frequency method, ISO 11254 and ISO 21254, and the binary search technique. These MLE based thresholds are analyzed for measurement bias similar to previous analysis and compared.

Keywords: Maximum likelihood method, laser damage threshold measurement, optimal design of damage thereshold measurement

8885-24, Session 7

Examination of multi-shot laser-induced damage on uncoated fused-silica substrates at the surface and in the bulk material using P-polarized 1 ns 1.5 kHz laser pulses at 1064nm

Furqan L. Chiragh, Oleg A. Konoplev, Alexey A. Vasilyev, Sigma Space Corp. (USA);
Demetrios Poulios, American Univ. (USA); **Mark A. Stephen, Michael A. Krainak,**
NASA Goddard Space Flight Ctr. (USA)

SPEAKER BIOGRAPHY: Mr, Furqan L. Chiragh is a Sigma Space Corp. employee currently working at NASA Goddard Space Flight Center in the Laser & Electro-Optics Branch supporting NASA's Ice, Cloud, and land Elevation Satellite-2 (ICESat-2) project. He received his Bachelors of Science degree in Electrical Engineering with minors in Mathematics and History from New Mexico Institute of Mining and Technology in May 2006. Mr. Chiragh received his Masters of Science degree in Electrical Engineering with a concentration in Optoelectronics at the University of New Mexico, where he was part of the Center of Excellence for High Energy Lasers, a joint venture among the Air Force Research Laboratory's Directed Energy Directorate, The University of New Mexico, and several other universities. Additionally, from August 2006 through May 2008, Mr. Chiragh was a recipient of the National Science Foundation's GK-12 Fellowship.

ABSTRACT TEXT: In this paper, we present laser damage threshold testing performed on Un-Coated Fused Silica (SiO_2) substrates after multiple laser pulse irradiation. We will outline our methods of testing and observation of laser damage. Using carefully prepared 1" optical flats with 0.25" thickness, we observe competition between laser damage on the surface and in the bulk of the optic. Damage in the bulk is observed at the level of approximately 40-50 J/cm^2 when irradiated with 1,000-3,000 shots per site. Damage appears initially on the back surface of the substrate (without visible damage to the front/focused surface) and propagates slowly in time through the bulk towards the front of the optic. We believe this is due to self-focusing of the laser beam in the bulk material. An understanding of surface damage threshold has important consequences for applications, such as LIDAR, laser machining, and the lifetime of optical components. This work was done within the laser mission testing for NASA's Ice, Cloud, and land Elevation Satellite-II (ICESat-II) program at Goddard Space Flight Center in Greenbelt, MD.

The laser is a 1064nm source that can be operated at 1.5 kHz with 1ns pulses. The laser was run by an in-house built LABView program that controlled the frequency and duration of when the laser is firing. The sample was also translated using translational stages controlled by the same LABView program. To observe the damage, low magnification microscopes and a Zygo white light interferometer was used.

Keywords: Laser-Induced Damage, LIDAR, Bulk Damage, Surface Damage, Fused Silica

8885-25, Session 8

A review of laser target debris and shrapnel studies by AWE

James E. Andrew, AWE plc (United Kingdom)

SPEAKER BIOGRAPHY: Jim Andrew is a Team Leader in the Plasma Physics Group at AWE plc.

ABSTRACT TEXT: Since the late 1990s staff at AWE have been studying the effects of high energy focussed laser beams [>100J] on a variety of plasma physics targets to understand the disassembly of targets and their effects on target chamber surfaces. Target geometries included metal foils, polymer foils, metal cylinders, gas bags, metal wires and complex geometries of combinations of the above. We define shrapnel as a target fragment that can cause a permanent change to a target chamber surface. The surface could be an optical component, a plasma physics diagnostic instrument or the vacuum vessel wall. In a similar way we define debris as a target by product that causes a reversible change to a surface. Depending on the particular form of the laser input [irradiance, spot size, pulse shape and pulse length] the target emissions can include X or gamma radiation, protons or neutrons. These high energy photons or particles can produce ablation or induce radioactivity in target components, fragments and mounts. The post shot target remnants have been studied by both optical microscopy and scanning electron microscopy. The morphology of exposed targets indicated phase changes and other physical phenomena [shock, spall, crater formation and material ejection]. Pre and post weighing of the targets has been used to determine mass lost from the target. Initially most of the material distribution analysis was performed by catching target by-products with glass or silica witness plates. Spatial and image analysis of micrographs has been used to measure angular distributions of material and its form. Spectrophotometry of the exposed witness plates in the UV-Vis-NIR region allowed transmission spectra to be determined and the reduction of transmittance at the laser wavelengths of interest. It also allowed estimation of average debris thickness. Shrapnel size and velocity has been studied by capturing fragments in silica aerogels. One unexpected aspect of studying the witness plates was the identification of secondary emissions from solid surfaces close to the irradiated target, this showed that the near environment of the target is also important in determining overall material distributions. We have been fortunate to find interested collaborators at other UK, European and US laboratories that have brought considerable insight into target disassembly processes and palliative measures. Although we have not developed numerical modelling of the processes other institutes have and we will describe some of their work that have used our experimental data.

Keywords: aerogel, crater, debris, glass, image analysis, shrapnel, silica, transmission spectra

Laser-induced contamination and its impact on laser damage threshold

Helmut B. Schröder, Deutsches Zentrum für Luft- und Raumfahrt e.V. (Germany); **Dimitrios Kokkinos,** Univ. de Liège (Belgium); **Wolfgang Riede,** Deutsches Zentrum für Luft- und Raumfahrt e.V. (Germany); **Adrian P. Tighe,** European Space Research and Technology Ctr. (Netherlands)

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

ABSTRACT TEXT: Laser-induced contamination is a well-known phenomenon, affecting in particular short wavelength laser systems operating under vacuum conditions. The interaction of outgassed organic molecules with energetic photons induces the formation of deposits on optical surfaces. In this paper the impact of laser-induced deposits on damage threshold is investigated. The onset and evolution of deposit formation and damage was observed by in-situ microscopy, laser-induced fluorescence and transmission monitoring. Ex-situ characterization of deposits and damage morphology was performed by Nomarski, fluorescence, white light interference, and atomic force microscopy. As contamination materials pure aromatic hydrocarbons (naphthalene, anthracene and toluene) were used in this basic study. The tests were run with pulsed UV light at 355 nm. Partial pressure of contamination material in the range of 10-4 mbar induced a drastic reduction of laser damage threshold compared to values obtained without contamination. As optical samples uncoated fused silica substrates and AR and HR coated optics with different coating morphology, depending on coating process (e-beam, ion beam sputtering, magnetron sputtering) were investigated. The influence of coating morphology on laser-induced contamination and damage threshold is discussed.

Keywords: Laser-induced contamination, Laser damage threshold , Fluorescence, Coating

Quantitative study of effect of contaminations on the damage threshold in optical coating

Hidetoshi Murakami, Osaka Univ. (Japan) and Promotion Ctr. for Laser Technology (Japan); **Takahisa Jitsuno,** Osaka Univ. (Japan); **Kota Kato,** Osaka Univ. (Japan) and Promotion Ctr. for Laser Technology (Japan); **Katsuhiro Mikami,** Osaka Univ. (Japan); **Shinji Motokoshi,** Institute for Laser Technology (Japan); **Tetsuji Kawasaki, Noriaki Miyanaga,** Hiroshi Azechi, Osaka Univ. (Japan)

SPEAKER BIOGRAPHY: Hidetoshi Murakami received his Ph. D. degree from the Hokkaido University, Japn in 1999, and he is currently a research staff in the Promotion Center for Laser Technology. His present research area is the improvement of damage-threshold in LFEX laser system.

ABSTRACT TEXT: In LFEX laser system in Osaka University had a very serious oil-contamination, which provided a large decrease of the damage-threshold (DT) of dielectric mirrors and gratings in ns region. This phenomenon was mitigated by the use of the silica-gel in the compression chamber. We have made an investigation to measure the dependence of damage threshold on the amount of contamination. We used Toluene and water as contaminants. A dielectric mirror is kept in a chamber in which contaminant is flowing using N2 gas. The damage threshold was measured in-situ condition. We changed the density of contaminant to see the decrease of DT in time. We observed about 1/2 decrease of DT in saturated toluene in N2 at 24 degree Celsius. At diluted toluene by pure N2 gas, the decrease of DT was smaller than the saturated toluene case. We will report the detail of our observation in different density of toluene vapor and other materials such as Paraffin-oil and Di-butyl phthalate (DBP).

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

Phase modulation in high-power optical systems caused by pulsed laser-driven particle ablation events

Manyalibo J. Matthews, Nan Shen, Alexander M. Rubenchik, John Honig, Jeffrey D. Bude, Lawrence Livermore National Lab. (USA)

SPEAKER BIOGRAPHY: Manyalibo J. Matthews has been in the laser program at Lawrence Livermore National Laboratory (LLNL) since 2006 researching optical damage and 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 Ph.D. in physics from M.I.T. and B.S. in applied physics from U.C. Davis.

ABSTRACT TEXT: Surface contamination has long been recognized as a performance-limiting issue in many areas of technology from microelectronics, bioengineering and optics. While debris accumulation on optical surfaces is generally problematic because of light scattering, diffraction and obscuration, it's impact on performance takes on new dimensions when considering optics for high-power laser systems. In these cases, contamination on surfaces generated through optical processing and handling can lead to damage initiation and local fracture that, if left uncorrected, can often limit optic lifetime in a pulsed-laser system after several successive laser shots. At the same time, low-fluence (0.1 J/cm^2) laser pulses can lead to 'laser cleaning' effects that can be devoid of fracture-type damage. However, subtle morphological and bulk changes in the surface region near an ejected particle can potentially cause perturbations in subsequent laser pulse propagation to affect downstream optics.

In this work we investigate the surface modification of fused silica windows caused by the ablation of surface-bound micro-particles under short-pulse laser irradiation. 2-150 µm diameter particles of polymer, metal and glass arranged on incident surfaces were shown to ablate, fragment and disperse following short-pulse, 351-nm irradiation at ~9 J/cm^2. Subsequent laser pulses resulted in eventual complete ablation and ejection of all debris material and surface pitting which was found to be dependent on material type and particle size. Surface pitting was found to be most significant for opaque materials (aluminum, steel, acetal homopolymer), with pits as deep as 600 nm caused by ~30 µm particles after 6 laser pulses. Transparent materials (PET copolymer, silica and absorbing glass) tended to eject more readily and cause less pitting than the opaque materials, with pit depths typically ~100 nm or less. It is shown that, while ~30-µm debris alone produces no appreciable Fresnel diffraction that could cause damage on the exit surface of the op[tic, the spreading of the debris and its interaction with the silica surface upon subsequent laser shots can lead to a larger phase object capable of causing damage. This class of debris-generated damage is unique from others in that it results in no local damage in the classical sense of significant spallation and fracture. A simple model is presented to explain some of salient features of the materials dispersal and creation of the phase object.

