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Technical Abstracts

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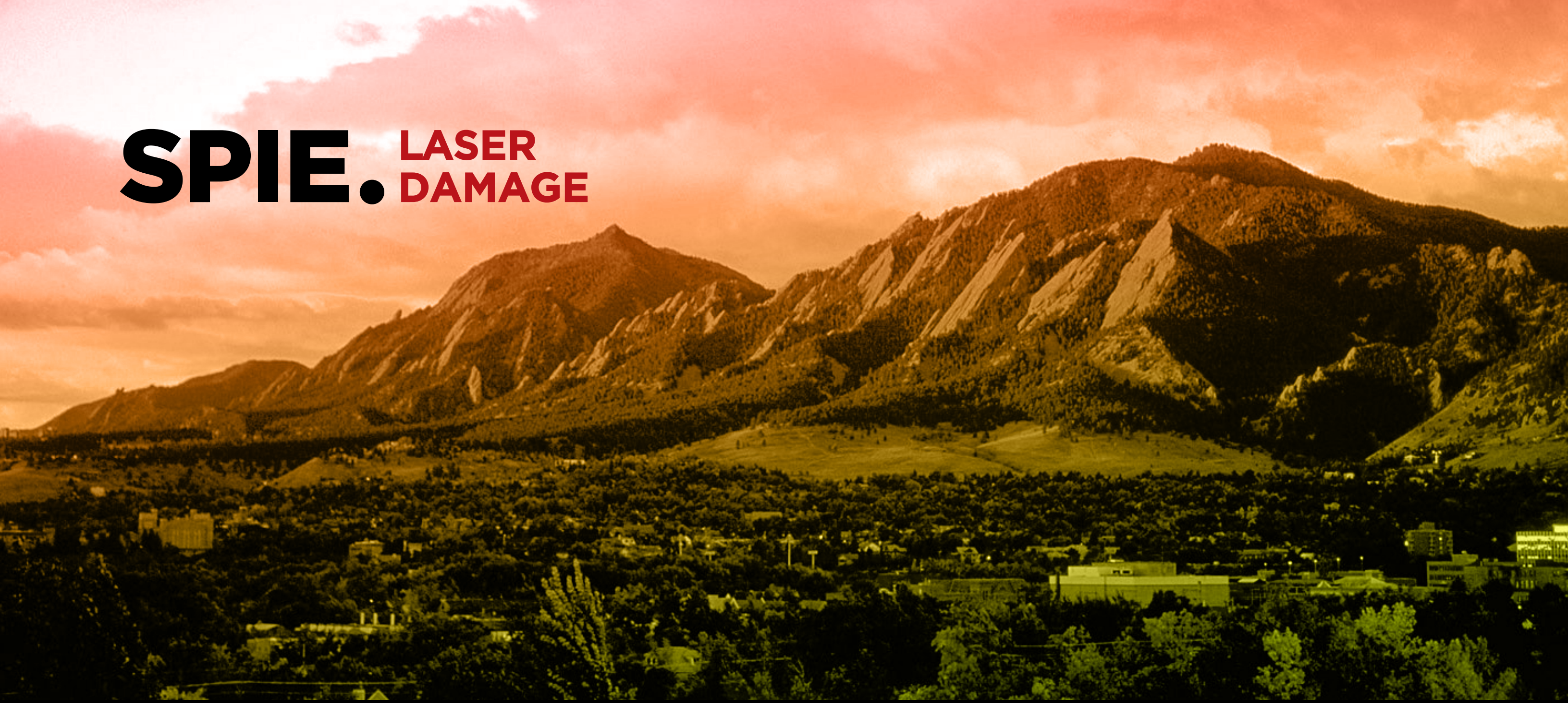
XLVII ANNUAL SYMPOSIUM ON OPTICAL MATERIALS FOR HIGH-POWER LASERS

National Institute of Standards and Technology
Boulder, Colorado, USA

Conference:
27–30 September 2015



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XLVII ANNUAL SYMPOSIUM ON OPTICAL MATERIALS FOR HIGH-POWER LASERS

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Joseph A. Menapace
Lawrence Livermore National Lab. (USA)

Detlev Ristau
Laser Zentrum Hannover e.V. (Germany)

MJ Soileau
Univ. of Central Florida (USA)

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XLVII ANNUAL SYMPOSIUM ON OPTICAL MATERIALS FOR HIGH-POWER LASERS

SPECIAL EVENTS

SUNDAY 27 SEPTEMBER

5:30 TO 8:30 PM

REGISTRATION MATERIAL PICK-UP AND MIXER AT THE BOULDER MARRIOTT

(2660 Canyon Blvd., Boulder)
Location: Montrachet Room (1st Floor)

NIST Security Badges will be available for attendees with a passport or photo ID.

6:00 TO 7:00 PM

TUTORIAL: DEFECT-INDUCED DAMAGE IN NANO- AND FEMTOSECOND REGIME

LOCATION: MONTRACHET ROOM (1ST FLOOR)

Chaired by: **Dr. Laurent Gallais,** Institut Fresnel (France)

This tutorial is focused on the fundamental effects and basic physics of laser-defect interactions with nanosecond and femtosecond laser pulses. It also will include statistical effects in laser-damage-threshold metrology, and implications of defects (including artificial ones) for applications.

7:00 TO 8:30 PM

WELCOME AND SOCIAL MIXER AT THE BOULDER MARRIOTT

LOCATION: MONTRACHET ROOM (1ST FLOOR)

Join your colleagues for light refreshments, appetizers, and mingling.

MONDAY 28 SEPTEMBER

6:30 TO 8:00 PM

OPEN HOUSE AND RECEPTION

TUESDAY 29 SEPTEMBER

6:30 TO 8:00 PM

WINE AND CHEESE TASTING RECEPTION AT NCAR

WEDNESDAY 30 SEPTEMBER

12:40 TO 1:40 PM

NIST FACILITY TOURS

DAILY EVENT SCHEDULE

SUNDAY **27 September**	**MONDAY** **28 September**	**TUESDAY** **29 September**	**WEDNESDAY** **30 September**
SPIE LASER DAMAGE 2015			
Sunday events held at: **BOULDER MARRIOTT*** Montrachet Room (1st floor)	**Monday to Wednesday events held at:** **NIST, Building 1 (Radio Bldg.)**		
REGISTRATION **MATERIAL PICK-UP,** 5:30 pm to 8:30 pm	**REGISTRATION** **MATERIAL PICK-UP,** 7:30 am to 4:00 pm	**REGISTRATION** **MATERIAL PICK-UP,** 7:30 am to 4:00 pm	**REGISTRATION** **MATERIAL PICK-UP,** 7:30 am to 3:00 pm
TUTORIAL **Defect-Induced Damage in Nano- and Femtosecond Regime** (Chaired by: Dr. Laurent Gallais), 6:00 to 7:00 pm	**Poster Placement at NIST,** 7:50 am to 8:30 am	**Poster Placement at NIST,** 7:50 am to 8:30 am	
Welcome and Social Mixer 7:00 to 8:30 pm *Registration Material Pick-up continues until 8:30 pm*	**Opening Remarks and 2014 Award Presentations** 8:30 to 9:00 am **Best Oral Presentation and Best Poster Presentation**	**SESSION 5** **Surfaces, Mirrors, and Contamination II,** 8:30 to 10:10 am	**SESSION 9** **Fundamental Mechanisms III,** 8:30 to 10:30 am
	SESSION 1 **Thin Films I,** 9:00 to 10:00 am		
	Monday Poster Overview, 10:00 am to 10:40 am	**Tuesday Poster Overview,** 10:10 to 10:40 am	**SESSION 10** **Materials and Measurements I,** 11:00 am to 12:40 pm
	Poster Viewing and Refreshment Break, 10:40 am to 11:40 am	**Poster Viewing and Refreshment Break,** 10:40 to 11:40 am	
	SESSION 2 **Thin Films II**, 11:40 am to 1:00 pm	**SESSION 6** **Mini Symposium: Laser-Induced Damage to Multilayers in Femtosecond Regime,** 11:40 am to 1:10 pm	
	Lunch Break 1:00 to 2:20 pm	**Lunch Break** 1:10 to 2:30 pm	**Lunch Break and NIST Tours** 12:40 pm to 2:30 pm **NIST FACILITY TOURS** (Two Tours Offered), 12:40 to 1:40 pm
	SESSION 3 **Thin Films III**, 2:20 to 4:00 pm	**SESSION 7** **Fundamental Mechanisms I,** 2:30 to 4:10 pm	**SESSION 11** **Materials and Measurements II,** 2:30 to 4:30 pm
	Poster Viewing and Refreshment Break, 4:00 pm to 4:50 pm	**Poster Viewing and Refreshment Break,** 4:10 pm to 5:00 pm	**Closing Remarks,** 4:10 to 4:20 pm
	SESSION 4 **Surfaces, Mirrors, and Contamination I,** 4:50 to 5:50 pm	**SESSION 8** **Fundamental Mechanisms II,** 5:00 to 6:00 pm	
	Closing Remarks, 5:50 to 6:00 pm	**Closing Remarks,** 6:00 to 6:10 pm	
	OPEN HOUSE AND RECEPTION, 6:30 to 8:00 pm	**WINE AND CHEESE TASTING RECEPTION,** 6:30 to 8:00 pm	


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CONFERENCE 9632

Sunday–Wednesday 27–30 September 2015 • Proceedings of SPIE Vol. 9632

Laser-Induced Damage in Optical Materials: 2015

Conference Chairs: **Gregory J. Exarhos,** Pacific Northwest National Lab. (United States); **Vitaly E. Gruzdev,** Univ. of Missouri-Columbia (United States); **Joseph A. Menapace,** Lawrence Livermore National Lab. (United States); **Detlev Ristau,** Laser Zentrum Hannover e.V. (Germany); **MJ Soileau,** Univ. of Central Florida Office of Research & Commercialization (United States)

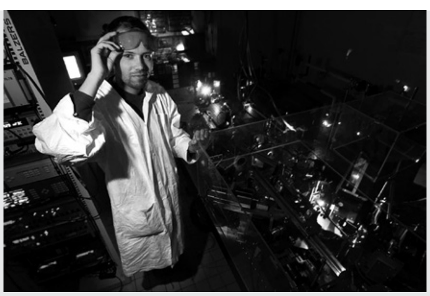
Program Committee: **Detlev Ristau,** Laser Zentrum Hannover e.V. (Committee Chair) (Germany); **James E. Andrew,** AWE plc (United Kingdom); **Jonathan W. Arenberg,** Northrop Grumman Aerospace Systems (United States); **Mireille Commandré,** Institut Fresnel (France); **Stavros G. Demos,** Lawrence Livermore National Lab. (United States); **Leonid B. Glebov,** CREOL, The College of Optics and Photonics, Univ. of Central Florida (United States); **Takahisa Jitsuno,** Osaka Univ. (Japan); **Klaus Mann,** Laser-Lab. Göttingen e.V. (Germany); **Carmen S. Menoni,** Colorado State Univ. (United States); **Masataka Murahara,** Tokai Univ. (Japan); **Jérôme Néauport,** Commissariat à l'Énergie Atomique (France); **Semyon Papernov,** Univ. of Rochester (United States); **Wolfgang Rudolph,** The Univ. of New Mexico (United States); **Jianda Shao,** Shanghai Institute of Optics and Fine Mechanics (China); **Michelle D. Shinn,** Thomas Jefferson National Accelerator Facility (United States); **Christopher J. Stolz,** Lawrence Livermore National Lab. (United States)

SUNDAY 27 SEPTEMBER

SUNDAY EVENTS
Boulder Marriott,
2660 Canyon Blvd., Boulder, Colorado

REGISTRATION MATERIAL PICK-UP

LOCATION: THE BOULDER MARRIOTT, MONTRACHET ROOM (1ST FLOOR) . . . . . . 5:30 PM TO 8:30 PM



TUTORIAL ON

Defect-Induced Damage in Nano- and Femtosecond Regime

LOCATION: THE BOULDER MARRIOTT, MONTRACHET ROOM (1ST FLOOR)
6:00 PM TO 7:00 PM

Moderator: **Dr. Laurent Gallais**, Institut Fresnel (France)

This tutorial is focused on the fundamental effects and basic physics of laser-defect interactions with nanosecond and femtosecond laser pulses. It also will include statistical effects in laser-damage-threshold metrology, and implications of defects (including artificial ones) for applications.

WELCOME AND SOCIAL MIXER

LOCATION: THE BOULDER MARRIOTT, MONTRACHET ROOM (1ST FLOOR) . . . . . . 7:00 PM TO 8:30 PM

Registration Material Pick-up continues until 8:30 pm.