This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344. [LLNL-ABS-635212]

8885-29, Session 8

Laser-induced damage and ripples on the surface of fused silica by nanosecond laser pulse

OuYang Sheng, Chengdu Fine Optical Engineering Research Ctr. (China)

ABSTRACT TEXT: The lifetime of optical components is determined by damage initiation and damage growth. When damage growth occurs, it is catastrophic for a laser system. In multi-shot laser-induced damage test on fused silica, we find a strong correlation between damage growth and plasma explosion. Once plasma explosion started, damage initiation sites begin to grow. Around the explosion core of damage site, ripples-like structure is observed. The period of ripples is about several hundred microns. The wave vectors of ripples in different damage sites have the same direction. The properties of ripples are investigated. In one-shot test, ripples are generated with different wavelength, laser input energy and orientation. Focused ion beam (FIB) is applied to observe damage sites and ripples. The detail structures of damage site and ripples are obtained by FIB etching.

Test samples are fused silica. The laser source is a Nd:Yag laser with the following characteristics: 1064 nm or 355nm wavelength, single longitudinal mode, Gaussian beam profile. During the test, the beam is focused on the exit surface of sample. Fluence fluctuations have a standard deviation of about 10%. An in situ observation system of irradiated area, by means of a long distance microscope and a CCD camera, is applied to monitor and record the laser-induced damage process. The minimum damage size detected is about 10 μm. Nomarski microscope and FIB are employed to observe the laser-induced damage morphology offline.

By analyzing the recorded laser-induced damage process, it shows that: if plasma explosion activates damage initiation sites, damage initiation becomes growth. Seed electrons are excited by laser light on account of existed surface defects or local temperature increasing. Ripples phenomenon is understood as interaction of the irradiated and scattered waves at the boundary air-material. But we think ripples are associated with plasma explosion in nanosecond laser pulse. Some information of laser-matter interactions could be extracted from ripples.

Keywords: laser-induced damage, surface damage, fused silica

Tuesday Poster Session • Rooms 1 & 2

Materials and Measurements

10:30 am to 11:20 am and 3:00 to 3:50 pm

Thin Films

Laser damage comparisons of broad-bandwidth high-reflection coatings having high index layers produced by e-beam evaporation of Ti_3O_5, Ta_2O_5, and Nb_2O_5, Ella S. Field, John C. Bellum, Damon Kletecka, Sandia National Labs. (USA) . . . . [8885-68]

Photothermal microscopy of thin films based on etalon effects, Zhangliang Sun, Luke A. Emmert, Xuerong Zhang, The Univ. of New Mexico (USA); Dinesh Patel, Carmen S. Menoni, Colorado State Univ. (USA); Wolfgang Rudolph, The Univ. of New Mexico (USA) . . . . [8885-72]

Development of high-resistant anti- and high-reflection coatings using Al_2O_3/SiO_2 layers, Yoshihiro Ochi, Keisuke Nagashima, Hajime Okada, Momoko Tanaka, Japan Atomic Energy Agency (Japan); Ryo Tateno, Yasuyuki Furukawa, Shimadzu Corp. (Japan); Akira Sugiyama, Japan Atomic Energy Agency (Japan) . . . . [8885-76]

A comparison of laser-induced-damage-thresholds of two types of dielectric polarizing beam splitters, Václav Škoda, Crytur Ltd. (Czech Republic). . . . . [8885-78]

Characterization and application of hafnia-silica mixtures produced by ion-beam sputtering technology, Simonas Kicas, Kestutis Juskevicius, Tomas Tolenis, Rytis Buzelis, Ramutis Drazdys, Institute of Physics (Lithuania); Gintare Bataviciute, Egidijus Pupka, Linas Smalakys, Andrius Melninkaitis, Vilnius Univ. (Lithuania). . . . . [8885-80]

Laser damage behavior of Ta_2O_5/SiO_2 interference coatings in the infrared, Dinesh Patel, Drew D. Schiltz, Peter Langton, Colorado State Univ. (USA); Luke A. Emmert, The Univ. of New Mexico (USA); Leandro Acquaroli, Cory Baumgarten, Brendan A. Reagan, Jorge J. Rocca, Colorado State Univ. (USA); Wolfgang Rudolph, The Univ. of New Mexico (USA); Ashot S. Markosyan, Roger Route, Martin M. Fejer, Stanford Univ. (USA); Carmen S. Menoni, Colorado State Univ. (USA) . . . . [8885-82]

Performance of multilayer optical coatings under long-term 532nm laser exposure, Demetrios Poulios, American Univ. (USA); Oleg A. Konoplev, Furqan L. Chiragh, Sigma Space Corp. (USA); Aleksey A. Vasilyev, Science Systems and Applications, Inc. (USA); Mark A. Stephen, NASA Goddard Space Flight Ctr. (USA); Kathy Strickler, ASRC Management Services, Inc. (USA) . . . . [8885-84]

Laser-induced damage resistance of 266nm AR coatings, Byungil Cho, Li-Ji Lyu, Newport Corp. (USA); Mark S. Feldman, Spectra-Physics®, a Newport Corp. Brand (USA) . . . [8885-85]

Database on damage thresholds for dichroic mirrors of 1064nm and 532nm, Shinji Motokoshi, Institute for Laser Technology (Japan); Katsuhiro Mikami, Takahisa Jitsuno, Osaka Univ. (Japan). . . . . [8885-86]

Surfaces, Mirrors, and Contamination

10:30 am to 11:20 am and 3:00 to 3:50 pm

8885-68, Session P3

Laser damage comparisons of broad-bandwidth high-reflection coatings having high index layers produced by e-beam evaporation of Ti_3O_5, Ta_2O_5, and Nb_2O_5

Ella S. Field, John C. Bellum, Damon Kletecka, Sandia National Labs. (USA)

SPEAKER BIOGRAPHY: Ella Field is an engineer at Sandia National Laboratories in Albuquerque, New Mexico. She develops optical coatings for the Z Backlighter Laser, and designs hardware for physics experiments on the Z Machine, the world's largest x-ray generator. She received a master's degree in mechanical engineering from the Massachusetts Institute of Technology in 2011, and received bachelor's degrees in mechanical engineering and Asian languages and literature from the University of Minnesota in 2009.

ABSTRACT TEXT: We do not yet have results to include by the April 15 abstract deadline, but expect to have them to add to this abstract by the middle of May. We plan to develop and characterize high index of refraction thin films by e-beam evaporation of Ti_3O_5, Ta_2O_5 and Nb_2O_5 in reactive, ion-assisted deposition processes. We then deposit broad bandwidth high reflection (HR) coatings based on quarter-wave stacks of these high index layers alternating with SiO_2 low index layers. The HR band is centered at 1054 nm and designed for 45° angle of incidence. We compare the laser induced damage thresholds of these coatings in order to explore tradeoffs between their laser damage properties and HR bandwidths.

Keywords: laser damage resistant optical coatings, broad bandwidth mirror coatings, high index oxides for thin films, e-beam evaporation, reactive ion-assisted deposition

Photothermal microscopy of thin films based on etalon effects

Zhangliang Sun, Luke A. Emmert, Xuerong Zhang, The Univ. of New Mexico (USA);
Dinesh Patel, Carmen S. Menoni, Colorado State Univ. (USA);
Wolfgang Rudolph, The Univ. of New Mexico (USA)

ABSTRACT TEXT: Photothermal microscopy is an established tool to measure absorption with spatial resolution. It is based on the sensing of a pump induced temperature change. Thermal lensing[1], beam deflection[2] and backscatter from an induced dielectric constant change[3] have successfully been exploited as signal generating mechanism. We present a concept, particularly suited for the inspection of thin films with submicron spatial resolution and ppm sensitivity, which makes use of the inherent property of a thin film to act as a Fabry-Perot etalon. The local temperature change gives rise to a change in Fabry-Perot resonance, which can be probed in reflection by a probe laser of suitable wavelength. We analyze theoretically the performance of the microscope and present absorption maps of high-quality dielectric films. We also study with spatial resolution ripple patterns often associated with laser damage.

1. Z. L. Wu, C. J. Stolz, S. C. Weakley, J. D. Hughes, and Q. Zhao, "Damage Threshold Prediction of Hafnia-Silica Multilayer Coatings by Nondestructive Evaluation of Fluence-Limiting Defects." Appl. Opt. 40, 1897–1906 (2001).
2. A. During, C. Fossati, and M. Commandré, "Photothermal Deflection Microscopy for Imaging Sub-Micronic Defects in Optical Materials." Opt. Comm. 230, 279–286 (2004).
3. S. Papernov, A. Tait, W. Bittle, A. W. Schmid, J. B. Oliver, and P. Kupinski, "Near-Ultraviolet Absorption and Nanosecond-Pulse-Laser Damage in HfO2 Monolayers Studied by Submicrometer-Resolution Photothermal Heterodyne Imaging and Atomic Force Microscopy." J. Appl. Phys. 109, 113106 (2011).

Keywords: photothermal , absorption microscope, etalon, dielectric thin film, 532 nm

Development of high-resistant anti- and high-reflection coatings using Al_2O_3/SiO_2 layers

Yoshihiro Ochi, Keisuke Nagashima, Hajime Okada, Momoko Tanaka, Japan Atomic Energy Agency (Japan); **Ryo Tateno, Yasuyuki Furukawa,** Shimadzu Corp. (Japan); **Akira Sugiyama,** Japan Atomic Energy Agency (Japan)

ABSTRACT TEXT: In a chirped pulse amplification (CPA) laser using thin-disk amplifier such as Yb:YAG, the output fluence is restricted by damage-resistance of the anti-reflection (AR) coating on the thin-disk. In general a Yb-doped thin-disk amplifier has low small signal gain, therefore intense pump and high output fluence are necessary to extract sufficient energy. So the high damage-resistant AR coating is one of the key issues in the development of thin-disk amplifiers. Typical pulse duration in the thin-disk CPA amplifier is hundred picoseconds. The bandwidth of the AR coating has to include 940 nm for the pump laser and 1030 nm for the seed laser.

We designed such AR coating for the Yb:YAG by use of Al_2O_3/SiO_2 multilayer. At first we fabricated the AR coating on the fused silica substrate in order to test the damage resistance. The irradiation test was made using 500 ps pulses at 1 kHz repetition extracted from the Yb:YAG thin-disk regenerative amplifier. The pulses were focused on the sample by a spherical lens with the focal length of 200 mm. The diameter of the beam waist was measured to be 56.5 μm at the 1/e2 intensity. The sample surface was set at the focus point (i.e. beam waist) and irradiated for 20 seconds. As the result the laser damage was occurred at 36 J/cm^2 (average value) firstly in the fused silica substrate by the self focusing. So the damage threshold of the AR coating was considered to be more than it.

We also designed and fabricated the high-reflection (HR) mirrors by adding a few Al_2O_3/SiO_2 layers on Ta_2O_5/SiO_2 layers. As results of irradiation tests, damage thresholds were estimated to be 47 J/cm^2 for 500 ps pulse and 0.53 J/cm^2 for 1ps pulse, respectively. We have designed the > 2 J/cm^2 damage threshold mirror for the 1 ps pulse by optimizing the layer thickness.

Keywords: high damage-resistance, picoseconds pulse, Al_2O_3/SiO_2 multilayer, Yb:YAG thin-disk CPA laser, high average power laser system

A comparison of laser-induced-damage-thresholds of two types of dielectric polarizing beam splitters

Václav Škoda, Crytur Ltd. (Czech Republic)

SPEAKER BIOGRAPHY: Václav Škoda received his MS degree in Physics from the Charles University in Prague, Faculty of Mathematics and Physics in 1975, PhD. degree in 1991 from the Czech Technical University in Prague, Faculty of Nuclear Science and Physical Engineering. He has been working as thin film specialist in Crytur Ltd. in Turnov, Czech Republic. He is member of SPIE.

ABSTRACT TEXT: Laser-induced-damage-threshold of polarizing Brewster-angle beam splitters based on two different layer system designs was measured using a laser apparatus working at 1060 nm wavelength with 10 ns pulse length and 1-on-1 test mode. As damage threshold was chosen the 50% damage probability level. A Nd:glass passively Q-switched laser with Pockels cell for pulse extraction and Nd:glass amplifier was used to obtain Gaussian pulses in both time and space domains. The laser beam was focused by a lens and the beam diameter used for our measurements was in range of 0.1 mm. The laser damage was detected by observation of plasma generation using a microscope and a camera. Both BK7 and fused silica substrates were used for manufacturing of samples and there were not found significant differences in damage threshold values between these two materials. Two different designs of layer system using TiO_2/SiO_2 coating materials were carried out. The first design shoved low values of internal electric field at S-polarization. The second design shoved higher values of internal electric field at S-polarization and slightly lower values of internal electric field at P-polarization in comparison with the first design. Two sets of samples were coated in a high-vacuum chamber by electron-beam deposition process at elevated temperature and using oxygen as reactive gas. As could be expected we measured higher (about 43 J/cm^2 vs. 14 J/cm^2) damage threshold in S-polarization at samples according to the first design. The damage threshold in P-polarization was significantly higher (about 38 J/cm^2 vs. 13 J/cm^2) at samples according to the second design (although the computed values of electric field were only slightly lower in comparison with the first design).

Keywords: laser-induced-damage, polarizing beam splitter, internal electric field

Characterization and application of hafnia-silica mixtures produced by ion-beam sputtering technology

Simonas Kicas, Kestutis Juskevicius, Tomas Tolenis, Rytis Buzelis, Ramutis Drazdys, Institute of Physics (Lithuania); **Gintare Bataviciute, Egidijus Pupka, Linas Smalakys, Andrius Melninkaitis,** Vilnius Univ. (Lithuania)

ABSTRACT TEXT: In the past years the usage of mixed oxide coatings leads to an important improvement of laser damage threshold and quality of optical elements. One of the reasons for this improvement is the ability to tailor optical characteristics, such as refractive index and extinction when mixing several different oxides. UV wavelength range experiences lack of suitable high refractive index coating materials with sufficiently high laser damage threshold. In this manner, usage of mixed materials can bring many advantages.

In this study different fractions of HfO_2 and SiO_2 mixtures were fabricated using Ion-beam sputtering technology (IBS). The influence of sputtering process gas and post annealing conditions to optical characteristics, surface roughness, stress and optical resistance of mixed monolayer's, as well as of high reflection coatings at 355 nm is examined.

Optical characteristics: refractive index and extinction coefficients were calculated from measured transmission spectra. Profilometer was used to measure bending of thin substrates to evaluate coating's induced stress by using Stoney's formula. Surface roughness before and after deposition was estimated with atomic force microscopy. Optical resistance was characterized for 355 nm, 50 Hz, 5 ns laser radiation performing 1-on-1 sample exposure test with high resolution micro-focusing approach. Finally, the conclusions about the quality and characteristics influencing factors of investigated processes were drawn.

Keywords: optical damage, high reflection coatings, ion beam sputtering, hafnium oxide mixtures

Laser damage behavior of Ta_2O_5/SiO_2 interference coatings in the infrared

Dinesh Patel, Drew D. Schiltz, Peter Langton, Colorado State Univ. (USA);
Luke A. Emmert, The Univ. of New Mexico (USA);
Leandro Acquaroli, Cory Baumgarten, Brendan A. Reagan, Jorge J. Rocca, Colorado State Univ. (USA); **Wolfgang Rudolph,** The Univ. of New Mexico (USA);
Ashot S. Markosyan, Roger Route, Martin M. Fejer, Stanford Univ. (USA);
Carmen S. Menoni, Colorado State Univ. (USA)

ABSTRACT TEXT: Ta_2O_5 and SiO_2 are important high and low index materials used in interference coating for high power lasers. Ion beam sputter deposition produces high density oxide films with low absorption losses near and mid and infrared wavelengths. In this work we report on the ion beam sputter deposition of single layers of Ta_2O_5 and SiO_2 culmination with the deposition of high reflectors with Ta_2O_5/SiO_2 quarter-wave thicknesses and anti-reflection structures for 1 micron wavelength operation using optimum conditions. Low absorption and scattering losses at 1 micron wavelength were measured in the single layers. Preliminary results on a Ta_2O_5/SiO_2 high reflector showed no damage even up to 5 MW/cm^2. Comparison of the laser damage behavior versus pulse duration will be discussed.

Keywords: ion beam sputtering, high reflector, laser damage, Ta_2O_5, SiO_2

Performance of multilayer optical coatings under long-term 532nm laser exposure

Demetrios Poulios, American Univ. (USA); **Oleg A. Konoplev, Furqan L. Chiragh,** Sigma Space Corp. (USA); **Aleksey A. Vasilyev,** Science Systems and Applications, Inc. (USA); **Mark A. Stephen,** NASA Goddard Space Flight Ctr. (USA); **Kathy Strickler,** ASRC Management Services, Inc. (USA)

ABSTRACT TEXT: The laser transmitter on board NASA's ICESat-2 mission will emit over one trillion high-intensity 532 nm laser pulses over its 3-year mission lifetime. A number of elements in the optical train will be exposed to high laser fluences (~0.5 J/cm^2) over the mission duration, raising concerns over long-term aging effects of optical thin-film coatings. Of particular concern are the anti-reflection coatings on the lithium triborate (LBO) frequency doubler, and the high reflection coatings of 45 degree turning mirrors. To investigate potential deleterious aging effects, an accelerated life test platform was constructed where optics were exposed to 532 nm radiation by a high repetition rate (625 kHz), short pulse (~1.2 ns) fiber amplifier with pulse energies up to 15 µJ. The first run of trillion-shot tests were conducted on E-beam deposited and ion beam sputtering (IBS) coated high reflecting mirrors with on-surface intensities ranging from 1.0-1.4 GW/cm^2. The reflected power and beam size on the optical surface were monitored and recorded throughout the test. After completing 1 trillion shots, the optical surfaces were profiled using a high-resolution 3D microscope. The E-beam coated mirrors tested failed catastrophically after only ~150 billion shots, while the IBS coated mirror was able to complete the test without noticeable loss of reflectivity. 3D surface profiling did reveal a ~10 nm deposit at the irradiation site along with cavitation/compaction of the surface, indicating photocontamination of the optic. For the LBO spot aging tests, the crystals were exposed to intensities ranging from 0.75-1.5 GW/cm^2 at multiple surface sites, and the transmitted power and on-surface beam size were monitored throughout the tests; periodic measurements of the beam quality (M^2) of the transmitted light were also made. No changes in transmitted power or M^2 were observed in any of the tests, but 3D surface profiling revealed photocontamination deposits at each site tested.

Keywords: photocontamination, spot aging, thin film, optical coatings

Laser-induced damage resistance of 266nm AR coatings

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Mark S. Feldman, Spectra-Physics®, a Newport Corp. Brand (USA)

SPEAKER BIOGRAPHY: Senior Thin Film Scientist, Newport Corporation, Irvine, California, USA. He has experience in development of the optical thin film with the high laser induced damage threshold, coating design, and coating processes optimization for the high power laser applications. He received the BS and MS degrees from Yonsei University, Seoul, Korea and received a Ph. D from the Univ. of Texas at Austin in 1994.

ABSTRACT TEXT: The 266 nm AR coatings consisting of HfO_2/SiO_2 and Sc_2O_3/SiO_2 were deposited on fused silica and CaF_2 substrates. The laser damage resistance (LDR) was measured to determine the laser fluence that a coating can withstand without damaging when exposed to a large number of pulses. The LDRs of AR coatings with Sc_2O_3/SiO_2 were higher than those with HfO_2/SiO_2. The surface roughness, absorption and subsurface damage were measured for both substrate materials and were correlated with the LDR. The LDR generally increases as the subsurface damage size decreases. The surface damage morphology was also studied.

Keywords: laser damage resistance, 266 nm AR coating, SiO_2, HfO_2, Sc_2O_3, fused silica,, calcium fluoride, subsurface damage

Database on damage thresholds for dichroic mirrors of 1064nm and 532nm

Shinji Motokoshi, Institute for Laser Technology (Japan);
Katsuhiro Mikami, Takahisa Jitsuno, Osaka Univ. (Japan)

SPEAKER BIOGRAPHY: Shinji Motokoshi is chief researcher for a group of laser and optical technology in Institute for Laser Technology, Japan. His main work is the development of optics for high-power lasers with Osaka university. And also, he has proceeded to compile databases on damage thresholds for optical devices in association with optics makers in Japan.

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 compile of databases on damage threshold of optics for high-power lasers, cooperating with Japanese coating makers. It will be connected with the design of laser systems and the improvement of optical technologies. We had presented the databases on damage thresholds for HR and AR coatings at wavelengths to 1064 nm from 248 nm in this symposium.[1, 2]) Previous databases were for optics with specification at one wavelength. In this time, database for dichroic mirrors with high transmission at 1064 nm and high reflection at 532 nm was presented. And also, the database was compared with that of optics for each wavelength. The samples were prepared 24 by 10 coating makers. The most frequent thresholds were 20 – 30 J/cm^2 at both wavelengths of 1064 nm and 532 nm. The results were compared with that of database for AR coatings at 1064 nm and for HR coatings at 532 nm.1)

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.

Keywords: Database, Damage threshold, Dichroic mirror, 1064 nm, 532 nm

Localized planarization of optical damage using laser-based chemical vapor deposition

Manyalibo J. Matthews, Selim Elhadj, Gabe M. Guss, Arun K. Sridharan, Isaac L. Bass, Norman D. Nielsen, Lawrence Livermore National Lab. (USA)

SPEAKER BIOGRAPHY: Manyalibo J. Matthews has been in the laser program at Lawrence Livermore National Laboratory (LLNL) since 2006 researching optical damage and 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 Ph.D. in physics from M.I.T. and B.S. in applied physics from U.C. Davis.