MONDAY 28 SEPTEMBER

CONFERENCE LOCATION
NIST, Building 1 (Radio Bldg.),
324 Broadway, Boulder, Colorado

REGISTRATION MATERIAL PICK-UP

LOCATION: NIST LOBBY AREA . . . . 7:30 AM TO 4:00 PM

Attendees must check in with NIST Security at entrance and have photo identification available. Please allow 15 minutes for extra time on Monday morning.

POSTER PLACEMENT AT NIST

LOCATION: ROOMS 1&2 . . . . 7:50 AM TO 8:30 AM

OPENING REMARKS, 2014 AWARD PRESENTATIONS

Location: NIST Auditorium . . . . 8:30 am to 9:00 am

2014 Best Paper Award Winners

BEST ORAL PRESENTATION

Ultrafast optical breakdown of multilayer thin-films at kHz and MHz repetition rates: a direct comparison [9237-16]

Ivan B. Angelov, Max-Planck-Institut für Quantenoptik (Germany); **Michael K. Trubetskov,** Max-Planck-Institut für Quantenoptik (Germany) and Moscow State Univ. (Russian Federation); **Vladislav S. Yakovlev**, Max-Planck-Institut für Quantenoptik (Germany) and Ludwig-Maximilians-Univ. München (Germany); **Olga Razskazovskaya,** Max-Planck-Institut für Quantenoptik (Germany); **Martin Gorjan**, Max-Planck-Institut für Quantenoptik (Germany) and Ludwig-Maximilians-Univ. München (Germany); **Helena G. Barros**, Ludwig-Maximilians-Univ. München (Germany); **Ferenc Krausz,** Max-Planck-Institut für Quantenoptik (Germany) and Ludwig-Maximilians-Univ. München (Germany); **Vladimir Prevak,** Ludwig-Maximilians-Univ. München (Germany) and UltraFast Innovations GmbH (Germany)

BEST POSTER PRESENTATION

Repair of a mirror coating on a large optic for high laser-damage applications using ion milling and over-coating methods [9237-51]

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

CONFERENCE 9632

SESSION 1

LOCATION: NIST AUDITORIUM . . . MON 9:00 AM TO 10:00 AM

Thin Films I

Session Chairs: **MJ Soileau,** Univ. of Central Florida (USA); **Vitaly E. Gruzdev,** Univ. of Missouri (USA)

9:00 am: **Dispersive dielectric mirror for ultrashort-pulse laser at high intensities** *(Keynote Presentation)*, Vladimir Pervak, Ludwig-Maximilians-Univ. München (Germany) . . . . [9632-1]

9:40 am: **Comparative study of the laser damage threshold and optical characteristics of Ta_2O_5-SiO_2 multilayers deposited using various methods**, Roelene Botha, Interstaatliche Hochschule für Technik Buchs NTB (Switzerland) and RhySearch (Switzerland); Silvia Schwyn Thöny, Evatec Ltd. (Switzerland); Martin Grössl, Safer Mourad, FISBA OPTIK AG (Switzerland); Clau Maissen, Jacobus I. Venter, SwissOptic AG (Switzerland); Martin Hoffmann, Univ. of Neuchâtel (Switzerland); Pavel V. Bulkin, Ecole Polytechnique (France); Sabine Linz-Dittrich, David Bischof, Markus Michler, Stefan J. Rinner, Andreas Ettemeyer, Interstaatliche Hochschule für Technik Buchs NTB (Switzerland) . . . . [9632-2]

MONDAY POSTER OVERVIEWS

LOCATION: NIST AUDITORIUM . . . . 10:00 AM TO 10:40 AM

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

POSTER VIEWING AND REFRESHMENT BREAK – MONDAY AM

LOCATION: ROOMS 1&2 . . . . 10:40 AM TO 11:40 AM

Posters will be displayed for viewing during refreshment breaks on Monday from 10:40 am to 11:40 am and again from 4:00 pm to 4:50 pm.

Thin Films

How reduced vacuum pumping capability in a coating chamber affects the laser damage resistance of HfO_2/SiO_2 antireflection and high-reflection coatings, Ella S. Field, John C. Bellum, Damon E. Kletecka, Sandia National Labs. (USA) . . . . [9632-46]

Ion-beam sputtered HfO_2-SiO_2 mixtures and their application for high laser-damage threshold multilayer coatings for 266nm wavelength????, Giedrius Abromavicius, Ramutis Drazdys, Kestutis Juskevicius, Danute Bakaityte, Rytis Buzelis, Ctr. for Physical Sciences and Technology (Lithuania); Irmantas Kakaras, Optida Co., Ltd. (Lithuania). . . . . [9632-48]

Control of the coating stress using a different deposition method, Takuma Murakami, Masaya Akimoto, Hiroki Omatsu, Tomosumi Kamimura, Osaka Institute of Technology (Japan) . . . . [9632-49]

Ultrafast beam dump materials and mirror coatings tested with the ELI beamlines LIDT test station, Michal Durák, Daniel Kramer, Galina Kalinchenko, Tomáš Medrík, Jan Hrebícek, Jirí Golasowski, Václav Štěpán, Michaela Kozlová, Bedrich Rus, Academy of Sciences of the Czech Republic (Czech Republic). . . . . [9632-50]

Test station development for laser-induced optical damage performance of broadband multilayer dielectric coatings, Kyle R. P. Kafka, Enam Chowdhury, The Ohio State Univ. (USA); Raluca A. Negres, Christopher J. Stolz, Jeffrey D. Bude, Andy J. Bayramian, Christopher D. Marshall, Thomas M. Spinka, Constantin L. Haefner, Lawrence Livermore National Lab. (USA) . . . . [9632-51]

Measurement and compensation of wavefront deformations and focal shifts in high-power laser optics, Klaus Mann, Bernd Schäfer, Martin Stubenvoll, Laser-Lab. Göttingen e.V. (Germany) . . . . . [9632-52]

Design and laser damage properties of a dichroic beam combiner coating for 22.5° incidence and S polarization with high-transmission at 527nm and high-reflection at 1054nm, John C. Bellum, Ella S. Field, Damon E. Kletecka, Patrick K. Rambo, Ian C. Smith, Sandia National Labs. (USA) . . . . [9632-82]

Materials and Measurements

Improved parametric spectroscopic performance of an optical fiber doped with erbium, Ghoumazi Mehdi, Nacer-Eddine Demagh, Azzedine Adouane, Badreddine Boubir, Abdel Kader Daoui, Ctr. de Développement des Téchnologies Avancées (Algeria) . . . . [9632-53]

Analysis of cumulative versus ISO-recommended calculation of damage probability using a database of real S-on-1 tests, Alexandru Zorila, Aurel Stratan, Ioana Dumitrache, Laurentiu Rusen, National Institute for Laser, Plasma and Radiation Physics (Romania); George Nemes, ASTiGMAT (USA) . . . . [9632-54]

Synthesis of Nd-doped $Y_3Sc_xAl_{[5-x]}O_{12}$ (χ = 0 to 2) composite ceramics with spectrum broadening and their damage resistance, Yuki Tamura, Takuya Kiriyama, Kazuki Kitabayashi, Kosuke Nuno, Tomosumi Kamimura, Osaka Institute of Technology (Japan); Yan Lin Aung, Akio Ikesue, World Lab Co., Ltd. (Japan) . . . . . [9632-55]

Lowering evaluation uncertainties in laser-induced damage testing, Lars O. Jensen, Marius A. Mrohs, Mark Gyamfi, Heinrich Mädebach, Detlev Ristau, Laser Zentrum Hannover e.V. (Germany). . . . . . [9632-57]

The role of fluence selection in the convergence and uncertainty of sensitivity measurements of laser damage behavior, Jonathan W. Arenberg, Northrop Grumman Aerospace Systems (USA); Michael D. Thomas, Spica Technologies, Inc. (USA) . . . . [9632-58]

An empirical investigation of the laser survivability curve: VI-nanosecond pulse widths, Jonathan W. Arenberg, Northrop Grumman Aerospace Systems (USA); Wolfgang Riede, Deutsches Zentrum für Luft- und Raumfahrt e.V. (Germany); Alessandra Ciapponi, European Space Research and Technology Ctr. (Netherlands); 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) . . . . [9632-59]

An empirical investigation of the laser survivability curve: VI-femtosecond pulse widths, Jonathan W. Arenberg, Northrop Grumman Aerospace Systems (USA); Andrius Melninkaitis, Vilnius Univ. (Lithuania); Wolfgang Riede, Deutsches Zentrum für Luft- und Raumfahrt e.V. (Germany); Allesandra Ciapponi, European Space Agency (Netherlands) and European Space Research and Technology Ctr. (Netherlands); Paul Allenspacher, Deutsches Zentrum für Luft- und Raumfahrt e.V. (Germany); Jonathan H. Herringer, Arrow Thin Films, Inc. (USA); Denny Wernham, European Space Agency (Netherlands) . . . . [9632-60]

Direct comparison of statistical damage frequency method and raster scan procedure, Gintare Bataviciute, Mindaugas Šciuka, Viktorija Plerpaite, Andrius Melninkaitis, Vilnius Univ. (Lithuania) . . . . [9632-61]

Characterization of damage precursor density from laser damage probability measurements with non-Gaussian beams, Frank R. Wagner, Institut Fresnel (France); Andrius Melninkaitis, Gintare Bataviciute, Vilnius Univ. (Lithuania); Céline Gouldieff, Alexandre Beaudier, Institut Fresnel (France); Linas Smalakys, Vilnius Univ. (Lithuania); Jean-Yves Natoli, Institut Fresnel (France) . . . . [9632-62]

Transmittance measurements of laser components using a combination of cavity ring-down and photometry, Bincheng Li, Institute of Optics and Electronics (China) and Univ. of Electronic Science and Technology of China (China); Hao Cui, Univ. of Electronic Science and Technology of China (China) and Institute of Optics and Electronics (China); Yanling Han, Institute of Optics and Electronics (China); Chunming Gao, Yafei Wang, Univ. of Electronic Science and Technology of China (China) . . . . [9632-63]

SESSION 2

LOCATION: NIST AUDITORIUM . . . . MON 11:40 AM TO 1:00 PM

Thin Films II

Session Chairs: **Stavros G. Demos,** Lawrence Livermore National Lab. (USA); **Jérôme Néauport,** Commissariat à l'Énergie Atomique (France)

11:40 am: **Investigating the relationship between material properties and laser-induced damage threshold of amorphous dielectric optical coatings at 1064 nm**, Riccardo Bassiri, Stanford Univ. (USA); Iain W. Martin, Univ. of Glasgow (United Kingdom); Caspar C. Clark, Helia Photonics Ltd. (United Kingdom); Ashot S. Markosyan, Stanford Univ. (USA); Sheila Rowan, Univ. of Glasgow (United Kingdom); Martin M. Fejer, Stanford Univ. (USA) . . . . [9632-3]

12:00 pm: **Influence of different-sized femtosecond fabricated substrate pits on nanosecond-laser-induced-damage in high-reflective mirrors**, Yingjie Chai, Meiping Zhu, Kui Yi, Weili Zhang, Yuanan Zhao, Jianda Shao, Shanghai Institute of Optics and Fine Mechanics (China) . . . . [9632-4]

12:20 pm: **Picosecond laser damage performance of the multilayer dielectric pulse compressor gratings and high reflectors for the advanced radiographic capability Petawatt laser system**, Raluca A. Negres, Isaac L. Bass, Kenneth A. Stanion, Gabriel M. Guss, David A. Cross, David A. Alessi, Jerald A. Britten, Christopher J. Stolz, Paul J. Wegner, Lawrence Livermore National Lab. (USA) . . . . . [9632-5]

12:40 pm: **A comparative study of the laser-induced damage characteristics of artificial nodules prepared by different processes**, Xinbin Cheng, Hongping Ma, Abudusalamu Tuniyazi, Tongji Univ. (China); Yongjian Tang, China Academy of Engineering Physics (China); Zhanshan Wang, Tongji Univ. (China). . . . . [9632-6]

Lunch Break . . . . Mon 1:00 pm to 2:20 pm

SESSION 3

LOCATION: NIST AUDITORIUM . . . . . MON 2:20 PM TO 4:00 PM

Thin Films III

Session Chairs: **Wolfgang Rudolph,** The Univ. of New Mexico (USA); **Joseph A. Menapace,** Lawrence Livermore National Lab. (USA)