ABSTRACT TEXT: Effective mitigation of pulsed laser-induced damage - responsible for limiting the lifetime of optics in high-fluence laser systems – can be achieved through selective CO_2 treatment of damaged material. However, the perturbation to the optical surface profile following the mitigation process can introduce a phase modulation in a propagating light beam, causing some amount of downstream intensity modulation with the potential to damage other optics. Control of the laser treatment process and measurement of the associated morphology-driven phase modulation is essential to prevent downstream 'fratricide' in damage-mitigated optical systems. At the same time, control of other factors such as residual stress and damage threshold must be maintained. While much progress has been made over the years to optimize either low temperature 'non-evaporative' or high temperature 'ablative' techniques, material removed by the damage process always leads to a surface pit and thus a finite perturbation to the incident beam. To date, we know of no approach which additively mitigates the damage by replacing lost material with high-grade substrate material.

In this work we present a method to heal damaged material using laser-based chemical vapor deposition (L-CVD) to shape the final surface to achieve minimal surface perturbations to incoming UV light. A CO_2 laser is used to heat damaged regions under controlled flow and composition to achieve a thermally activated polymerization of the tetraethylorthosilicate (TEOS) precursor to form silica. Laser parameters are adjusted to optimize precursor decomposition kinetics and material transport, which results in the desired material properties and morphology. Measured deposition rates and morphological evolution as a function of temperature agree well with a heterogeneous phase model implemented using finite element methods. We show that unlike typical L-CVD processes, a finite heat-diffused boundary layer facilitates both gas phase and surface reactions which can be exploited for high deposition rates. Along with optimizing deposition rates and morphology, we also show that the deposited silica is structurally identical to high-grade silica substrates using vibrational spectroscopy, and possesses high UV laser damage thresholds. Successful application of such a method could reduce processing costs, extend optic lifetime, and lead to more damage resistant laser optics used in high power applications.

This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344. [LLNL-ABS-635243]

Improving UV laser lifetimes by minimizing trace contamination

Timothy Shuman, Floyd E. Hovis, Fibertek, Inc. (USA);
Chris A. Hostetler, NASA Langley Research Ctr. (USA)

ABSTRACT TEXT: Long life operation of pulsed solid-state UV lasers is a fundamental requirement for a number of NASA's proposed space missions including Aerosol/Cloud/Ecosystems (ACE), 3-D Winds, and the Global Atmospheric Composition Mission (GACM). The primary limitation of current UV laser technology is the optical component lifetime as demonstrated by NASA's Goddard Lidar Observatory for Winds (GLOW) and ESA's Atmospheric Laser Doppler Instrument (ALADIN). Numerous mechanisms degrade and damage the optics and crystals within these lasers but, arguably, the most difficult to prevent is damage induced by trace contamination. The presence of trace contaminants can reduce the lifetime of a UV nonlinear conversion crystal to less than 1,000 hours at fluence levels as low as 0.1 J/cm^2. Unfortunately, these fluence levels are well below those required to achieve optimum conversion to the UV. Thus, minimizing the amount of residual contamination within the laser assembly is critical to maximizing the UV laser lifetime. To date, Fibertek has demonstrated more than 2,800 hours and 500 million shots of 50 Hz, 355 nm operation without measurable degradation by taking the necessary steps to minimize contamination: procuring high quality crystals and coatings, using a minimal amount of polymers in the crystal ovens and housing and processing all parts through a combination of solvent cleaning and elevated temperature bake-outs. Two separate crystal and coating vendors are being tested. To ensure the impact of contamination was studied, the maximum UV fluence in the crystal was limited to < 1 J/cm^2. This level is safely below the catastrophic damage threshold of the crystal and their AR coatings. We are continuing the lifetime testing and will provide additional details and an update on the results.

Keywords: ultraviolet, trace contamination, long life, LBO, degradation

8885-73, Session P4

Laser removal of ion-implanted novolak resist without occurring surface laser-induced damage to the silicon wafer

Hiroki Muraoka, Osaka Institute of Technology (Japan); **Yousuke Goto,** Kanazawa Institute of Technology (Japan); **Yuta Kuroki, Kiwamu Kuroda, Takuya Kiriyama, Hiroyuki Kuramae, 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: In the fabrication of semiconductors and liquid crystal display (LCD), several processes such as deposition, resist coat, exposure, development, ion-implantation, etching, and resist removal are performed repeatedly. After ion-implantation process, resist surface changes in quality chemically and physically. Because the removal with the medicinal solution is difficult, ashing by the oxygen plasma is put together in the resist removal process. On our past results, resist removal for a positive-tone DNQ / novolak resist by using a laser irradiation in water have been succeeded without occurring laser-induced damage to the silicon wafer. The irradiated laser beam passes through resist and arrives at the silicon wafer surface. Resist stripping results from energy absorbed at the silicon surface. In this study, we have investigated the laser removal of ion-implanted positive-tone DNQ / novolak resist by using a pulsed laser beam from visible to near-infrared. Spectral characteristic of ion-implanted resist was measured with spectral photometer. Regardless of the change in quality of the resist surface by the ion-implantation, the laser beam was found to arrive at the silicon wafer surface. When the laser beam from visible to near-infrared was irradiated to the ion-implanted resist, the ion-implanted resist was successfully stripped from silicon surface without occurring surface laser-induced damage.

Keywords: resist stripping, ion-implanted resist, positive-tone diazonaphthoquinone, novolak resist, laser irradiatio, laser damage, silicon wafer

Investigation of subsurface damage impact to resistance of laser radiation of fused silica substrates

Kestutis Juskevicius, Simonas Kicas, Tomas Tolenis, Rytis Buzelis, Ramutis Drazdys, Institute of Physics (Lithuania); **Gintare Bataviciute, Egidijus Pupka, Linas Smalakys, Andrius Melninkaitis,** Vilnius Univ. (Lithuania)

ABSTRACT TEXT: It is well known that the conventional CeO_2 abrasive polishing techniques cause subsurface damage of fused silica glass, which is the main limiting feature of light absorption, especially in UV wavelength of laser radiation. Subsurface damages are defined as residual digs and scratches filled with polishing slurry and covered with the so-called Bielby layer (polished layer).

In this study surface treatment by acid etching was applied to remove Bielby layer and “clean out” digs and scratches containing residual polishing materials. Compositional analysis of polished layer after different etching duration was performed by XPS spectroscopy. Laser induced damage threshold tests 1-on-1 with high resolution micro-focusing approach were used for all etched samples. Measurements were performed for 355 nm, 50 Hz, 5 ns laser radiation. Results are compared with the bulk fused silica sample.

Keywords: subsurface damage, optical damage, fused silica polishing, optical surface etching

Pilot scale demonstration of scratch repair by using a CO_2 laser on fused silica optic

Philippe Cormont, Sandy Cavaro, Gael Gaborit, 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. During optics production steps, unwanted defaults as scratches are generated. Scratches are unwanted on laser optics because they initiate UV-laser damage at lower fluence than the other part of optics. With the actual state of art, it seems difficult and very expensive to produce optics without scratches. That is the reason why several studies are conducted to understand and to correct their negative effect.

Last year, we proposed a process to remove the unwanted scratches. A CO_2 laser was used to locally melt the silica in the scratched area. The laser damage resistance was increased to a safe operating level for LMJ.

We have applied this process to an optic of large size which has been polished according to the LMJ standard. Care should be taken to locate precisely and exhaustively the defects and then to apply CO_2 laser along the identified scratches.

We report here some difficulties that we encountered in moving from sample to a LMJ optic and we present our latest results.

Keywords: fused silica, laser mitigation, CO_2 laser, scratch repair

8885-79, Session P4

Effects of subsurface removal on surface damage resistance of optical coatings in deep-UV wavelength

Yoshiaki Matsura, Yuta Kuroki, Kiwamu Kuroda, Takuya Kiriyama, Tomosumi Kamimura, Osaka Institute of Technology (Japan);
Katsuhiro Mikami, Shinji Motokoshi, Takahisa Jitsuno, Osaka Univ. (Japan)

SPEAKER BIOGRAPHY: Yoshiaki Matsura is graduate student at the Major in Electrical and Electronic of Graduate School 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: The laser induced damage threshold (LIDT) of a polished surface is much lower than the dielectric breakdown threshold of its bulk. The effect of surface contamination and surface defects on the surface LIDT of transmissive optics has already been extensively studied. In addition, scratches and subsurface damage are known to lower the surface LIDT. In this paper, we have investigated the effects of subsurface removal on surface damage resistance of optical coatings in deep UV wavelength. The subsurface of the polished fused silica substrate was removed by surface treatment. Laser damage test was performed with light of wavelength of 213 and 193 nm. At the wavelength 213nm, LIDT of treated surface was improved 2.0 times as compared with that of as-polished surface. In contrast, at the wavelength of 193nm, LIDT of treated surface was increased by 2.3 times. SiO_2 and Al_2O_3 of the monolayer were coated to the fused silica substrate where a subsurface was removed by a surface treatment, respectively. Surface LIDT of optical coating was 2.0 times higher as compared with that of coated-on untreated substrate. The damage morphology and its dependence on wavelength will be discussed.

Keywords: deep UV, surface LIDT, subsurface, surface treatment, optical coatings

8885-81, Session P4

Rapid evaporation of fused silica under single infrared laser pulse exposure

Rajesh N. Raman, Norman D. Nielsen, Gabriel M. Guss, Manyalibo J. Matthews,
Lawrence Livermore National Lab. (USA)

SPEAKER BIOGRAPHY: Dr. Rajesh N. Raman received his Ph.D. in Engineering, Applied Science from the Department of Applied Science, University of California, Davis, in 2008. He is currently a researcher in the optical materials group in the Physical and Life Sciences Directorate at Lawrence Livermore National Laboratory. His research focuses on developing non-destructive methods for characterizing the state of damage and repair in optical materials. He is also interested in the characterization of the state of diseased and injured tissue for the guidance of therapy. He is a member of SPIE and the Optical Society of America.

ABSTRACT TEXT: Exposure of fused silica to infrared (IR) laser pulses at intensities beyond the evaporation threshold has been found to effectively mitigate the growth of laser-induced damage by vaporizing and removing the defective volume. A better understanding of the response of silica exposed to IR laser pulses in the evaporative regime will lead to better control of the material removal and shaping process.

An array of pits was generated in pristine silica, each by a single tunable CO_2 laser pulse with specific values of wavelength (ranging from 9.2 - 10.9 µm), peak intensity (2 - 800 kW/cm^2), and pulse duration (5-500 s). Correlation was sought between laser parameters, material response, and effect on propagated UV laser light.

In order to gauge the material response, several properties of each pit were characterized. A depth profile of the densified region was obtained as a function of the different laser pulse conditions. This information was obtained by measuring the axial dependence of the fictive temperature using confocal Raman microscopy. In addition, the morphology of the pit structure was measured with profilometry. This surface profile was assessed for possible local and far-field intensification of propagated UV laser light that could lead to damage to this or downstream optical components. Preliminary results suggest that rapid evaporation with near ~9 µm wavelength leads to finer control of the resulting pit morphology due to the shorter absorption depth in silica at this wavelength and consequent spatial localization of IR energy absorption.