2:20 pm: **Impact of laser-contaminant interaction on the performance of the protective cap layer of 1w HR mirror coatings**, Siping R. Qiu, Mary A. Norton, Rajesh N. Raman, Alexander M. Rubenchik, Lawrence Livermore National Lab. (USA); Amy L. Rigatti, Univ. of Rochester (USA); Paul B. Mirkarimi, Christopher J. Stolz, Manyalibo J. Matthews, Charles D. Boley, Lawrence Livermore National Lab. (USA) . . . . [9632-7]

2:40 pm: **Laser damage resistant interference coatings for 1.6 µm wavelength operation**, Drew D. Schiltz, Dinesh Patel, Cory Baumgarten, Brendan A. Reagan, Jorge J. Rocca, Carmen S. Menoni, Colorado State Univ. (USA) . . . . [9632-8]

3:00 pm: **Sheet resistivity and optical absorption of Al-doped ZnO thin films: a "conductive" layer to reduce the charging effects**, Ashot S. Markosyan, Riccardo Bassiri, Stanford Univ. (USA); Ric P. Shimshock, MLD Technologies, LLC (USA); Brian T. Lantz, Roger Route, Martin M. Fejer, Stanford Univ. (USA) . . . . [9632-9]

3:20 pm: **The role of film interfaces in near-ultraviolet absorption and pulsed-laser damage in ion-beam–sputtered coatings based on HfO_2/SiO_2 thin-film pairs**, Semyon Papernov, Alexei A. Kozlov, James B. Oliver, Christopher Smith, Univ. of Rochester (USA); Lars O. Jensen, Detlev Ristau, Stefan Günster, Heinrich Mädebach, Laser Zentrum Hannover e.V. (Germany) . . . . [9632-10]

3:40 pm: **Broadband low-dispersion mirror thin film damage competition**, Christopher J. Stolz, Lawrence Livermore National Lab. (USA); Kyle R. P. Kafka, Enam Chowdhury, The Ohio State Univ. (USA); Matthew S. Kirchner, Kapteyn-Murnane Labs., Inc. (USA) . . . . [9632-11]

POSTER VIEWING AND REFRESHMENT BREAK – MONDAY PM

LOCATION: ROOMS 1&2 . . . . MON 4:00 PM TO 4:50 PM

Poster Viewing and Refreshment Break

Posters will be displayed for viewing during refreshment breaks on Monday from 10:40 am to 11:40 am and again from 4:00 pm to 4:50 pm.

SESSION 4

LOCATION: NIST AUDITORIUM . . . . . MON 4:50 PM TO 5:50 PM

Surfaces, Mirrors, and Contamination I

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

4:50 pm: **Volume holographic elements for high-power laser applications** *(Keynote Presentation)*, Leonid B. Glebov, CREOL, The College of Optics and Photonics, Univ. of Central Florida (USA) and OptiGrate Corp. (USA) . . . . [9632-12]

5:30 pm: **Dedicated contamination experiments in the Orion laser target chamber**, James E. Andrew, AWE plc (United Kingdom) . . . . [9632-13]

CLOSING REMARKS

LOCATION: NIST AUDITORIUM . . . . . MON 5:50 PM TO 6:00 PM

Open House and Reception

MON 6:30 TO 8:00 PM

Come, relax, and join your colleagues at ATFilms for an enjoyable evening of refreshments and pleasant conversation. Invitation and Driving Instructions included in Registration Packet.

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CONFERENCE 9632

TUESDAY 29 SEPTEMBER

REGISTRATION MATERIAL PICK-UP
LOCATION: NIST LOBBY AREA ..... TUE 7:30 AM TO 4:00 PM

Attendees must check in with NIST Security at entrance and have photo identification available.

POSTER PLACEMENT AT NIST
LOCATION: ROOMS 1&2 .... TUE 7:50 AM TO 8:30 AM

SESSION 5
LOCATION: NIST AUDITORIUM .....TUE 8:30 AM TO 10:10 AM

Surfaces, Mirrors, and Contamination II

Session Chairs: **Christopher J. Stolz,** Lawrence Livermore National Lab. (USA); **Gregory J. Exarhos,** Pacific Northwest National Lab. (USA)

8:30 am: **Study of laser-induced damage at 1064nm in fused silica samples in vacuum environment**, Romain Diaz, Maxime Chambonneau, Pierre Grua, Jean-Luc Rullier, Commissariat à l'Énergie Atomique (France); Jean-Yves Natoli, Institut Fresnel (France); Laurent Lamaignère, Commissariat à l'Énergie Atomique (France) . . . .[9632-14]

8:50 am: **Laser-induced damage of fused silica on high-power laser: beam intensity modulation, optics imperfection, contamination**, Dongfeng Zhao, Shanghai Institute of Optics and Fine Mechanics (China) . . . .[9632-15]

9:10 am: **Laser-induced shallow pits on silica output surfaces: formation and resulting light scattering**, Eyal Feigenbaum, Rajesh N. Raman, Norman D. Nielsen, Manyalibo J. Matthews, Lawrence Livermore National Lab. (USA) . . . .[9632-16]

9:30 am: **Sub-wavelength microstructures for high-power laser application on fused silica**, Ye Xin, Jin Huang, Ruifang Ni, Laixi Sun, Xiaodong Jiang, Wanguo Zheng, China Academy of Engineering Physics (China) . . . .[9632-17]

9:50 am: **Effect of reaction ion etching process on laser-damage performance of fused silica optics**, Laixi Sun, Hongjie Liu, Jin Huang, Xin Ye, Xiaodong Jiang, Weidong Wu, China Academy of Engineering Physics (China) . . . .[9632-18]

TUESDAY POSTER OVERVIEWS
LOCATION: NIST AUDITORIUM ....10:10 AM TO 10:40 AM

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

POSTER VIEWING AND REFRESHMENT BREAK- TUESDAY AM
LOCATION: ROOMS 1&2 ....10:40 AM TO 11:40 AM

Posters will be displayed for viewing during the refreshments breaks on Tuesday from 10:40 am to 11:40 am and again at 4:10 pm to 5:00 pm.

Fundamental Mechanisms

Direct absorption measurements in thin rods and optical fibers, Christian Mühlig, Simon Bublitz, Martin Lorenz, Leibniz-Institut für Photonische Technologien e.V. (Germany) . . . .[9632-64]

Bulk damage and absorption in fused silica due to high-power laser applications, Frank Nuernberg, Heraeus Quarzglas GmbH & Co. KG (Germany) . . . .[9632-65]

Refined metrology of spatio-temporal dynamics of nanosecond laser pulses: application to nonlinear Kerr effect and its influence on the measurement of laser-induced surface damage in thick fused silica window, Romain Diaz, Roger Courchinoux, Jacques Luce, Claude Rouyer, Jean-Luc Rullier, Jean-Michel Sajer, Commissariat à l'Énergie Atomique (France); Jean-Yves Natoli, Institut Fresnel (France); Laurent Lamaignère, Commissariat à l'Énergie Atomique (France) . . . .[9632-66]

Synchrotron micro-XRF study of metal inclusions distribution and variation in potassium dihydrogen phosphate (KH2PO4) induced by ultraviolet laser pulses, Zhiqiang Cao, Xin Ju, Chunyan Yan, Chang Liu, Univ. of Science and Technology Beijing (China) . .[9632-67]

Optimization of the concentration of populations of an optical fiber doped with erbium, Ghoumazi Mehdi, Nacer-Eddine Demagh, Azzedine Adouane, Badreddine Boubir, Abdel Kader Daoui, Ctr. de Développement des Téchnologies Avancées (Algeria) . . . .[9632-68]

Nano-Kelvin calorimeter for optical absorption spectroscopy at the level of parts per billion, Behshad Roshanzadeh, S. T. P. Boyd, Wolfgang Rudolph, The Univ. of New Mexico (USA) . . . .[9632-69]

Defects characterization of optical materials by photothermal microscopy and optical scattering microscopy, Jingtao Dong, Bingbing Li, Jian Chen, Zhouling Wu, ZC Optoelectronic Technologies, Ltd. (China) . . . .[9632-70]

Surfaces, Mirrors, and Contamination

Improving laser-damage resistance of optics by optimizing the interface structure, Xiaodong Jiang, China Academy of Engineering Physics (China) . . . .[9632-73]

Improved laser damage threshold performance of calcium fluoride optical surfaces via accelerated neutral atom beam (ANAB) processing, Michael J. Walsh Jr., Sean Kirkpatrick, Richard Svrluga, Exogenesis Corp. (USA); Michael D. Thomas, Spica Technologies, Inc. (USA) . . . .[9632-74]

Scaling of laser-induced contamination growth at 266nm and 355nm, Matthias Ließmann, Lars O. Jensen, Istvan Balasa, Michael Hunnekuhl, Alexander Büttner, Peter Wessels, Jörg Neumann, Detlev Ristau, Laser Zentrum Hannover e.V. (Germany) . . . .[9632-75]

Enhancement of surface-damage resistance by removing a polishing contamination in CaF_2 crystal, Keita Kawasaki, Yoshizumi Inagaki, Ryoya Ota, Tomosumi Kamimura, Osaka Institute of Technology (Japan) . . . .[9632-77]

Retrieval of defect densities from STEREO-LID (spatio-temporally resolved optical laser induced damage) data and comparison with traditional damage tests, Yejia Xu, Luke A. Emmert, Wolfgang Rudolph, The Univ. of New Mexico (USA). . . . .[9632-78]

SESSION 6

LOCATION: NIST AUDITORIUM . . . . . . TUE 11:40 AM TO 1:10 PM

Mini Symposium: Laser-Induced Damage to Multilayers in Femtosecond Regime

Session Chairs: **Vladimir Pervak,** UltraFast Innovations GmbH (Germany); **Klaus Mann,** Laser-Lab. Göttingen e.V. (Germany)

11:40 am: **Optical coatings excited by femtosecond lasers near the damage threshold: challenges and opportunities** *(Plenary)*, Luke A. Emmert, Cristina Rodriguez, Zhanliang Sun, Wolfgang Rudolph, The Univ. of New Mexico (USA) . . . . [9632-19]

12:10 pm: **Analysis of energy deposition and damage mechanisms in single layers of HfO_2 and Nb_2O_5 submitted to 500fs pulses**, Dam-Bé L. Douti, Mhamad Chrayteh, Serge Monneret, Mireille Commandre, Laurent Gallais, Institut Fresnel (France). . . . . [9632-20]

12:30 pm: **Ultrafast pre-damage dynamics in ultraviolet reflector**, Juan Du, Zehan Li, Shanghai Institute of Optics and Fine Mechanics (China); Bing Xue, Takayoshi Kobayashi, The Univ. of Electro-Communications (Japan); Yuanan Zhao, Yuxin Leng, Shanghai Institute of Optics and Fine Mechanics (China) . . . . [9632-21]

12:50 pm: **Laser-damage resistance of optical components in sub-picosecond regime in the infrared**, Jérôme Néauport, Martin Sozet, Commissariat à l'Énergie Atomique (France) . . . . [9632-22]

Lunch Break . . . . Tue 1:10 pm to 2:30 pm

SESSION 7

LOCATION: NIST AUDITORIUM . . . . . . TUE 2:30 PM TO 4:10 PM

Fundamental Mechanisms I

Session Chairs: **Leonid B. Glebov,** CREOL, The College of Optics and Photonics, Univ. of Central Florida (USA); **Semyon Papernov,** Univ. of Rochester (USA)

2:30 pm: **What time-resolved measurements tell us about femtosecond laser damage?** *(Keynote Presentation)*, Andrius Melninkaitis, Vilnius Univ. (Lithuania), LIDARIS Ltd. (Lithuania); Nerijus Šiaulys, Balys Momgaudis, Julius Vaicenavicius, Simona Barkauskaite, Valdas Sirutkaitis, Vilnius Univ. (Lithuania); Laurent Gallais, Ecole Centrale Marseille (France); Stéphane Guizard, Commissariat à l'Énergie Atomique (France), Ctr. National de la Recherche Scientifique (France), Ecole Polytechnique (France) . . . . [9632-23]

3:10 pm: **Laser damage threshold: useful idea or dangerous misconception?**, Jonathan W. Arenberg, Northrop Grumman Aerospace Systems (USA) . . . . [9632-24]

3:30 pm: **Characterization of laser-induced structural modification in bulk of broken-down dielectrics**, Karol A. Janulewicz, Zia U. Rehman, Yavor V. Grigorov, Khoa A. Tran, Le T. Na, Vinh H. Nguyen, Gwangju Institute of Science and Technology (Korea, Republic of) . . . . [9632-25]

3:50 pm: **Single-shot femtosecond laser ablation of copper: experiment versus simulation**, Enam Chowdhury, Kyle R. P. Kafka, Robert A. Mitchell III, Kevin Werner, Noah Talisa, Hui Li, Allen Yi, Douglass W. Schumacher, The Ohio State Univ. (USA) . . . . . . [9632-26]

POSTER VIEWING AND REFRESHMENT BREAK TUESDAY PM

LOCATION: ROOMS 1&2 . . . . 4:10 PM TO 5:00 PM

Posters will be displayed for viewing during refreshment breaks on Tuesday from 10:40 am to 11:40 am and again from 4:10 pm to 5:10 pm.

SESSION 8

LOCATION: NIST AUDITORIUM . . . . . TUE 5:00 PM TO 6:00 PM

Fundamental Mechanisms II

Session Chairs: **Detlev Ristau,** Laser Zentrum Hannover e.V. (Germany); **Wolfgang Rudolph,** The Univ. of New Mexico (USA)

5:00 pm: **Probing the properties of laser super-heated fused silica following exit surface damage**, Stavros G. Demos, Raluca A. Negres, Rajesh N. Raman, Michael D. Feit, Kenneth R. Manes, Alexander M. Rubenchik, Lawrence Livermore National Lab. (USA) . . . . [9632-27]

5:20 pm: **Gigashot optical degradation in silica optics at 351 nm**, Sonny S. Ly, Lawrence Livermore National Lab. (USA) . . . . . . [9632-28]

5:40 pm: **In situ study of irradiation effects on fused silica induced by high-repetitive laser pulses at 355 nm**, Jian Chen, Jingtao Dong, Bingbing Li, Zhouling Wu, ZC Optoelectronic Technologies Ltd. (China) . . . . [9632-29

CLOSING REMARKS

LOCATION: NIST AUDITORIUM . . . . 6:00 PM TO 6:10 PM

Wine and Cheese Tasting Reception

TUE 6:30 TO 8:00 PM

SPONSORED BY

SPIE and the Conference Co-chairs of Laser Damage XLVII

Reception at NCAR-National Ctr. for Atmospheric Research

1850 Table Mesa Dr., Boulder, CO

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

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CONFERENCE 9632

WEDNESDAY 30 SEPTEMBER

REGISTRATION MATERIAL PICK-UP

LOCATION: NIST LOBBY AREA . . . . .7:30 AM TO 3:00 PM

Attendees must check in with NIST Security at entrance and have photo identification available.

SESSION 9

LOCATION: NIST AUDITORIUM . . . WED 8:30 AM TO 10:30 AM

Fundamental Mechanisms III

Session Chairs: **Jonathan W. Arenberg,** Northrop Grumman Aerospace Systems (USA); **James E. Andrew,** AWE plc (United Kingdom)

8:30 am: **Energetic laser cleaning of metallic particles and surface damage on silica optics: Investigation of the underlying governing mechanisms**, Nan Shen, Stavros G. Demos, Raluca A. Negres, Alexander M. Rubenchik, Candace D. Harris, Manyalibo J. Matthews, Lawrence Livermore National Lab. (USA) . . . .[9632-30]

8:50 am: **Delay dependency of two-pulse femtosecond laser damage**, Mark Gyamfi, Peter Juergens, Lars O. Jensen, Detlev Ristau, Laser Zentrum Hannover e.V. (Germany) . . . .[9632-31]

9:10 am: **Self-consistent modeling of photoionization and the Kerr effect in bulk solids**, Jeremy R. Gulley, Kennesaw State Univ. (USA) . . . .[9632-32]

9:30 am: **First principles simulations of laser-induced periodic surface structure using the particle-in-cell method**, Robert A. Mitchell III, Douglass W. Schumacher, Enam Chowdhury, The Ohio State Univ. (USA) . . . .[9632-33]

9:50 am: **Calculation of nonlinear optical damage from space-time-tailored pulses in dielectrics**, Thomas E. Lanier, Jeremy R. Gulley, Kennesaw State Univ. (USA) . . . .[9632-34]

10:10 am: **The photo-ionization and band structure of solids: non-evident interplay**, Vitaly E. Gruzdev, Univ. of Missouri (United States) . . . .[9632-35]

Refreshment Break .Wed 10:30 am to 11:00 am

SESSION 10

LOCATION: NIST AUDITORIUM . . . WED 11:00 AM TO 12:40 PM

Materials and Measurements I

Session Chair: **Jérôme Néauport,** Commissariat à l'Énergie Atomique (France)

11:00 am: **Characterization of extremely high-purity optical materials for solid state laser cooling** *(Keynote Presentation)*, Mansoor Sheik-Bahae, Nathan Giannini, The Univ. of New Mexico (USA). . . . . [9632-36]

11:40 am: **Laser-induced damage of rapid-grown KDP crystals**, Yuanan Zhao, Yueliang Wang, Guohang Hu, Meiping Zhu, Weili Zhang, Xiaoyi Xie, Jianda Shao, Shanghai Institute of Optics and Fine Mechanics (China). . . . .[9632-37]

12:00 pm: **Laser damage of calcium fluoride by ArF excimer laser irradiation**, Minako Kashimoto, Eiichiro Nakahata, Nikon Corp. (Japan). . . . .[9632-38]

12:20 pm: **High-speed quantitative phase imaging of dynamic thermal deformation in laser irradiated films**, Lucas N. Taylor, Joseph J. Talghader, Univ. of Minnesota, Twin Cities (USA) . .[9632-39]

Lunch Break and NIST Tours . . . . Wed 12:40 pm to 2:30 pm

NIST FACILITY TOURS

Location: NIST Lobby Area . . . . 12:40 pm to 1:40 pm

NIST has generously offered to provide 2 limited tours of the facility, including the **NIST-F2 Atomic Clock** and the **NIST Laser Welding Lab.**

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 SPIE registration desk.

SESSION 11

LOCATION: NIST AUDITORIUM . . . . . WED 2:30 PM TO 4:10 PM

Materials and Measurements II

Session Chairs: **Carmen S. Menoni,** Colorado State Univ. (USA); **Stavros G. Demos,** Lawrence Livermore National Lab. (USA)

2:30 pm: **Comparative STEREO-LID (spatio-temporally resolved optical laser-induced damage) studies of critical defect distributions in IBS, ALD, and electron-beam coated dielectric films**, Yejia Xu, The Univ. of New Mexico (USA); Drew D. Schiltz, Colorado State Univ. (USA); Luke A. Emmert, The Univ. of New Mexico (USA); Andrew K. Brown, Joseph J. Talghader, Univ. of Minnesota, Twin Cities (USA); Damon E. Kletecka, Ella S. Field, John C. Bellum, Sandia National Labs. (USA); Dinesh Patel, Carmen S. Menoni, Colorado State Univ. (USA); Wolfgang Rudolph, The Univ. of New Mexico (USA) . . . .[9632-40]

2:50 pm: **Heat treatment of fused silica optics repaired by CO_2 laser**, Thomas Doualle, Laurent Gallais, Institut Fresnel (France); Philippe Cormont, Jean-Luc Rullier, Commissariat à l'Énergie Atomique (France) . . . .[9632-41]

3:10 pm: **Damage growth analysis at the National Ignition Facility**, Zhi M. Liao, Michael C. Nostrand, Pam K. Whitman, Jeffrey D. Bude, Lawrence Livermore National Lab. (USA) . . . .[9632-42]

3:30 pm: **Alternate fitting methods for sensitivity measurements of laser damage behavior**, Jonathan W. Arenberg, Northrop Grumman Aerospace Systems (USA); Clemens Heese, European Space Research and Technology Ctr. (Netherlands) . . . .[9632-43]

3:50 pm: **Tunable laser source based on storage device using Bragg grating**, Chinmayee V. Prabhu Dessai, I. V. Anudeep K. Reddy, P. Saidi Reddy, G. R. C. Reddy, National Institute of Technology, Goa (India). . . . .[9632-44]

CLOSING REMARKS

LOCATION: NIST AUDITORIUM . . . . 4:10 PM TO 4:20 PM

TECHNICAL SUMMARIES

CONFERENCE 9632

Laser-Induced Damage in Optical Materials: 2015

CONTENTS

9632-1, SESSION 1

Dispersive dielectric mirror for ultrashort-pulse laser at high intensities *(Keynote Presentation)*

Vladimir Pervak, Ludwig-Maximilians-Univ. München (Germany)

SPEAKER BIOGRAPHY: Vladimir Pervak received his MSc degree in Physics from the Kiev National Taras Schevchenko University, Ukraine, in 2004. In 2006, he received his PhD in Physics at the Max-Planck-Instiute of Quantum Optics, Germany, and Kiev National Taras Schevchenko University, Ukraine. Currently, he is leading his team in the research group of Prof. Ferenc Krausz at the Max Planck Institute of Quantum Optics and Ludwig Maximilians University both in Munich. He has more than 200 technical and scientific publications. His research interests include interference coatings, ultrafast sources, and nonlinear optics.

ABSTRACT TEXT: The generation of ultrashort pulses with large pulse energies is constrained by the laser-induced damage threshold (LIDT) of the optics involved. In particular, the LIDT of the dispersive optics is one of the bottlenecks in the development of high-power ultrafast systems. We present direct comparison of damage threshold at kHz and MHz repetition rate for 1 ps pulses.

In femtosecond regime, dispersive coatings had damage thresholds close to that of a single layer of the high index material used for the respective coating [1 - 4]. We have shown that the damage fluence of multilayer stacks scales linearly with the band gap of the used high-index material if the damage threshold is normalized with respect to electric field. This suggests that thermal effects do not play a significant part in the ultrashort pulse damage mechanism at kHz and MHz repetition rates.

Additionally, we have observed a nonlinear response of dispersive dielectric multilayer. It was demonstrated that the structure of the mirror itself causes strong enhancement of the electric field inside the multilayer stack consequently triggering two-photon absorption. We have developed a mathematical model, that allows estimation of the coefficient of the two-photon absorption of thin films layers.

REFERENCE:

[1] I. Angelov, A. Conta, S. A. Trushin, Z. Major, S. Karsch, F. Krausz, and V. Pervak, “Investigation of the laser-induced damage in dispersive coatings,” SPIE Proceeding 8190, 6 (2011).

[2] M. Mero, J. Liu, W. Rudolph, D. Ristau, and K. Starke, “Scaling laws of femtosecond laser pulse induced breakdown in oxide films,” Physical Review B, 71, 11 (2005).

[3] B. Mangote, L. Gallais, M. Commandré, M. Mende, L. Jensen, H. Ehlers, M. Jupé, D. Ristau, A. Melninkaitis, J. Mirauskas, V. Sirutkaitis, S. Ki?as, T. Tolenis, and R. Drazdys, Opt. Let., 37, 1478-1480 (2012).

[4] I. B. Angelov, M. von Pechmann, M. K. Trubetskov, F. Krausz, and V. Pervak, “Optical breakdown of multilayer thin-films induced by ultrashort pulses at MHz repetition rates,” Opt. Express 21, 31453-31461 (2013).

Keywords: *dispersive mirrors, chirped mirrors, damage threshold, femtosecond laser, ultrafast optics*

9632-2, SESSION 1

Comparative study of the laser damage threshold and optical characteristics of Ta_2O_5-SiO_2 multilayers deposited using various methods

Roelene Botha, Interstaatliche Hochschule für Technik Buchs NTB (Switzerland) and RhySearch (Switzerland); **Silvia Schwyn Thöny,** Evatec Ltd. (Switzerland); **Martin Grössl, Safer Mourad,** FISBA OPTIK AG (Switzerland); **Clau Maissen, Jacobus I. Venter,** SwissOptic AG (Switzerland); **Martin Hoffmann,** Univ. of Neuchâtel (Switzerland); **Pavel V. Bulkin,** Ecole Polytechnique (France); **Sabine Linz-Dittrich, David Bischof, Markus Michler, Stefan J. Rinner, Andreas Ettemeyer,** Interstaatliche Hochschule für Technik Buchs NTB (Switzerland)

SPEAKER BIOGRAPHY: Roelene Botha is senior research engineer at the Institute for Production Metrology, Materials and Optics PWO at NTB Buchs, Switzerland. She received her PhD in Applied Physics at the Ecole Polytechique, Palaiseau (France) in 2008. She is responsible for the LIDT measurement system at the NTB, Buchs and the future build-up of the RhySearch centre for Optical High End Coatings.