This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344. [LLNL-ABS-635257]

Keywords: rapid evaporation, infrared pulsed laser, damage repair, tunable CO_2 laser, confocal Raman microscopy, field enhancement, fictive temperature, infrared absorption

Magneto-rheological fluid finishing: A tool to study and remove pre-existing defects in fused silica optics

Jérôme Néauport, Commissariat à l'Énergie Atomique (France)

The MegaJoule laser being constructed at the CEA near Bordeaux (France) is designed to focus more than 1 MJ of energy at 351 nm, on a millimeter scale target in the centre of an experiment chamber. The final optic assembly of this system operating at a wavelength of 351nm is made up of large fused silica optics, working in transmission, that are used to convey and focus the laser beam. Limited Lifetime of final optical assembly fused silica optics when submitted to high fluences (i.e. more than 5 J/cm^2 for 3 ns pulses) is a major concern for fusion scale laser facilities. Previous works have evidenced that surface finishing process used to manufacture these optical components can leave subsurface cracks (SSD), pollution or similar defects that act as initiators of the laser damage. We used the magneto-rheological fluid finishing technique (MRF) as a tool to study and remove these damage precursors since MRF enables to process optics with very small normal stresses applied to the surface during material removal. This study offers a better understanding of the nature of pre-existing defects as well as of the efficiency of MRF polishing to eliminate them.

This work is supported by the Conseil Régional d'Aquitaine and is performed in the framework of the EFESO project. We also aknowledge support from the EUROTALENT program, co-funded by CEA and the European Union in the framework of the 7th Framework Program for Research and Development (FP7)

Keywords: polishing, silica, MRF

Notes

Wednesday AM • 25 September

7:30 am to 4:00 pm Registration Material Pick-up, NIST Lobby Area

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Wed 8:20 am to 10:40 am • SESSION 9

Surfaces, Mirrors, and Contamination II

Session Chairs: **James E. Andrew,** AWE plc (United Kingdom); **Takahisa Jitsuno,** Osaka Univ. (Japan)

8:20 am: **The influence of scratches on laser-induced damage threshold of 3ω mirrors**, Hongfei Jiao, Xinbin Cheng, Ganghua Bao, Bin Ma, Pengfei He, Zhanshan Wang, Tongji Univ. (China) . . . . [8885-30]

8:40 am: **Investigation of the dynamics of material ejection in various optical materials during exit surface breakdown by ns pulses**, Stavros G. Demos, Raluca A. Negres, Rajesh N. Raman, Michael D. Feit, Alexander M. Rubenchik, Lawrence Livermore National Lab. (USA) . . . . [8885-31]

9:00 am: **Mapping of total scattering as a tool for long-term investigations in the cleaning state of the functional coated samples**, Puja Kadkhoda, Laser Zentrum Hannover e.V. (Germany) . . . . [8885-32]

9:20 am: **Removing subsurface damage by micro-jet polishing process**, Junlin Wang, Changchun Institute of Optics, Fine Mechanics and Physics (China). . . . . [8885-33]

9:40 am: **Mitigation of laser damage on NIF optics in volume production**, James A. Folta, Michael C. Nostrand, John Honig, Jen N. Wong, Frank Ravizza, Paul Geraghty, Michael G. Taranowski, Gary W. Johnson, Glenn R. Larkin, Douglas L. Ravizza, John E. Peterson, Paul J. Wegner, Lawrence Livermore National Lab. (USA) . . . . . . [8885-34]

10:00 am: **Thermal-dynamical analysis of blister formation in chirped mirror irradiated by single femtosecond lasers**, Shunli Chen, Yuanan Zhao, Yanzhi Wang, Meiping Zhu, Zhou Fang, Yuxin Leng, Xiaofeng Liu, Guohang Hu, Kui Yi, Jianda Shao, Shanghai Institute of Optics and Fine Mechanics (China) . . . . [8885-35]

10:20 am: **Study on wavefront precompensation of thermal deformation aberrations in a beam path by FEM and Zernike polynomials,** Qiong Zhou, Werguang Liu, Zongfu Jiang, National Univ. of Defense Technology (China) . . . . [8885-36]

10:40 am to 11:10 am • Coffee Break

Wednesday AM • 25 September (continued)

11:10 am to 12:50 pm • SESSION 10

Mini Symposium: To High Power Limits of Fiber Lasers

Session Chairs: **Leonid Glebov,** CREOL, The College of Optics and Photonics, Univ. of Central Florida (USA); **Jonathan W. Arenberg,** Northrop Grumman Aerospace Systems (USA)

11:10 am: **Feasibility of maximum achievable powers and energies in fiber lasers** *(Keynote Presentation)*, Valentin P. Gapontsev, IPG Photonics Corp. (USA). . . . . [8885-37]

11:40 am: **Power limits of narrow-linewidth Raman fiber lasers** *(Plenary)*, Mike Klopfer, Ravinder K. Jain, The Univ. of New Mexico (USA); Leanne J. Henry, Air Force Research Lab. (USA) . . . . [8885-38]

12:10 pm: **Time-dependent investigation of single-mode fiber output damage by 405nm CW laser light**, Cornell P. Gonschior, Technische Hochschule Mittelhessen (Germany) and City Univ. London (United Kingdom); Karl-Friedrich Klein, Technische Hochschule Mittelhessen (Germany); Tong Sun, Ken T. V. Grattan, City Univ. London (United Kingdom). . . . . [8885-39]

12:30 pm: **Theory of phase-locking of multistable fiber amplifier arrays**, Erik J. Bochove, Air Force Research Lab. (USA); Mohammad R. Zunoubi, State Univ. of New York at New Paltz (USA); Christopher J. Corcoran, Corcoran Engineering Inc. (USA) . . . . [8885-40]

12:50 pm to 2:40 pm • Lunch Break

1:45 pm to 2:40 pm · 2 tours offered • NIST Facility Tours

NIST has generously offered to provide 2 limited tours of the facility, including one of the NIST-F1 and NIST-F2 Atomic Clocks. Space is limited. Sign up onsite by 2:00 pm 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.

The influence of scratches on laser-induced damage threshold of 3ω mirrors

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

ABSTRACT TEXT: The impact of scratches on the laser damage resistance of the 3ω high reflectance mirrors was investigated. Scratches with different width were produced on the surface of fused silica substrates using a diamond tip, then the 3ω mirrors were prepared on these substrates. The dependence of laser induced damage threshold of 3ω mirrors on the scratch properties was investigated. Moreover, electric filed enhancement in the vicinity of the scratches was also simulated using finite difference time domain code. The contribution of electric filed enhancement on damage originating from scratches was also analyzed.

Keywords: laser damage, 3ω mirrors, scratches, finite difference time domain

Investigation of the dynamics of material ejection in various optical materials during exit surface breakdown by ns pulses

Stavros G. Demos, Raluca A. Negres, Rajesh N. Raman, Michael D. Feit, Alexander M. Rubenchik, Lawrence Livermore National Lab. (USA)

SPEAKER BIOGRAPHY: Stavros G. Demos is an experimental physicist and has been involved in the field of Laser Damage since he joined 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 100 journal publications and 100 conference proceedings and 20 patents in the fields of laser-defect interactions in optical and laser materials, laser damage, optical characterization/diagnostics instrumentation, and biomedical photonics.

ABSTRACT TEXT: Recent work aimed at understanding exit surface damage initiation and growth in fused silica has helped better recognize and understand the involvement of an array of interacting discrete processes involved. These include the initial electronic excitation of the material followed by plasma formation and expansion, initiation and growth of radial and circumferential cracks and a prolonged process of material ejection spanning up to about 4-20 microseconds. We hypothesize that the material ejection is governed by the properties of the host material exposed to the high pressures and temperatures involved during the initial period before the onset of material ejection (found to be on the order of about 30 ns for the case of fused silica). In this work, we explore this hypothesis by using time resolved microscopy to capture the kinetics of material ejection in an array of transparent dielectric materials. All experiments were performed by inducing laser damage (breakdown) on the exit surface of each material using laser pulses at 1064 nm having pulse durations of about 10 ns FWHM. The materials used in this study were both glass and crystalline and represent a wide range of band gap energies and mass densities (~2.7-12 eV and ~2-8 g/cm^3, respectively) .

The experimental results indicate that, in general, a jet of material clusters with diameters on the order of 1-10 μm is formed following laser-induced damage on the exit surface. Although the spectrum of sizes of the ejected particles is similar in all cases, the speed of the ejected particles appears to be strongly related to the material mass density. It is evident that the ejection of these micro-scale particles is accompanied by material evaporation and/or formation of particles of smaller spatial dimensions that cannot be individually monitored by optical microscopy. However, their presence can be detected in some cases as they can scatter, refract or absorb the strobe illumination light. The kinetics of these gaseous byproducts of laser breakdown is strongly affected by the surrounding environment due to their small size. As all of our experiments were performed in ambient environment, observation of their kinetics after the initial expansion provides an indication of the airflow following laser-induced surface damage. The experimental results suggest that the expansion phase during the initial few microseconds is followed by contraction of the region containing these byproducts which are subsequently pushed near the surface of the optic by the airflow. This effect can give rise to contamination of the surface (such as re-condensation) or divert the travel path of the slower ejected particles towards the surface.

This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344. [LLNL-ABS-635246]

Mapping of total scattering as a tool for long-term investigations in the cleaning state of the functional coated samples

Puja Kadkhoda, Laser Zentrum Hannover e.V. (Germany)

SPEAKER BIOGRAPHY: CV: P. Kadkhoda is research scientist at the department of Thin Film Technology at LZH since 1995. He received his Diploma in Physics at University of Hannover (Germany). At Laser Zentrum Hannover, P. Kadkhoda is responsible for spectral photometry, Total Scatter and ARS investigations of optical components.

ABSTRACT TEXT: In optical coating production the generation of particles and defects is always an undesirable side effect and con not be completely avoided in the handling steps of the optical components. Particles and defects on the substrates and in the functional coatings lead to scattering and absorption, which causes a lower damage threshold for components of high power laser application.

In this study, results of a long term investigation in the quality and the state of the cleanliness of multilayer systems produced by different evaporation techniques are presented. Coated samples of seven different plants are investigated with the help of a Fast Total Scatter scanning system. Adapted data reduction algorithms for determination of the particle sizes from the scattering measurements were developed and applied to the measurement results. On this basis, the density distribution of particle contamination on the samples was evaluated for selected coating runs over a long term period. The calculated statistics of the samples were related to the corresponding production processes installed in the individual coating plants to extract specific effects of the process concepts. The present study will summarize and discuss the corresponding results in the context of particle mitigation in optical coating production.

Keywords: Total Scattering, ISO 13696, surface inspection, particle density distribution

Removing subsurface damage by micro-jet polishing process

Junlin Wang, Changchun Institute of Optics, Fine Mechanics and Physics (China)

SPEAKER BIOGRAPHY: Wang Junlin,1967-,male,born in Jiangsu Province, Doctor of Engineering, now engaged in ultraprecision optical manufacturing.