ABSTRACT TEXT: Four different manufacturing processes from both the private and academic sectors were used to deposit both anti-reflective (AR) coatings and high reflective (HR) coatings. Coatings were composed of Ta2O5 as high-index material and SiO_2 as low-index material. The deposition techniques used included two Ion Assisted Deposition (IAD) systems, an Ion Beam Sputtering (IBS) system and a Magnetron Sputtering (MS) system. All coatings were performed on fused silica (Corning 7980 1C) substrates polished by two different suppliers. The paper presents a comparison of the coatings in terms of the laser damage threshold values. Measurements were performed using a Q-Switched Nd:YAG laser operating at 1064nm. The results from the detailed characterization of the deposited films are also shared. The material properties and quality of the substrates are then related with the measured damage threshold values.

Keywords: *laser induced damage threshold, Ta205, Si02, ion beam sputtering, magnetron sputtering, ion assisted deposition, optical properties, 1064 nm*

9632-46, SESSION PSMON

How reduced vacuum pumping capability in a coating chamber affects the laser damage resistance of HfO/SiO_2 antireflection and high-reflection coatings

Ella S. Field, John C. Bellum, Damon E. Kletecka, Sandia National Labs. (United States)

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 manages operations at the Optical Support Facility. 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: Optical coatings with the highest laser damage thresholds rely on clean conditions in the vacuum chamber during the coating deposition process. A low base pressure in the coating chamber, as well as the ability of the vacuum system to maintain the required pressure during deposition, are important aspects of limiting the amount of contamination in the optical coating that could induce laser damage. Our large optics coating chamber at Sandia National Laboratories normally relies on three cryopumps to maintain low pressures for e-beam coating processes. However, on occasion, one or more of the cryopumps have been out of commission. In light of this circumstance, we decided to explore how deposition under compromised vacuum conditions resulting from the use of only one or two cryopumps affects the laser-induced damage thresholds of optical coatings. The coatings of this study consist of HfO2 and SiO_2 layer materials and include antireflection coatings for 527 nm, and high reflection coatings for 527 nm, 45 degrees, in P-polarization.

Keywords: *laser damage, optical coatings, HfO_2, SiO_2, vacuum, antireflection, high reflection, deposition conditions*

9632-48, SESSION PSMON

Ion-beam sputtered HfO_2-SiO_2 mixtures and their application for high laser damage threshold multilayer coatings for 266nm wavelength????

Giedrius Abromavicius, Ramutis Drazdys, Kestutis Juskevicius, Danute Bakaityte, Rytis Buzelis, Ctr. for Physical Sciences and Technology (Lithuania); **Irmantas Kakaras,** Optida Co., Ltd. (Lithuania)

SPEAKER BIOGRAPHY: Giedrius Abromavicius has graduated and earned MS degree from Physic Faculty in Vilnius University in 2003. Since then he has been working for almost 10 years as a thin-film engineer and researcher in Optida Co Ltd and as R&D engineer at Optical Coating laboratory at former Institute of Physics.

At 2013 Giedrius has started PhD studies at Optical Coating laboratory in Center of Physical Sciences and Technology. The topic of PhD thesis is "Optical and microstructural properties of ion-beam sputtered metal oxide thin films and their application for UV spectral range"

ABSTRACT TEXT: Hafnium oxide and its application to produce high damage threshold thin films and optical coatings has been the scope of intensive research efforts for many years [1,2,3]. During the past few decades, many extensive works were dedicated to investigation of HfO_2 optical and physical properties, using advanced coating technologies like IBS, DIBS, RLVIP, MS [4,5,6]. Ion beam sputtering technology is considered one of the most advanced thin film coating technologies, which also easily allows to form mixtures of metal oxides with superior physical and optical properties [7,8]. Several studies have demonstrated the potential of HfO_2 and its mixtures for making high damage threshold dielectric mirrors. [9, 10].

The aim of this work was to investigate optical properties of different ion-beam sputtered HfO_2-SiO_2 mixtures depending on partial oxygen pressure during the sputtering process. Obtained results demonstrate, that optical absorption depends on the amount of backfilled oxygen, which should be fine tuned to achieve the minimal absorption within the sputtered mixtures.

High reflectance multilayer coatings for 266 nm were formed using selected hafnia mixtures. Optical properties and LIDT values in ns regime were determined for experimental coatings. Obtained LIDT values were compared with pure HfO_2/SiO_2 multilayer coatings deposited using IBS as well as conventional e-beam technology and were found to be more than two times higher.

REFERENCES

[1] R. Thielsch, A. Gatto, J. Heber, N. Kaiser, A comparative study of the UV optical and structural properties of SiO2, Al2O3, and HfO2 single layers deposited by reactive evaporation, ion-assisted deposition and plasma ion-assisted deposition, Thin Solid Films, 410 p. 86–93 (2002).

[2] J. B. Oliver, S. Papernov, A. W. Schmid, J. C. Lambropoulos, Optimization of laser-damage resistance of evaporated hafnia films at 351nm, Proc. SPIE 7132, Laser-Induced Damage in Optical Materials: 2008, 71320J

[3] Alvisi, M., Di Giulio M., Marrone S.G., Perrone M.R., Protopapa M.L., Valentini A., and Vasanelli L. HfO2 films with high laser damage threshold. Thin Solid Films, 358, p.250-258 (2000)

[4] A. Hallbauer, D. Huber, G.N. Strauss, S. Schlichtherle, A. Kunz, H.K. Pulker, Overview about the optical properties and mechanical stress of different dielectric thin films produced by reactive-low-voltage-ion-plating, Thin Solid Films 516, p. 4587–4592 (2008)

[5] D. Patel, P. Langston, A. Markosyan, E. M. Krous, B. Langdon, F. Furch, B. Reagan, R. Route, M.M. Fejer, J.J. Rocca and C.S. Menoni, SiO2/HfO2 multilayers: impact of process parameters and stack geometry on the optical and structural properties, Proc. of SPIE Vol. 7132 (2008) 71320L-1

[6] V. Pervak, F. Krausz, A. Apolonski, Hafnium oxide thin films deposited by reactive middle-frequency dual magnetron sputtering, Thin Solid Films 515, p. 7984–7989 (2007)

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

[8] M. Mende, S. Schrameyer, H. Ehlers, D.Ristau and L.Gallais, Laser damage resistance of ion-beam sputtered Sc2O3/SiO2 mixture optical coatings, Applied Optics / Vol. 52, No. 7, p 1368-1376 (2013)

[9] Lars O. Jensen, Mathias Mende, , Holger Blaschke, , Detlev Ristau, , Duy Nguyen, Luke Emmert and W. Rudolph, Investigations on SiO2/HfO2 mixtures for nanosecond and femtosecond pulses Proc. of SPIE Vol. 7842, 78420 (2010).

[10] M. Mende, L.O. Jensen, H. Ehlers, W. Riggers, H. Blaschke, and D. Ristau, Laser induced damage of pure and mixture material high reflectors for 355nm and 1064nm wavelength, Proc. SPIE 8168, 816821 (2011).

Keywords: *hafnium oxide, mixtures, ion beam sputtering, LIDT, optical properties, UV multilayer coatings*

9632-49, SESSION PSMON

Control of the coating stress using a different deposition method

Takuma Murakami, Masaya Akimoto, Hiroki Omatsu, Tomosumi Kamimura, Osaka Institute of Technology (Japan)

ABSTRACT TEXT: Multilayer coatings fabricated by thermal evaporation or sputtering exist in a stressed condition. As for multilayer coatings,the stress levels often exceed the breaking strength of the bulk of a material. The control of coating stress is significant in production of the multilayer coating. The stress control by the combination of different deposition methods was performed in this study. A prepared chamber can use electron-beam evaporation and magnetron sputtering deposition. SiO_2 and HfO_2 were deposited onto a fused silica substrate. In the case of electron-beam evaporation, the HfO_2 thin film showed a tensile stress of 2000 kgf/cm^2. In contrast,the HfO_2 thin film deposited by magnetron sputtering showed a compressive stress of 2500 kgf/cm^2. The stress of the SiO_2 film was approximately 0, and no difference by the deposition methods was found in this experiment. Then, the AR coatings with a center wavelength 355 nm was designed with 4 layer structure. At first, HfO_2 film was deposited onto the fused silica substrate by sputtering and then SiO_2 ,HfO_2 and SiO_2 coatings were deposited by electron beam. As a result, a stress was controlled to 80 kgf/cm^2 as compared with stress 1810 kgf/cm^2 of the AR film which was produced by magnetron sputtering technique. These results indicated that the combination of different deposition methods is effective for stress control in a multilayer film deposition.

Keywords: *coating stress, AR coatings, combination of different deposition methods*

9632-50, SESSION PSMON

Ultrafast beam dump materials and mirror coatings tested with the ELI beamlines LIDT test station

Michal Durák, Daniel Kramer, Galina Kalinchenko, Tomáš Medrík, Jan Hrebícek, Jirí Golasowski, Václav Štepán, Michaela Kozlová, Bedrich Rus, Academy of Sciences of the Czech Republic (Czech Republic)

ABSTRACT TEXT: The ELI Beamlines project will deliver ultrafast laser pulses with peak powers up to 10PW available every minute and PW class beams at 10Hz complemented by a 10TW 1kHz beamline. To properly determine damage thresholds of involved optical components in conditions similar to the operational environment and with expected laser parameters, a high vacuum LIDT test station was constructed at PALS facility. Our study presents results of ISO based S-on-1 tests in femtosecond regime (50fs, 800nm, 10Hz/1kHz) performed on two different types of coatings: a) high-absorption black coatings with low outgassing rates, intended for use as a beam dump surface; and b) high-reflectivity, low-dispersion 45° AOI ultrafast mirror coatings. Testing of absorptive coatings was accompanied with QMS residual gas analysis to verify, that high intensity laser radiation approaching the damage threshold does not increase concentration of volatile organic compounds in the vacuum chamber. In case of HR mirror coatings, we also investigate the effect of cleaning on LIDT value, comparing characteristic S-on-1 curves of given sample with values obtained after 12h immersion in CH3CH2OH water solution.

Keywords: *laser damage threshold, femtosecond, outgassing*

9632-51, SESSION PSMON

Test station development for laser-induced optical damage performance of broadband multilayer dielectric coatings

Kyle R. P. Kafka, Enam Chowdhury, The Ohio State Univ. (United States); **Raluca A. Negres, Christopher J. Stolz, Jeffrey D. Bude, Andy J. Bayramian, Christopher D. Marshall, Thomas M. Spinka, Constantin L. Haefner,** Lawrence Livermore National Lab. (United States)

SPEAKER BIOGRAPHY: Mr. Kafka is a graduate student at the Femtosecond Solid Dynamics Laboratory, Department of Physics, The Ohio State University. His research topic includes intense field light matter interaction, Laser induced periodic surface structures, laser damage of materials.

ABSTRACT TEXT: The High Repetition Rate Advanced Petawatt Laser System (HAPLS) is a diode pumped, high average power short pulse laser system currently developed by Lawrence Livermore National Laboratory for the Extreme Light Infrastructure (ELI-Beamlines) in Czech Republic. HAPLS is designed to be capable of delivering laser pulses with 1 PW peak power at a repetition rate of 10 Hz. The energetic laser pulses are generated by a chain of short pulse amplifiers and require broadband, high reflective mirrors for beam transport which can withstand the high fluencies and high repetition rates. The design and production of multilayer, dielectric coatings with high damage threshold and supporting broadband laser pulses is challenging and requires therefore a robust performance verification and validation protocol before these optics are integrated into the laser system.

A specialized testing protocol and system have been developed as a collaborative effort between LLNL and OSU for Laser Induced Damage Threshold (LIDT) determination in air of these high reflectors to evaluate the damage performance of commercially available multilayer dielectric (MLD) coatings suitable for this application. This protocol, based on NIF nanosecond LIDT method, takes into account the broad bandwidth nature of the pulses interacting with the multilayer stack, the lowering of LIDT due to spatially varying quality of coatings (localized defects) and ambient contamination.