ABSTRACT TEXT: The level of subsurface damage (SSD) in optical components is proportional to the surface scattering and related to the laser damage threshold. And it is always a major objective for optical fabrication to eliminate subsurface damage in polished materials. In this paper, a new superpolishing method named micro-jet polishing (MJP) is applied to remove SSD in fused silica component which is ground and polished traditionally. MJP works with nanoparticle fluid in a noncontact way. White-light interferometer (WLI) and atomic force microscope (AFM) are used to characterize the removing process. The results show that MJP removes SSD by a laminar removal behavior to the uppermost surface atoms on the surface. No new scratches were produced when the nanoparticles removed the atoms away from the surface. The flaws and defects are eliminated from the surface, The waveness and roughness decreased monotonously with the removal of subsurface damage layer, and were reduced to less than 0.12 and 0.06 nm RMS,respectively. Power spectral density(PSD) analyses have been performed to evaluate the quality of the surface. The power spectral density curves show that the surface has been well smoothed in mid-high spatial frequency range with MJP.

Keywords: micro-jet polishing , subsurface damage, noncontact, waveness, roughness, removing, AFM, WLI

Mitigation of laser damage on NIF optics in volume production

James A. Folta, Michael C. Nostrand, John Honig, Jen N. Wong, Frank Ravizza, Paul Geraghty, Michael G. Taranowski, Gary W. Johnson, Glenn R. Larkin, Douglas L. Ravizza, John E. Peterson, Paul J. Wegner,
Lawrence Livermore National Lab. (USA)

SPEAKER BIOGRAPHY: James Folta manages optics processing for the National Ignition Facility laser system at Lawrence Livermore National Laboratory. Previously he was the multilayer coating group leader for the LLNL Extreme Ultraviolet Lithography program for which his team developed sputter deposition processes to meet stringent thickness control requirements for curved EUVL optics and also ultra-low defect multilayers for the EUVL mask. He worked previously in microfabrication, thin film deposition and etching, and micro-electro-mechanical systems. He received his Ph.D. in Chemical Engineering from the University of Illinois at Urbana-Champaign. He has coauthored over 50 patents and journal and proceedings articles.

ABSTRACT TEXT: The National Ignition Facility has recently achieved the milestone of delivering over 1.8 MJ and 500 TW of 351 nm laser energy and power on target, which required average fluences of 10 J/cm^2 (3 ns equivalent) in the final optics system. Commercial fused silica laser-grade UV optics typically have a maximum operating threshold of 5 J/cm^2. We have developed an optics recycling process which enables NIF to operate above the laser damage initiation and growth thresholds. We previously reported a method to mitigate laser damage with laser ablation of damage site to leave benign cone shaped pits1. We have since developed a production facility with four mitigation systems capable of performing the mitigation protocols on full-sized (430 mm) optics in volume production. We have successfully repaired over 700 NIF optics (unique serial numbers), some of which have been recycled as many as 10 times. We describe the mitigation systems, the optics recycle loop process, and optics recycle production data.

This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344. [LLNL-ABS-635242]

1. I. L. Bass, G. M. Guss, M. J. Nostrand, P. L. Wegner, “An Improved Method of Mitigating Laser Induced Surface Damage Growth in Fused Silica Using a Rastered, Pulsed CO_2 Laser”, Proceedings of SPIE Vol. 7842, 2010

8885-35, Session 9

Thermal-dynamical analysis of blister formation in chirped mirror irradiated by single femtosecond lasers

Shunli Chen, Yuanan Zhao, Yanzhi Wang, Meiping Zhu, Zhou Fang, Yuxin Leng, Xiaofeng Liu, Guohang Hu, Kui Yi, Jianda Shao, Shanghai Institute of Optics and Fine Mechanics (China)

SPEAKER BIOGRAPHY: Yuanan Zhao received PhD degree at Shanghai Institute of Optics and Fine Mechanics(SIOM), Chinese Academy of Sciences. He is currently a Professor at SIOM. His current research interests include laser-induced damage to optics and measurement of properties of optical coatings.

ABSTRACT TEXT: In this paper, laser-induced damage behaviors of the chirped mirrors (CMs) are studied by single 800nm-38fs lasers. The CMs provide group delay dispersion (GDD) of around -50fs2 and average reflectivity of about 99.4% with bandwidth range of 200nm~300nm at a central wavelength of 800nm. Interestingly, a circular blister feature appears in the CMs at a wide range of laser fluence. Optical Microscope, Atomic Force Microscope, Scanning Electron Microscope and Surface Profiler, are applied to describe the blister characteristics. An adiabatic expansion model of ideal gas is adopted to illustrate the formation dynamics of blisters. The evolution of blisters can be explained by partial evaporation of the film and a subsequent gas expansion, driving the bulging of the film stack up to the stress limit, where the blister fractures. According to this model, the energy absorption efficiency of blisters increases monotonously with increasing laser fluence.

Keywords: chirped mirror, femtosecond laser damage, blister formation, adiabatic expansion

8885-36, Session 9

Study on wavefront pre-compensation of thermal deformation aberrations in the beam path by FEM and Zernike polynomials

Qiong Zhou, Wenguang Liu, Xiaojun Xu, Zongfu Jiang,
National Univ. of Defense Technology (China)

ABSTRACT TEXT: We present a new method to calculate wavefront pre-compensation of the thermal deformation aberrations based on the finite element method (FEM) and Zernike polynomials. The thermal deformation aberrations of a plat circular Si mirror are theoretically analyzed in detail. Model of the beam path with 4 reflective mirrors and a uniform incident laser source is established. With the above model, performances of the outgoing laser with and without wavefront pre-compensation are calculated, respectively. The results show that the Strehl ratio of the outgoing laser beam is increased from 0.13 to 0.66 with wavefront pre-compensation using the new method. The influence of Fresnel number on the ability of wavefront pre-compensation was also studied. The value of SR increases to 0.83 as the Fresnel number is 257. The ability of wavefront pre-compensation is limited when the Fresnel number is small.

8885-37, Session 10

Feasibility of maximum achievable powers and energies in fiber lasers *(Keynote Presentation)*

Valentin P. Gapontsev, IPG Photonics Corp. (USA)

ABSTRACT TEXT: Laser induced damage on the surface and in bulk of fused silica plays a major role in determining the optics lifetime in high power laser system and in the limitation of achievable maximum power and energy from lasers in conjunction with parasitic non-linear phenomena. The damage threshold of fused silica optics depends on the quality of surfaces and absorptive impurities and defects. Well known is that the surface damage threshold is smaller usually than the bulk one but in the limit it may be made equal to the bulk threshold. As previous studies have shown the bulk threshold irradiance in pure fused silica is about 470-480 GW/cm^2 for pulses with some ns duration. In this review we consider maximum power and energy feasibility of fiber lasers operating in CW and in pulsed mode operation with regards to damage thresholds, non-linear effects and heat dissipation. Comparison of fiber lasers with DPSS and other lasers will be given with the advantages of the full fiber format laser technology by minimizing of the number of open surfaces, usage of special beam expanding techniques and improved surface quality by polishing and coating as has been accepted at IPG Photonics.

Keywords: Fiber optics amplifiers , Fiber optics oscillators, Fiber lasers, fibers

Power limits of narrow-linewidth Raman fiber lasers

Mike Klopfer, Ravinder K. Jain, The Univ. of New Mexico (USA);
Leanne J. Henry, Air Force Research Lab. (USA)

ABSTRACT TEXT: High power narrow linewidth (NLW) lasers are needed for numerous applications, such as for creating synthetic “sodium guidestar” 589 nm beacons for adaptive optic compensation of aberrations caused by atmospheric turbulence[1], and for the production of singlet oxygen for photodynamic therapy via NLW 1270 nm laser excitation[2, 3]. The feasibility of generating high cw laser powers at nearly arbitrary wavelengths via stimulated Raman scattering in fibers[4 - 7] has made fiber Raman amplifiers and lasers valuable sources for many applications at which NLW atomic, ionic, or molecular transitions are not readily achievable. In particular, the <3 GHz sodium 589 nm beacon[1] is readily achievable by second harmonic generation (SHG) of high-power 1178 nm radiation[8-10] obtained from suitably-designed fiber Raman amplifiers (FRAs) or fiber Raman lasers (FRLs). Even though the sodium guidestar application itself only needs laser linewidths of the order of 3 GHz, phase matching requirements of optimally-designed SHG crystals may necessitate generation of linewidths as small as 30 MHz at the 1178 nm fundamental wavelength [8,9], resulting in a major constraint in the design and implementation of optimized 1178 nm laser sources.

The FRL design[10] described here is limited by the power handling capability of the fiber Bragg gratings (FBGs) on the ends of the Raman oscillator as well as the power rating of the tapered fiber bundle (TFB) used to pump the ytterbium fiber amplifier (YFA). The alternative FRA design[8] must be pumped by a laser at 1120 nm which also requires FBGs and a TFB for pumping the laser. Thus we will investigate the power limits of FBGs and TFBs although our literature search has located limited research on this topic[15].

This paper will discuss theoretical and experimental results on the power limits of the FRL design considering variations in cavity length, FBG bandwidth, cavity dispersion, the nonlinear processes of SBS, SRS, FWM, SPM, XPM and the damage limits of FBGs and TFBs. We will use a generalized nonlinear Schrodinger equation (GNLSE) to model FRL spectral broadening[11, 12]; our theoretical model will also incorporate the role of the birefringence of the PM fibers[13, 14] used in our experiments. The effect of the length of the Raman gain fiber and the bandwidth of the FBG reflectors will also be analyzed, since the cavity length affects the nonlinear interaction as well as the spacing between longitudinal modes. We will compare the results of this analysis to detailed experimental data that will be taken between the date of this summary submission and the date of the presentation.

We will also consider the use of acoustically-tailored fiber designs[16] and multiple temperature zones (or external longitudinally-distributed stress zones) in the 1121 nm Raman gain fiber to broaden the SBS linewidth and thereby increase the SBS generation threshold, especially in the high power stage, while maintaining the intracavity power below the damage limit of the FBGs — 300 W and 1000 W respectively — in the two stages.

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Keywords: high power fiber lasers, fiber Raman lasers, damage thresholds of FBGs, damage thresholds of tapered fiber bundles, nonlinear conversion problems in high power fiber lasers, SBS and FWM in optical fibers, SRS in optical fibers

Time-dependent investigation of single-mode fiber output damage by 405nm CW laser light

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

ABSTRACT TEXT: In the past, the output power degradation of 405 nm fiber-coupled diode laser systems was investigated in detail with focus on the input end. No photo-degradation or contamination absorbed or attenuated the laser light at this wavelength. The coupling and transmission loss of the laser light was associated to the growth of a periodic structure on the input surface. To reduce this damage, which is related to the power density, a short launch-fiber with a good surface quality was used on the input end surface. Thereby the power transmission was stabilized for at least one month. However, damage structures appeared on the output surface of the single-mode fiber. To investigate this effect, damaged samples were taken after different periods of time for comparison at the same power density. The samples were examined with a scanning electron microscope (SEM) and bulges with a submicron periodic structure were found in the core region. The influence of the bulge and its structure on the beam quality were investigated and compared to simulation results. Additionally, measurements of spectral loss were performed, showing the formation of color centers in the deep UV along the length of the fiber.

Keywords: fiber damage, surface damage, periodic surface structures, UV defects, single-mode laser, single-mode fiber

Theory of phase-locking of multistable fiber amplifier arrays

Erik J. Bochove, Air Force Research Lab. (USA);
Mohammad R. Zunoubi, State Univ. of New York at New Paltz (USA);
Christopher J. Corcoran, Corcoran Engineering Inc. (USA)

ABSTRACT TEXT: We present the analytical solution of time-independent differential propagation equations for an array of externally coupled fiber amplifiers with internal reflection (regeneration), saturable gain and Kerr and resonant nonlinearities, in the form of a single transcendental equation for each amplifier. The multiple solutions of that equation are then used to determine the gain and phasing properties of large arrays using numerical tools, and the relative contribution of the two types of nonlinearity (Kerr and resonant) are compared. Numerical/analytical results for global coupling, self-Fourier and diffractive cavities are also presented. Additionally, the results of a first-order approximation of the time-dependent stability analysis will be presented. Finally, we will discuss our early computational efforts for studying the space-time dynamics of the passively- phased fiber laser arrays.

*Supported by the AFOSR (Dr. Arje Nachman)

Notes

2:40 pm to 4:20 pm • SESSION 11

Fundamental Mechanisms I

Session Chairs: **Jérôme Néauport,**
Commissariat à l'Énergie Atomique (France);
Gregory J. Exarhos, Pacific Northwest National Lab. (USA)

2:40 pm: **Laser damage in dielectric films: What we know and what we don't** *(Plenary)*, Wolfgang Rudolph, Luke A. Emmert, The Univ. of New Mexico (USA); Carmen S. Menoni, Dinesh Patel, Colorado State Univ. (USA) . . . . [8885-41]

3:20 pm: **General model for nanosecond-laser induced damage in KTP**, Frank R. Wagner, Aix-Marseille Univ. (France); Guillaume Duchateau, Univ. Bordeaux 1 (France); Jean-Yves Natoli, Mireille Commandré, Aix-Marseille Univ. (France) . . . . [8885-42]

3:40 pm: **Understanding of the physics and material dynamics of multipulse femtosecond laser interactions with surfaces**, Troy Anderson, Craig Zuhlke, Chris Wilson, Corey Kruse, Sidy Ndao, George Gogos, Dennis R. Alexander, Univ. of Nebraska-Lincoln (USA). . . . . [8885-43]

4:00 pm: **Two different growth mechanisms of laser-induced damage in fused silica optics with nanosecond pulses at 355nm**, Chunhong Li, Xin Ju, Univ. of Science and Technology Beijing (China); Yingao Ma, Shanghai Jiaguang Optics Group (China) . . . . [8885-44]

4:20 pm to 4:50 pm • Coffee Break

4:50 pm to 6:30 pm • SESSION 12

Surfaces, Mirrors, and Contamination Fundamental Mechanisms II

Session Chairs: **Vitaly E. Gruzdev,**
Univ. of Missouri-Columbia (USA); **Joseph A. Menapace,** Lawrence Livermore National Lab. (USA)

4:50 pm: **Application of time-resolved digital holographic microscopy to study femtosecond damage process in thin films**, Nerijus Siaulys, Andrius Melninkaitis, Vilnius Univ. (Lithuania); Laurent Gallais-During, Institut Fresnel (France). [8885-45]

5:10 pm: **Investigating high-damage mechanisms and precursor properties in fused silica**, Nan Shen, Jeffrey D. Bude, Lawrence Livermore National Lab. (USA) . . . . . . [8885-46]

5:30 pm: **Plasma dynamics during bulk damage of borosilicate glass generated by 1.064 micron nanosecond laser pulses**, Binh T. Do, Ball Aerospace & Technologies Corp. (USA); Mark W. Kimmel, Sandia National Labs. (USA); Arlee V. Smith, AS-Photonics, LLC (USA); Michael V. Pack, Sandia National Labs. (USA); Stavros G. Demos, Lawrence Livermore National Lab. (USA) . . . . [8885-47]

5:50 pm: **Interaction of laser pulse with confined plasma during exit surface ns laser damage**, Michael D. Feit, Alexander M. Rubenchik, Stavros G. Demos, Lawrence Livermore National Lab. (USA) . . . . [8885-48]

6:10 pm: **Thermal kinetics of annealed optical damage**, Rajesh N. Raman, Christopher W. Carr, Selim Elhadj, Manyalibo J. Matthews, Lawrence Livermore National Lab. (USA) . . . . [8885-49]

6:30 pm to 6:40 pm • Closing Remarks

8885-41, Session 11

Laser damage in dielectric films: What we know and what we don’t

Wolfgang Rudolph, Luke A. Emmert, The Univ. of New Mexico (USA);
Carmen S. Menoni, Dinesh Patel, Colorado State Univ. (USA)

ABSTRACT TEXT: Damage mechanisms in thin films are reviewed from femtosecond pulse to CW laser illumination. Special emphasis is given to the role of native and laser induced defects, recent successes and the need for better diagnostic tools.

Keywords: laser-induced damage, dielectric thin films

General model for nanosecond-laser induced damage in KTP

Frank R. Wagner, Aix-Marseille Univ. (France); Guillaume Duchateau, Univ. Bordeaux 1 (France); **Jean-Yves Natoli, Mireille Commandré,** Aix-Marseille Univ. (France)

ABSTRACT TEXT: Most studies on nanosecond laser induced damage in nonlinear optical materials varied only a few parameters. A fact that inhibits the development of a general laser damage model.

We studied laser induced damage in the bulk of potassium titanyl phosphate (KTP, KTiOPO4) and rubidium titanyl phosphate (RTP, RbTiOPO4) after irradiation with a small number of intense nanosecond, longitudinal multi mode laser pulses. A large variety of effects has been observed on the basis of which we were able to develop a physical model for laser induced damage in the used conditions.

The model we propose comprises two subsequent steps both appearing during the pulse length of 6 ns. In a first step, unstable color centers are created by multi-photon absorption. This step is more efficiently triggered by 532 nm photons. In a second step, conduction band electrons that are injected by the color centers are heated by electron-photon-phonon interaction. This step is more efficiently triggered by 1064 nm photons.

This model explains, at least qualitatively, all observations: The strong cooperatives between 532 nm and 1064 nm pulses, the polarization dependent anisotropy, the independence of the laser damage data with respect to crystal quality variations and the observed fatigue behavior.

Keywords: Laser damage, model, KTiOPO4, RbTiOPO4, nanosecond lasers, KTP, RTP

Understanding of the physics and material dynamics of multipulse femtosecond laser interactions with surfaces

Troy Anderson, Craig Zuhlke, Chris Wilson, Corey Kruse, Sidy Ndao, George Gogos, Dennis R. Alexander, Univ. of Nebraska-Lincoln (USA)

SPEAKER BIOGRAPHY: Dr. Anderson has extensive experienced in femtosecond laser processing and pump probe spectroscopy. Dr. Anderson earned his Masters and doctoral degrees in Optics at the Center for Research and Education in Optics and Lasers (CREOL) at the University of Central Florida in the field of femtosecond laser materials interaction. His dissertation focused on the unique physics associated with the interaction of femtosecond laser pulses with various materials. . He has worked for years with the practical aspects of laser machining and is well-versed in the optical and mechanical considerations including beam delivery and programming computer-controlled three-dimensional translation stages. After graduation, Dr. Anderson has continued his work in the field of femtosecond laser interaction physics and material modifications using femtosecond lasers at the University of Nebraska – Lincoln.

ABSTRACT TEXT: Although the interaction of high power femtosecond laser with various materials have been studied for years, the physics and understanding of the formation of surface structures as a result of these interactions has been limited to mostly semiconductor materials. In this paper, we present the detailed interactions of 800 nm femtosecond pulses with a pulse length of 50 fs with a nickel surface as a function of both laser fluence and shot number. We present a detailed parameter study on a grid plot of laser fluence versus shot number that demonstrates the isolated impact of each of these parameters. These plots are then used to identify regions of where various structures are forming. For example, at low fluence and high shot numbers (2,000-20,000 pulses at ~0.2 J/cm^2) the characteristic laser induced periodic structures (LIPPS) form along with pyramid-shaped structures. On the other extreme of high fluence (2.5 J/cm^2) and 1000 pulses the surface modifications are dominated by spikes and deep pits.

A shot-by-shot analysis of the femtosecond laser pulse interactions with two select fluence values chosen from the parameter study is presented using high resolution scanning electron microscope (SEM) still images spliced together to make stop-motion movies of the interaction dynamics and subsequent surface modification. These high resolution SEM movies provide a powerful and novel means to observe the material flow dynamics (surface structuring) as a function of pulse number. The formation of self-organized micro- and nano-structured surfaces on nickel via both above surface growth (ASG) and below surface growth (BSG) mechanisms using femtosecond laser pulse illumination are reported. The stepped growth experiments demonstrate that conical mound-shaped surface structure development is characterized by a balance of growth mechanisms including scattering from surface structures and geometric effects causing preferential ablation of the valleys, flow of the surface melt, and redeposition of ablated material; all of which are influenced by the laser fluence and the number of laser shots on the sample. BSG-mound formation is dominated by scattering, while ASG-mound formation is dominated by material flow and redeposition. The impact of the different formation mechanisms is confirmed through a TEM/EDX analysis of cross-sections of the structures. This is the first demonstration to our knowledge of the use of femtosecond laser pulses to fabricate metallic surface structures that rise above the original surface. These results are useful in understanding the details of multipulse femtosecond laser interaction with metals. Any modeling of multipulse laser interaction must incorporate the developing complex surface features and the corresponding electromagnetic field interactions.

The application of multiscale surface structures fabricated through femtosecond laser surface processing to both heat transfer and electrolysis is also briefly described. We have demonstrated the ability to control surface wetting from superhydrophilic to superhydrophobic through tailored multiscale surfaces. For example, we have utilized pyramid structures in stainless steel formed at a low fluence and high shot number to increase the Leidenfrost temperature (the temperature corresponding to the transition from nucleate to film boiling) by 175 degrees, which significantly expands the operating range of efficient heat transfer.

Keywords: Femtosecond laser surface processing, Physics of multipulse laser-matter interaction, Micro/nanostructured surfaces, Superhydrophobic/Superhydrophilic materials

Two different growth mechanisms of laser-induced damage in fused silica optics with nanosecond pulses at 355nm

Chunhong Li, Xin Ju, Univ. of Science and Technology Beijing (China);
Yingao Ma, Shanghai Jiaguang Optics Group (China)

SPEAKER BIOGRAPHY: Dr. C. H. Li gets his doctor's degree in physics from Univ of Sci & Tech Beijing in 2011. His research interest focuses on laser-induced damage mechanism in key optics such as fused silica lens and KDP/DKDP crystals.

ABSTRACT TEXT: Growth mechanism of laser-induced damage in fused silica optics is of very important meaning for lifetime predicting model and mitigation and repair techniques of large size optics (430 mm x 430 mm).