The LIDT measurement setup was constructed at the Femtosecond Solid Dynamics Lab at OSU using a stretched Chirped Pulse Amplification system based on Ti:Sapphire, LN cooled regenerative amplifier producing 6 mJ pulses at 500 Hz with a center wavelength of 773 nm,1/e2 spectral width of 48 nm and temporal width of 150 ps (autocorrelation measurement). An external Pockels cell/ polarizer combo was used to control the pulse repetition rate and the number of pulses arbitrarily. The laser beam was focused at the sample's input surface by an f = 200 mm achromat to a 1/e2 beam waist radius of 40 μm while the pulse energy was monitored and controlled via uncoated surface pickoffs and a waveplate/polarizer combo. In addition, the sample surfaces were illuminated by a co-propagating HeNe laser and positioned in focus (±3μm accuracy) by imaging the interaction region with an infinity conjugate 10x objective onto a CCD camera. This system allowed in situ observation of laser induced damage during the interaction. The f/# (~80) of the system allowed long Raleigh range of the focus to minimize uncertainties in the interaction volume. Another high magnification imaging system was constructed in line with the laser propagation direction behind the sample mount to enable spot size measurements at the focal plane any time the samples were removed from the testing setup. A zero-order, broadband half wave plate was used to rotate the polarization to allow LIDT measurement of s- or p-polarization at 45 degree angle of incidence (AOI). The RMS energy fluctuation of the laser system was < 2%, and pulse to pulse fluctuation was < 10%. The LIDT tests were performed for both 0 and 45 degree AOI. A precision 2-axis micro-mover stage system was constructed to move the sample optic surface in xy plane to test different areas of the sample and also to allow for large area scans. Results from different approaches to LIDT measurements on available mirror samples will be presented.

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Keywords: *Laser damage, high power laser, short pulse lasers, multi-layer dielectric film*

9632-52, SESSION PSMON

Measurement and compensation of wavefront deformations and focal shifts in high-power laser optics

Klaus Mann, Bernd Schäfer, Martin Stubenvoll, Laser-Lab. Göttingen e.V. (Germany)

SPEAKER BIOGRAPHY: Klaus R. Mann received his diploma in physics in 1981 and the PhD in 1984 from Univ. of Göttingen, the latter with a thesis written at the Max-Planck-Institut für Strömungsforschung. After a post-doctoral appointment at the IBM Research Ctr. In Yorktown Heights (NY/USA) and work in industry (Alcan Deutschland GmbH) he joined Laser-Laboratorium Göttingen in 1988, where he currently leads the ´Optics / Short Wavelengths´ department.

His research activities cover projects in optics characterization and quality assurance (especially deep UV), laser beam diagnostics and propagation, wavefront analysis, as well as laser-produced plasmas for generation of extreme UV and soft x-ray radiation. He is author of more than 100 scientific publications and also involved in supervision of bachelor, master and PhD students.

ABSTRACT TEXT: Thermal effects in optical elements and systems represent a major challenge for industrial high power laser applications. In order to reduce focal shifts due to thermal lensing, passive compensation schemes can be considered by combining suitable materials with specifically matched dn/dT behavior. In this paper we demonstrate the feasibility of passive compensation of the thermal lens effect in fused silica optics, placing optical materials with negative dn/dT in the beam path of a high power near IR fiber laser.

Suitable optical materials for this purpose are characterized, compared, and assessed using a photothermal absorption measurement system based on a Hartmann-Shack sensor, accomplishing spatially resolved monitoring of thermally induced wavefront distortions. Since the extent of wavefront 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 are performed for both the characterization of materials and the optimization of the complete optical system, utilizing a 500 W Yb:YAG fiber laser (? = 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, a separation of bulk and surface / coating absorption was achieved. Furthermore, complete F-Theta lenses and other focusing objectives were tested to gain understanding of the thermal behavior of complex optical systems. By means of caustic measurements during high-power operation (average laser power up to 500W) we were able to demonstrate a 60 % reduction of the focal shift in F-Theta lenses through passive compensation.

Keywords: *thermal lens, wavefront aberration, absorption, thermal compensation, focus shift, near-infrared optics*

9632-82, SESSION PSMON

Design and laser damage properties of a dichroic beam combiner coating for 22.5 degree incidence and S polarization with high-transmission at 527nm and high-reflection at 1054nm

John C. Bellum, Ella S. Field, Damon E. Kletecka, Patrick K. Rambo, Ian C. Smith, Sandia National Labs. (United States)

ABSTRACT TEXT: We have designed a dichroic beam combiner coating consisting of 11 HfO_2/SiO_2 layer pairs deposited on a fused silica substrate. The design provides high transmission at 527 nm and high reflection at 1054 nm for light propagating into the coating from air (or vacuum) at 22.5o angle of incidence (AOI) in S polarization (Spol). We will present the coating's design and implementation in the 527 nm/1054 nm dual wavelength combiner arrangement. We will also report on the results of laser-induced damage threshold measurements on the coating for Spol at the use AOI with ns pulses at 532 nm and 1064 nm. The beam combiner is based on 527 nm light incident on the coating from air and 1054 nm light incident on the coating from both air and the substrate.

9632-53, SESSION PSMON

Improved parametric spectroscopic performance of an optical fiber doped with erbium

Ghoumazi Mehdi, Nacer-Eddine Demagh, Azzedine Adouane, Badreddine Boubir, Abdel Kader Daoui, Ctr. de Développement des Téchnologies Avancées (Algeria)

ABSTRACT TEXT: In recent years, the rare earth ions and primarily Er played a crucial role in the development of the technology of optical telecommunications. The Emission of erbium ions at 1.53 microns is important for optical telecommunications because this emission corresponds to minimum mitigation of silica fibers which used as purpose to transport information. At first, we study the evolution of the signal powers and the pump powers along the propagation in the optical fiber amplifier Erbium doped. In addition, we study the variation of Erbium ions concentration for different spectroscopic parameters such as signal strength with (0, 1µW, 1mW) and the power of the pump going up 200 mW.

Keywords: *Fiber doped, optical Amplifier, optical fiber, rare earth,*

9632-54, SESSION PSMON

Analysis of cumulative versus ISO-recommended calculation of damage probability using a database of real S-on-1 tests

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

SPEAKER BIOGRAPHY: Doctor of Science, Electronics and Telecommunications Engineering specialty. Doctoral School of the Faculty (Dept.) of Electronics, Telecommunications, and Information Technology, University "Politehnica" of Bucharest. He is currently Head of the ISOTEST Laboratory and is involved in using, maintaining and developing the two automated test stations for measuring LIDT of optical materials in accordance to ISO standards.

ABSTRACT TEXT: An automated test station to measure the laser-induced damage threshold (LIDT) according to ISO 21254 standards was recently developed and described [1]. The laser is a single longitudinal mode, 500 mJ, 6 ns, Q-switched, 10 Hz, linearly polarized, 1064 nm laser, with 2-nd and 3-rd harmonic capabilities. Currently we operate the S-on-1 test (S = 500) or the Assurance Type 2 test on various substrates and coatings. So far, the implemented software calculates the damage probability in the conventional way, according to ISO 21254-2 standard, i.e., by considering only the damaged and the non-damaged sites corresponding to a certain fluence interval. Also, we use a linear fit of the damage probability versus fluence. Recently, an interesting algorithm to determine the damage probability points was suggested, the so-called the cumulative method [2]. According to this method, within a certain fluence interval are considered not only the sites belonging to that interval (conventional method sites), but also the damaged ones belonging to the lower fluence intervals, and the non-damaged ones belonging to the higher fluence intervals than the current fluence interval of interest (hence, the cumulative method name).

In this paper, using a database from real S-on-1 tests, we interpret each damage experiment in four different ways, i.e., by using both, the conventional and the cumulative method to determine the points of damage probabilities, and by fitting these points versus fluence with both, linear and nonlinear functions, respectively, the latter developed in [3].

The database used in this study is obtained from a number of 20 S-on-1 tests performed on different uncoated optical substrates of fused-silica and BK7 type. According to manufacturer's specifications, the working surfaces of these substrates have a polishing grade of P2 and P3 (as defined in the ISO 10110-8 standard). The fluence of the laser spot in the target plane is measured with an expanded uncertainty (i.e., a confidence interval of 95%) of less than 10% [4]. Results concerning the following parameters are presented and discussed:

- Threshold fluences for 0% and 50% damage probability, calculated for N = 1 and N = 500 number of pulses; statistical uncertainty of the damage probability points (error bars); fitting error of the probability curves.
- Extrapolated damage threshold to large number of pulses (N = 108) for 0% and 50% damage probability.

Preliminary data indicate that, for example, for the standard fit error the best (smallest) value is obtained for the nonlinear fit used with the cumulative method, supporting the promising role of the cumulative method.

REFERENCES

1. A. Stratan, A. Zorila, L. Rusen, S. Simion, C. Blanaru, C. Fenic, L. Neagu, G. Nemes, "Automated test station for laser-induced damage threshold measurements according to ISO 21254-1,2,3,4 standards", Proc. SPIE 8530, 85301Y (2012).
2. S. Schrameyer, M. Jupe, L. Jensen, D. Ristau, "Algorithm for cumulative damage probability calculation in S-on-1 laser damage testing?", Proc. SPIE 8885, 88851J (2013).
3. J.O. Porteus, S.C. Seitel, "Absolute onset of optical surface damage using distributed defect ensembles", Appl. Opt. 23, 3796-3805 (1984).
4. A. Stratan, A. Zorila, L. Rusen, and G. Nemes, "Measuring effective area of spots from pulsed laser beams", Opt. Eng. 53, 122513 (2014).

Keywords: *laser-induced-damage-threshold, ISO-standards, automated-stations, S-on-1 test, damage probability, conventional and cumulative, linear and nonlinear fitting errors*

9632-55, SESSION PSMON

Synthesis of Nd doped $Y_3Sc_xAl_{[5-x]}O_{12}$ (x = 0 to 2) composite ceramics with spectrum broadening and their damage resistance

Yuki Tamura, Takuya Kiriyama, Kazuki Kitabayashi, Kosuke Nuno, Tomosumi Kamimura, Osaka Institute of Technology (Japan); **Yan Lin Aung, Akio Ikesue,** World Lab Co., Ltd. (Japan)

ABSTRACT TEXT: Basic properties needed for a high energy laser material are large product of ? (cross-section of stimulated emission) and ? (life time of fluorescence), high thermal conductivity for material cooling and chemical stability. Especially, broadening for absorption and emission spectrum are important in the high energy laser field. Nd doped $Y_3Sc_xAl_{[5-x]}O_{12}$ (x = 0 to 2) ceramics was one of the candidates for high energy laser with broadband. As for Nd doped $Y_3Sc_xAl_{[5-x]}O_{12}$ (x = 0 to 2), PL spectral shift and width can be controlled with a composition ratio of Sc to Al. When the Sc to Al ratio become larger, the fluorescence lifetime has become longer than that of 1at%Nd:YAG. A composite structure with three compositions in Nd doped $Y_3Sc_xAl_{[5-x]}O_{12}$ (x = 0 to 2) ceramics was successfully fabricated for the first time by using "diffusion bonding technique". Regardless of the complicated compositions, it was confirmed that transparent quality of Nd:YSAG ceramic composites can be fabricated without mechanical stress due to bonding. The emission spectrum of multi-layered YSAG composite was more than 5 times broader compared to that of 1at% Nd:YAG. The laser oscillation experiment was performed for the fabricated Nd:YSAG composite sample. At a pumping power density of 1 kW/cm^2, output power 3 W was obtained with a slope efficiency of 75%. The laser oscillation test showed that the multi-layered composite made of Nd:YSAG ceramics reached laser grade optical quality. No detectable laser induced damage was observed at the bonding interface. This kind of YSAG composite wit h complicated compositions is highly expected for the application in high energy laser field and short pulse laser.

Keywords: *Nd doped $Y_3Sc_xAl_{[5-x]}O_{12}$ (x = 0 to 2), composite structure, diffusion bonding, laser induced damage, bonding interface*

9632-57, SESSION PSMON

Lowering evaluation uncertainties in laser-induced damage testing

Lars O. Jensen, Marius A. Mrohs, Mark Gyamfi, Heinrich Mädebach, Detlev Ristau, Laser Zentrum Hannover e.V. (Germany)

ABSTRACT TEXT: As a consequence of the statistical nature of laser-induced damage threshold measurements in the nanosecond regime, the evaluation method plays a vital role. The selected approach fundamentally depends on the test protocol and the way how data is recorded. Within the test procedure outlined in the corresponding ISO standard, several steps of data reduction are required, and the resulting damage probability distribution as a function of laser fluence needs to be fitted either based on an empirical regression function or described by models for the respective damage mechanism.

Especially when performing a test with a laser pulse duration, which generates inclusion or defect induced damage, the resulting raw test data might scatter over a wide range. With limits on the statistics (for example a limited test area) this can cause uncertainties in the derived threshold value far beyond the requirements of many applications. Following up on a previous contribution, we present thoughts on how data can be added to reduce the statistical error and therefore uncertainties in experimental measurement results.

The fundamental problem with an algorithm to treat empirical data is the lack of analytical proof for the validity of the suggested approach. With this inherent drawback, a procedure is discussed which can work without a fitting function as long as only the threshold value is of interest or the goal of the test.

Keywords: *LIDT data evaluation*

9632-58, SESSION PSMON

The role of fluence selection in the convergence and uncertainty of sensitivity measurements of laser damage behavior

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

SPEAKER BIOGRAPHY: Jonathan W Arenberg has been working as an optical and systems engineer for over 30 years. His work experience has included tactical and high-power laser components and systems and major space astronomical projects such as Chandra and the James Webb Space Telescope. He holds degrees in physics and engineering from the University of California, Los Angeles and currently the Chief Engineer for Northrop Grumman Aerospace Systems on the James Webb Space Telescope. Dr. Arenberg is an SPIE fellow.

ABSTRACT TEXT: This paper extends recent research into so-called sensitivity measurements of laser damage behavior. Previous efforts have concentrated on data collected from randomly selected fluence levels. This year's report will concentrate on the role of fluence selection protocols on the rate of convergence of the sensitivity method and the resulting uncertainty in model parameters. The role of damage probability models will also be discussed.

Keywords: *sensitvity tests, probability of damage, convergence, test methods, least squares, maximum likelihood, kernel density estimation*

9632-59, SESSION PSMON

An empirical investigation of the laser survivability curve: VI-nanosecond pulse widths

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

SPEAKER BIOGRAPHY: Jonathan W Arenberg has been working as an optical and systems engineer for over 30 years. His work experience has included tactical and high-power laser components and systems and major space astronomical projects such as Chandra and the James Webb Space Telescope. He holds degrees in physics and engineering from the University of California, Los Angeles and currently the Chief Engineer for Northrop Grumman Aerospace Systems on the James Webb Space Telescope. Dr. Arenberg is an SPIE fellow.

ABSTRACT TEXT: 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. In this year's paper we apply the promising scaling of fluence with shot number that was reported last year. Last year, an example was shown where the scaled result was shown to be very close the observed results providing a basis for extrapolation to very large values of n. In this year's report we apply this method to archival data and apply to new samples, to demonstrate the viability of this scaling method for nanosecond pulse widths.

Keywords: *Laser damage testing, qualification of laser optics, life testing, scaling, ISO 215254-2*

9632-60, SESSION PSMON

An empirical investigation of the laser survivability curve: VI-femtosecond pulse widths

Jonathan W. Arenberg, Northrop Grumman Aerospace Systems (United States); **Andrius Melninkaitis,** Vilnius Univ. (Lithuania); **Wolfgang Riede,** Deutsches Zentrum für Luft- und Raumfahrt e.V. (Germany); **Allesandra Ciapponi,** European Space Agency (Netherlands) and European Space Research and Technology Ctr. (Netherlands); **Paul Allenspacher,** Deutsches Zentrum für Luft- und Raumfahrt e.V. (Germany); **Jonathan H. Herringer,** Arrow Thin Films, Inc. (United States); **Denny Wernham,** European Space Agency (Netherlands)

SPEAKER BIOGRAPHY: Jonathan W Arenberg has been working as an optical and systems engineer for over 30 years. His work experience has included tactical and high-power laser components and systems and major space astronomical projects such as Chandra and the James Webb Space Telescope. He holds degrees in physics and engineering from the University of California, Los Angeles and currently the Chief Engineer for Northrop Grumman Aerospace Systems on the James Webb Space Telescope. Dr. Arenberg is an SPIE fellow.

ABSTRACT TEXT: 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. In this year's paper we apply the promising scaling of fluence with shot number that was reported last year. Last year, an example was shown for nanosecond pulsewidths where the scaled result was shown to be very close the observed results providing a basis for extrapolation to very large values of n. In this year's report we apply this method to archival and new samples, to demonstrate the extension of this scaling method to femtosecond pulse widths.

Keywords: *laser optics qualification, lifetime, femtosecond pulses, scaling, ISO 21254-2*

9632-61, SESSION PSMON

Direct comparison of statistical damage frequency method and raster scan procedure

Gintare Bataviciute, Mindaugas Šciuka, Viktorija Plerpaite, Andrius Melninkaitis,
Vilnius Univ. (Lithuania)

ABSTRACT TEXT: Presented study addresses the nano-size defects acting as damage precursors in nanosecond laser pulse irradiation regime. Such defects are inherent in optics manufacturing processes and namely glass shaping, polishing and deposition procedures. Various subsurface cracks, absorbing inclusions and nodules are the defects responsible for the so-called extrinsic damage initiation that possesses statistical behavior. Defect properties are investigated in terms of defects ensembles, which define the localized damage threshold distribution of the defects. Defect ensemble can be characterized by two approaches: damage frequency method and raster scan procedure. Both techniques were directly compared on the same set of samples. Tests were performed on uncoated fused silica substrate and SiO_2 monolayer film exposed under nanosecond UV radiation (355 nm, 4.8 ns). If both methods were unbiased, they should be able to reproduce the same results. However, direct comparison reveals that reported defect ensembles are conflicting with each other. In order to explain these differences, several experimental limitations of the raster scan procedure are discussed. Firstly, experimental data has to be corrected for the uncertainty caused by measurement procedure. A revised approach is suggested to characterize pulse-to-pulse variation of laser intensity. Secondly, the surface of a sample is shown to be affected by debris of ablated particles, when exposed under peak laser fluence higher than defect damage threshold. Contamination by debris can't be distinguished by optical microscopy, thus alternative methods of surface inspection should be applied, for instance: atomic force microscopy. Finally, clustering of the particles is considered as a possible limitation factor for over- or underestimation in defect density data determined by raster scan procedure. All those findings should be considered in order to determine true defect ensemble.

Keywords: *Laser-Induced Damage, 1-on-1 test procedure, Raster scan procedure, Fused silica, SiO2 monolayer, Defect ensemble, Surface contamination, Damage frequency method, Damage density measurements*

9632-62, SESSION PSMON

Characterization of damage precursor density from laser damage probability measurements with non-Gaussian beams

Frank R. Wagner, Institut Fresnel (France); Andrius Melninkaitis, Vilnius Univ. (Lithuania); **Gintare Bataviciute,** Vilnius Univ. (Lithuania); **Céline Gouldieff, Alexandre Beaudier,** Institut Fresnel (France); **Linas Smalakys,** Vilnius Univ. (Lithuania); **Jean-Yves Natoli,** Institut Fresnel (France)

ABSTRACT TEXT: One of the easiest ways to quantify the laser damage resistance of optical components is to measure their single-pulse laser damage probability as function of the peak fluence of the beam. Especially for pulses of nanosecond durations resistance of dielectric optics is limited by so called extrinsic defects. In this case damage probability can be described by models relying on the probability to encounter at least one laser damage precursor that causes damage deterministically when irradiated above its threshold within the high-fluence region of the test beam. In the simplest case, all damage precursors have the same threshold, nevertheless different distributions of the thresholds (either power law or Gaussian) may also be assumed.

The aim of fitting damage probability curves arising from these models to the measurements always consists of extracting the physical parameters of the model as well as their estimated uncertainties. In the simplest case there are two parameters: the precursor threshold and the precursor density. Besides the peak fluence, the beam surface above the precursor threshold is essential for a correct estimation of the precursor density from the measurements.

When using laser systems with beams that cannot be easily described by an analytical formula, the effective surface area Aeff is the only parameter that links the pulse energy to the peak fluence of the beam. However the estimated value of the defect density is strongly affected by the real intensity distribution of the beam.To address this issue we discuss possibility to consider real experimental beams (non-Gaussian, non-flat-top) in the fitting procedure without introducing significant errors in the physical parameters deduced from fitting. We also give recommendations how to implement the fit procedure using an experimental beam profile image and discuss possibilities to take into account the fluctuations in the beam profile.

Keywords: *Nanosecond laser damage, damage probability measurement, damage precursor density, beam profile, beam shape*

9632-63, SESSION PSMON

Transmittance measurements of laser components using a combination of cavity ring-down and photometry

Bincheng Li, Institute of Optics and Electronics (China) and Univ. of Electronic Science and Technology of China (China); **Hao Cui,** Univ. of Electronic Science and Technology of China (China) and Institute of Optics and Electronics (China); **Yanling Han,** Institute of Optics and Electronics (China); **Chunming Gao, Yafei Wang,** Univ. of Electronic Science and Technology of China (China)

ABSTRACT TEXT: A combined cavity ring-down (CRD) and photometry technique is employed to measure the transmittance of optical laser components in a range extending from below 0.01% to over 99.99%. In this combined technique, the conventional photometric configuration is used to measure, by ratioing the transmitted light power to the input power, the transmittance ranging from below 0.01% to over 99% with a typical uncertainty below 0.3%, and the CRD configuration is used to measure the transmittance higher than 99% with an uncertainty below 0.01%. Eight test samples with transmittance in the range of nearly 99.99% to approximately 0.013% are experimentally measured. Uncertainties of approximately 0.0001% for the transmittance of 99.9877% and of 0.003% for the transmittance of 0.013% are achieved with respectively the CRD and photometric schemes of a simple experimental apparatus. The experimental results showed that the combined technique is capable of measuring the transmittance of any practically fabricated optical laser components.

Keywords: *cavity ring-down, photometry, transmittance, optical components*

9632-3, SESSION 2

Investigating the relationship between material properties and laser-induced damage threshold of amorphous dielectric optical coatings at 1064 nm

Riccardo Bassiri, Stanford Univ. (United States); **Iain W. Martin,** Univ. of Glasgow (United Kingdom); **Caspar C. Clark,** Helia Photonics Ltd. (United Kingdom); **Ashot S. Markosyan,** Stanford Univ. (United States); **Sheila Rowan,** Univ. of Glasgow (United Kingdom); **Martin M. Fejer,** Stanford Univ. (United States)

ABSTRACT TEXT: The Laser Induced Damage Threshold (LIDT) and material properties of various mono- and multi-layer amorphous dielectric optical coatings, including Nb_2O_5, Ta_2O_5, SiO_2, TiO_2, ZrO_2, AlN, SiN, LiF and ZnSe, have been studied.

The development of these coatings is aimed at high optical fluence products, such as high power solid-state laser modules, optical filters, multi-cavity wavelength-splitting free-space filters for telecoms, datacoms and microscopy products.

The coatings were produced by ion assisted electron beam and thermal evaporation; and RF and DC magnetron sputtering at Helia Photonics Ltd, Livingston, UK. The coatings were characterized by optical absorption measurements at 1064 nm by Photothermal Common-path interferometry. Surface roughness and damage pits were analyzed using atomic force microscopy. LIDT measurements were carried out at 1064 nm, with a pulse duration of 9.6 ns and repetition rate of 100 Hz, in both 1000-on-1 and 1-on-1 regimes.

We present the 1064 nm optical absorption of the coatings, with values ranging from 1 to 165 ppm and surface roughness between 1.4 to 11.5 nm. We also show a high damage threshold observed in an anti-reflection multi-layer ZrO_2/SiO_2 coating, which has an absorption of 10 ppm and surface roughness of 11.5 nm. Finally, the relationship between absorption, roughness and LIDT of the coatings will be discussed along with LIDT improvement techniques.

Keywords: *Laser Induced Damage Threshold, Coatings, Absorption, Roughness, Material properties, Dielectric*

9632-4, SESSION 2

Influence of different-sized femtosecond fabricated substrate pits on nanosecond-laser-induced-damage in high-reflective mirrors

Yingjie Chai, Meiping Zhu, Kui Yi, Weili Zhang, Yuanan Zhao, Jianda Shao, Shanghai Institute of Optics and Fine Mechanics (China)

SPEAKER BIOGRAPHY: Meiping Zhu has been in coating research group at Key Laboratory of Materials for High Power Laser, Shanghai Institute of Optics and Fine Mechanics since 2006 researhing high power laser coatings.

ABSTRACT TEXT: The laser damage resistance of high reflective coatings in high power laser systems depends significantly on the surface quality of the substrate. There is a general agreement that substrate structure defect is one of the major factor affecting the high-reflective coating performance and laser-induced damage threshold designed for 1?, nanosecond-scale, pulsed-laser applications. Recently, a new approach for studying laser interaction with micro-scale structure defects is implemented, by which well-characterized, precisely controlled isolated pits are introduced on the substrate surface. Different size of pits (2~8 μm) are fabricated on fused silica, respectively, by 800 nm-femtosecond-laser to prevent the emergence of subsurface cracks. The HfO_2/SiO_2 high-reflective coatings at 1064 nm are deposited by conventional e-beam evaporation onto fused silica substrates with and without pits, respectively. The substrate micro-pit sensitivity on the laser resistance of high-reflective coatings was investigated. Simulations by the finite element method are carried out and the results demonstrate the modulation of a high reflector multilayer geometry may lead to electrical-field amplification and consequently reduce laser damage resistance.