Statistically, at least three kinds of damage growth rules were discovered, such as exponential growth, linear growth and static growth. However, the underlying physical mechanism of morphology growth is not clear. Does it rely on laser fluence, shots, or frequency? Does it rely on micro-scale structural characteristics of the initial damage? We designed experimental work to answer these questions. Pulsed Nd-YAG laser was employed at ambient conditions. The wavelength, pulse length were 355 nm and 6.8 ns, respectively. The examined fluence ranged from 0 to 10 J/cm^2 and the examined frequency was 1/5/10 Hz.

Based on the high resolution synchrotron based X-ray CT technique, we obtained the panoramic 3-D visualization of damage scenario from micron scale to millimeter scale. By virtue of SEM methods, the fine structure of the LID induced by laser pulses with various parameters was acquired. Two different growth mechanisms of LID were identified. Under low fluence (<4 J/cm^2) laser irradiation, the damage growth was governed by energy absorption, melting, ablation and spalling. While, rarefaction wave transportation controlled the damage growth under high fluence irradiation. Based on these analyses, we tried to build the understanding of damage growth rules and to guide the repair process of large size optics.

Keywords: Laser-induced damage, Fused silica, Growth mechanism, Fine structure

Application of time-resolved digital holographic microscopy to study femtosecond damage process in thin films

Nerijus Siaulys, Andrius Melninkaitis, Vilnius Univ. (Lithuania);
Laurent Gallais-During, Institut Fresnel (France)

SPEAKER BIOGRAPHY: Nerijus Siaulys received his Bachelor degree of Physics from the Vilnius University in 2012. His Bachelor Degree Thesis "Propagation of Femtosecond Laser Pulses in GaN Film: Investigation of Optical Response by Time Resolved Digital Holography" was awarded a scholarship from Dr. Remis Gaska and Sensor Electronic Technology, INC. Now he continues his Master's degree studies at Vilnius University in Lithuania and holds position as a Research assistant in Laser Research Center (VULRC).

ABSTRACT TEXT: The damage of dielectric materials induced with ultra-short laser pulses having durations from femtoseconds up to several tens of picoseconds is the result of electronic processes. Free electrons are generated during the laser pulse up to a level of critical density. At this point dielectric material develops a metal-like behavior and possesses strong linear absorption of the laser energy: a runaway process can take place leading to the thermal and mechanical damage.

The understanding and characterization of these effects was the objective of this work. While seeking to investigate the fundamental aspects of the femtosecond laser irradiation and optical coating interaction we performed series of time-resolved optical observations by employing time-resolved digital holographic microscopy. Early evolution of femtosecond laser damage initiation was directly observed in single layer dielectric Ta_2O_5 thin films of different thicknesses. The transient processes induced with fluence levels slightly above the damage threshold by femtosecond pump (1030nm/300fs) were captured in transmission mode with visible pulses of 25 fs duration. Laser-induced free-electron gas generation and plasma dynamics were captured during the pump pulse propagation as well as the early material modification dynamics was recorded after the laser exposure. The fundamental time constants and values that drive the damage processes were extracted by changing the time delay between the pump and probe pulses. Based on these results, the amplitude and phase measurements are traced back to the permittivity and hence electronic density in the films.

Keywords: time-resolved digital holographic microscopy , femtosecond damage process, Ta_2O_5 films, early evolution of femtosecond laser damage, single layer dielectric thin films

8885-46, Session 12

Investigating high-damage mechanisms and precursor properties in fused silica

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SPEAKER BIOGRAPHY: Nan Shen received her Ph.D. in physics studying the interaction of ultrafast laser pulses with transparent materials. She joined the Lawrence Livermore National Laboratory in 2003 and investigated cellular response and organelle functions using ultrafast laser light. She continues to work on understanding the physics behind laser induced damage in optics. She is currently a member of the Target Systems Optics Technology Group at the National Ignition Facility, and focuses her works on identifying damage precursors in fused silica optics and developing mitigation strategies.

ABSTRACT TEXT: The damage performance of fused silica laser optics has been improving steadily over the years. However, surface damage still occurs at a fluence well below the fused silica band gap (~9 eV). A model of laser damage initiation has been proposed. As the high fluenceprecursors in silica absorb the laser energy, the temperature of the surrounding glass also elevates. The bulk silica material becomes absorbing and a temperature-activated, laser-driven solid-state absorption wavefront propagates back toward the laser (thermal run-away), superheating a micron-sized region to temperatures which result in explosive material ejection. However, a more comprehensive picture of this complex physical process is still being investigated. For example, it is unclear what temperature the precursor needs to reach in order to launch the absorption front and start damage initiation.

In order to better understand the high-damage initiation in SiO_2, it is important to isolate the strongly coupled absorptions from precursor and glass. In our study, we deposit thin films of absorbers (e.g. Au, Al and Si) as artificial damage precursors on fused silica substrate, then damage test and characterize the sample. With the optical and thermal properties of these precursors known, we can control the temperature of the absorbing layer and probe the temperature activated absorption in glass as a function of laser parameters. Ab-initio simulations of the temperature activated absorption are performed and compared with experimental results. This engineered precursor system also allows us to identify key characteristics of high fluenceprecursors on real fused silica optics for damage initiation such as size, absorption coefficient, adhesion strength and thermal diffusion and expansion properties.

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Keywords: high-damage precursors, fused silica, absorption front, Al film

8885-47, Session 12

Plasma dynamics during bulk damage of borosilicate glass generated by 1.064 micron nanosecond laser pulses

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SPEAKER BIOGRAPHY: Binh Do is a test engineer of Ball Aerospace Technologies Corporation.

ABSTRACT TEXT: We investigate the dynamics of the plasma formed during the damage process in the bulk of borosilicate glass by a 1.064 micron nanosecond laser pulse. The temporal behavior of the transmitted and reflected pump beam provides direct information on the dynamics of the forming plasma and also on the interaction of the laser pulse with this plasma. This information reveals the important role of this interaction in the damage process.

Damage initiation was induced in the material using a single-longitudinal-mode, TEM_{00} spatial mode, 8-ns pulsed laser at 1.064 micron. The laser beam was tightly focused into the bulk of a borosilicate glass window to avoid secondary effects associated with the generation of stimulated Brillouin scattering and also to better confine the generation of the plasma. We collected the temporal and spatial profile of the pump beam reflected by the overcritical plasma, and also collected and compared the transmitted pump beam through a close and open aperture. These experimental results provide information on the dynamics of plasma generation and expansion at the focal region. We found that the refractive index of the focus spot undergoes an anomalous dispersion as the electron gas at the focus transitions from sub-critical to over-critical density.

From the experimental results, we were able to calculate the spatial profile of the reflected beam at its origin; this information indicates the size of the overcritical plasma region. The temporal profile of the pump beam reflected by the plasma shows that the plasma survives until the end of the laser pulse and the physical damage in the material, such as cracks were formed in borosilicate glass after the laser pulse ceased.

Keywords: Laser-induce damage, Borosilicate glass, Plasma dynamics, over-critical plasma, sub-critical plasma

8885-48, Session 12

Interaction of laser pulse with confined plasma during exit surface ns laser damage

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SPEAKER BIOGRAPHY: Michael D. Feit is a theoretical physicist at Lawrence Livermore National Laboratory where he has served on the scientific staff for 40 years. He is a Fellow of the American Physical Society and of the Optical Society of America. With more than 200 publications, his research interests include laser material interactions, optic fabrication and optical propagation.

ABSTRACT TEXT: Interpretation of spatial and time resolved images of rear surface ns laser damage in dielectrics requires understanding of the dynamic interaction of the incoming laser beam with the confined expanding plasma in the material. The detailed kinetics of the plasma, involving both expansion and retraction, depends on details of reflection and absorption in the hot material. The growth of the high temperature and pressure region as a result of energy deposition depends on the density and speed of sound of the solid as well as the incoming laser intensity. In particular, the measurement of particle ejection velocities provides important information about the pressure internal to the solid.

We calculate the reflection of laser light from the evolving plasma, which depends on conduction band electron density and scattering time, in order to show that the experimentally observed slow down in growth of depth of plasma is not due to reflection of laser light. We propose that this behavior arises for hydrodynamic effects related to the elastic and plastic deformation of the surrounding cold material. The growth of the hot region is treated using a model previously developed to understand laser peening. The pressure is found to scale as the square root of laser intensity and drops off slowly after energy deposition is complete. For example, for the conditions of our experimental observations in fused silica, our model predicts a pressure of about 9 GPA and a surface expansion velocity of 1.5 km/sec, in good agreement with experimental observation.

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Thermal kinetics of annealed optical damage

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SPEAKER BIOGRAPHY: Dr. Rajesh N. Raman received his Ph.D. in Engineering, Applied Science from the Department of Applied Science, University of California, Davis, in 2008. He is currently a researcher in the optical materials group in the Physical and Life Sciences Directorate at Lawrence Livermore National Laboratory. His research focuses on developing non-destructive methods for characterizing the state of damage and repair in optical materials. He is also interested in the characterization of the state of diseased and injured tissue for the guidance of therapy. He is a member of SPIE and the Optical Society of America.

ABSTRACT TEXT: Previous work has demonstrated that thermal annealing of optical damage arrests growth upon exposure to subsequent laser pulses and significantly increases the threshold fluence at which damage re-occurs. This result suggests that the laser-induced flaws and defects generated in silica can be thermally relaxed. Historically, optical damage growth and thermally-driven repair have been characterized in terms of the morphological response of the material to local laser energy deposition (e.g., the crater, cracks, and cleaved surfaces which remain). However, fused silica undergoes complex micro-structural changes upon laser-induced damage growth and repair which are not well-understood. Uncovering the evolution of this micro-structure during healing would provide better insight into the mechanisms governing the kinetics of damage growth and repair on the molecular level.

Several mechanisms have been hypothesized to contribute to damage growth: 1) Intensification of the optical field by means of interference from multiple reflections off of cracks, 2) absorption of the optical energy by sub-bandgap defect states, 3) thermal stresses generated by local boiling and thermal expansion, and 4) mechanical failure once the brittle fracture limit is exceeded.

Our objective in this study is to determine which of these mechanisms are responsible for the observed enhancement in damage fluence threshold by probing the evolution of the silica micro-structure as a function of thermal treatment. Damage sites on the exit surface of silica were annealed by either infrared laser exposure or isothermal oven treatment over a range of temperatures and hold times in order to probe the kinetics of silica response ex situ. In particular, the micro-structure was probed with photoluminescence micro-spectroscopy to monitor kinetics of electronic defect healing and FTIR reflectance spectroscopy to monitor kinetics of molecular structural defect healing. Damage site morphology was recorded using back-illuminated and edge-illuminated microscopy. Damage testing revealed an exponential dependence of the fluence threshold with temperature and a power-law dependence with time. Damage testing above the threshold revealed that the anneal significantly reduced the growth rate of damage sites. A model for the damage fluence threshold was developed based on energy absorption, critical fracture, and crack tip blunting which agrees well with the experimental results.

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Keywords: thermal anneal, IR laser anneal, silica microstructure, kinetics of damage growth, kinetics of damage repair, photoluminescence, FTIR reflectance, damage fluence threshold

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