Keywords: *Laser-induced damage, Thin films, Femtosecond fabricated method, Micro-scale pits*

9632-5, SESSION 2

Picosecond laser damage performance of the multilayer dielectric pulse compressor gratings and high reflectors for the advanced radiographic capability Petawatt laser system

Raluca A. Negres, Isaac L. Bass, Kenneth A. Stanion, Gabriel M. Guss, David A. Cross, David A. Alessi, Jerald A. Britten, Christopher J. Stolz, Paul J. Wegner, Lawrence Livermore National Lab. (United States)

SPEAKER BIOGRAPHY: Raluca A. Negres has been a Research Scientist with Lawrence Livermore National Laboratory since 2004. Her research interests include time-resolved imaging and spectroscopic studies of dynamic events during laser-induced damage in optical materials and characterization of high performance optical materials for high average and peak power laser systems.

ABSTRACT TEXT: High-energy petawatt laser systems such as the Advanced Radiographic Capability (ARC) rely on grating pulse compressors and focusing optics to generate high peak power and irradiance on target. The final optics operate in a vacuum environment to avoid nonlinear effects that occur while propagating in air. The ARC laser system will implement chirped pulse amplification on 4 beamlines of the National Ignition Facility (NIF) to produce eight petawatt-class short pulses (1-50 ps), 1053 nm beams with a total energy of 3.2-13.6 kJ. The peak irradiance of the ARC system is limited by optical damage on the final optics making it of great interest to qualify the performance of these components in their use environment and gain insight into the fundamental damage mechanisms in the picosecond (ps) regime.

We have assessed the laser damage resistance of witness samples (multilayer dielectric pulse compressor gratings and high reflectors) using a recently upgraded vacuum damage test station driven by a 1053-nm, OPCPA laser system capable of delivering 6 mJ, 1-50 ps pulses at 10 Hz repetition rate. We employ standard R-on-1 as well as raster scanning using a small area beam test methodologies to estimate the pulsewidth scaling, probe the effects of the test area on the damage onset and determine whether or not damage with ps pulses is extrinsic (defect driven) in nature, as is the case with ns pulses. The results obtained from representative sub-scale witness samples can be used to predict the full-scale optics performance at the ARC operation fluence.

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Keywords: *short pulse laser-matter interactions, multilayer dielectric coatings, laser induced damage, coating defects*

9632-6, SESSION 2

A comparative study of the laser-induced damage characteristics of artificial nodules prepared by different processes

Xinbin Cheng, Hongping Ma, Abudusalamu Tuniyazi, Tongji Univ. (China); Yongjian Tang, China Academy of Engineering Physics (China); **Zhanshan Wang,** Tongji Univ. (China)

SPEAKER BIOGRAPHY: Xinbin Cheng received his PHD in 2008 from the Tongji University. He is an associate professor for Optics at Tongji University. Since 2010 he heads the group High Power Laser Coatings in the Institute of Precision Optical Engineering of Tongji University. His research interests comprise high power laser coatings, XUV multilayers and nanometrological transfer standards.

ABSTRACT TEXT: The laser-induced damage characteristics of artificial nodules in 1064nm high reflectors were investigated via a comparative study. Four types of 1064nm high reflectors were prepared using two material combinations (HfO_2/SiO_2, Ta_2O_5/SiO_2) and two deposition processes (electron beam evaporation and ion assisted deposition), and four sizes of SiO_2 microspheres were incorporated into the coatings to created engineered nodules. For the nodules in the high reflectors prepared by the electron beam evaporation process, the damage growth threshold was higher than the nodules ejection threshold. Whereas, for the nodules in the high reflectors prepared by the ion assisted deposition process, the damage growth threshold was lower than the nodules ejection threshold. Moreover, the damage growth speed was different for different kinds of artificial nodules. The above observed laser-induced damage characteristics were interpreted from the aspects of coating material property, electric-field enhancement, thermomechanical stability, etc.

Keywords: *Artificial nodules, laser-induced damage, High reflector, damage growth*

9632-7, SESSION 3

Impact of laser-contaminant interaction on the performance of the protective cap layer of 1w HR mirror coatings

Siping R. Qiu, Mary A. Norton, Rajesh N. Raman, Alexander M. Rubenchik, Lawrence Livermore National Lab. (United States); **Amy L. Rigatti,** Univ. of Rochester (United States); **Paul B. Mirkarimi, Christopher J. Stolz, Manyalibo J. Matthews, Charles D. Boley,** Lawrence Livermore National Lab. (United States)

ABSTRACT TEXT: The performance of dielectric high reflective multilayer coatings in high peak power laser systems can be limited by damage induced through coupling between the laser and contaminating particles on the surface. An absentee layer of protective cap is often used to improve the coating resistance to laser damage, including that induced by laser-contaminant interaction. In order to facilitate the effective selection and design of cap material, it is important to understand the underlying mechanism by which laser-particle interaction leads to the cap layer damage. In the present study, a single laser shot at 10 J/cm^2 and beam area of ~0.2 cm^2 is used to investigate laser damage initiation on two silica-hafnia multilayer coating samples with different cap layer (Al_2O_3 vs. SiO_2). The two test samples are coated on 2" round BK7 substrates by e-beam physical vapor deposition with high reflectivity (>99%) at 1053 nm (1, 45, P polarization). A sample contaminated with commercially available spherical Ti particles (diameter ~ 50 µm) was mounted vertically in air and exposed to the 1 beam (duration 14 ns FWHM) at 45 from the surface normal. For the sample with the Al_2O_3 cap layer, the single exposure led to damage sites, up to 400 ?m in size, at locations of particles. The damage sites resulted from the mechanical breakdown and subsequent delamination of the cap layer and exhibited a distorted oval shape. For the sample with the SiO_2 cap layer, laser-exposed Ti particles led to modified regions with a similarly distorted oval shape and size. However, instead of layer removal, the modified areas resulted from a shallow depression of the cap layer. It is speculated that the laser-Ti interaction at the coating surface generates plasma ejecting towards the incident beam which leads to surface layer heating at the particle locations. The difference in damage behavior observed between the two cap layers is attributed to the large contrast in the thermal expansion coefficient between them with that of the Al_2O_3 being approximately 15 times greater. Modelling suggests that with the oblique incidence, a spherical shaped particle, and a high reflective surface, the damaged areas can be substantial, as observed.

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9632-8, SESSION 3

Laser damage resistant interference coatings for 1.6 µm wavelength operation

Drew D. Schiltz, Dinesh Patel, Cory Baumgarten, Brendan A. Reagan, Jorge J. Rocca, Carmen S. Menoni, Colorado State Univ. (United States)

ABSTRACT TEXT: We fabricated high reflection and anti-reflection interference coatings for 1.6 µm wavelength based on stacks of metal oxides deposited by ion beam sputtering. Employing an optical parametric chirped pulse amplifier, the interference coatings were tested at wavelength using pulses of two picoseconds. A laser damage threshold fluence of ~7.0 J/cm2 was measured for HfO_2/SiO_2 and Y_2O_3/SiO_2 stacks. This damage fluence is near that of the infrared grade fused silica substrates on which the interference coatings are deposited. This behavior challenges current understanding of picosecond laser damage, as the damage appears unimpaired by nonlinear absorption processes and by electric field interference effects.

Keywords: *laser induced damage, interference coating, ion beam sputtering, optical properties*

9632-9, SESSION 3

Sheet resistivity and optical absorption of Al-doped ZnO thin films: a “conductive” layer to reduce the charging effects

Ashot S. Markosyan, Riccardo Bassiri, Stanford Univ. (United States); Ric P. Shimshock, MLD Technologies, LLC (United States); Brian T. Lantz, Roger Route, Martin M. Fejer, Stanford Univ. (United States)

ABSTRACT TEXT: Charge build up on the ultra-low loss dielectric optical coatings can be a source of unwanted effects such as displacement noise in high performance devices, e.g. AdLIGO interferometer, as well as be a potential damage precursor in high-power laser systems. One way of mitigating the problem straightforwardly is deposition of a partially conductive thin layer between the mirror substrate and the interference coating stack coupled with a UV discharge point on the barrel of the optic. Analytical modeling of the surface charge spreading suggests that sheet resistivities of ~1014 ?/sq (100 T?/sq) would be sufficient to keep spurious charge relaxation processes less than one second.

In this work the experimental results on optical absorption and sheet resistivity of low-loss (< 5 ppm) Al-doped ZnO films with Al concentration varying in the range 9 to 27 at.% are presented. With thickness of 500 nm, the sheet resistivity of these films is less than 200 G/sq. for Al/Zn ratio less than 0.34.

The experimental data are discussed assuming that the Al-doped ZnO films are n-type wide bandgap semiconductors in which the n-carrier concentration varies with Al-doping.

Keywords: *optical absorption of Al-doped ZnO films, conductive transparent Al-doped ZnO optical thin films*

9632-10, SESSION 3

The role of film interfaces in near-ultraviolet absorption and pulsed-laser damage in ion-beam–sputtered coatings based on HfO_2/SiO_2 thin-film pairs

Semyon Papernov, Alexei A. Kozlov, James B. Oliver, Christopher Smith, Univ. of Rochester (United States); **Lars O. Jensen, Detlev Ristau, Stefan Günster, Heinrich Mädebach,** Laser Zentrum Hannover e.V. (Germany)

ABSTRACT TEXT: The role of thin film interfaces in the near-ultraviolet absorption and pulsed laser-induced damage was studied for ion-beam-sputtered coatings comprised from HfO_2 and SiO_2 thin-film pairs. In order to separate contributions from bulk of the film and from interfacial areas, comparative absorption measurements were performed for one-wave (355-nm) thick HfO_2 monolayer film deposited on supporting SiO_2 layer and for coating containing seven narrow HfO_2layers separated by SiO_2 layers. The seven-layer coating was designed to have total optical thickness of HfO_2 layers equal to one wave at 355 nm and E-field peak and average intensity similar to monolayer HfO_2 film. Absorption in both types of films was measured using photothermal heterodyne imaging and laser calorimetry. The results, normalized to internal E-field distribution, permitted estimation of the contribution to total absorption from thin film interfaces. Relevance of obtained absorption data to coating pulsed-laser damage was verified by conducting damage threshold measurements and damage-morphology characterization. The results of this study were compared to data recently reported for similarly designed electron-beam deposited coatings.

Keywords: *Absorption, Thin films, Laser damage*

9632-11, SESSION 3

Broadband low-dispersion mirror thin film damage competition

Christopher J. Stolz, Lawrence Livermore National Lab. (United States); **Kyle R. P. Kafka, Enam Chowdhury,** The Ohio State Univ. (United States); **Matthew S. Kirchner,** Kapteyn-Murnane Labs., Inc. (United States)

SPEAKER BIOGRAPHY: Christopher Stolz has been in the laser program at Lawrence Livermore National Laboratory (LLNL) since 1989 researching high-power laser coatings. He is currently responsible for the Optics Production group for the National Ignition Facility (NIF). Chris has served as a cochair or program chair for numerous conferences including Laser Induced Damage in Optical Materials and Optical Interference Coatings. He has coauthored over 90 journal and proceeding articles and 2 book chapters.

ABSTRACT TEXT: Broadband low dispersion mirrors are a fluence-limiting component in short pulse lasers. For this study the mirrors meet a minimum reflection of 99.5% GDD of <± 100 fs2 over a spectral range of 773 nm ± 50 nm. The participants select the coating materials, design, and deposition method. Laser damage testing was performed using a raster scan method with a 150 ps pulse length on a single testing facility to facilitate a direct comparison among the participants. Group Dispersion Delay measurements were also performed on each sample. Details of the deposition processes, cleaning method, coating materials, layer count, and spectral results are shared.

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9632-12, SESSION 4

Volume holographic elements for high-power laser applications *(Keynote Presentation)*

Leonid B. Glebov, CREOL, The College of Optics and Photonics, Univ. of Central Florida (United States) and OptiGrate Corp. (United States)

SPEAKER BIOGRAPHY: Leonid Glebov got his Ph.D. from State Optical Institute, Leningrad, Russia (1976) and has been affiliated with it up to 1995. Since 1995 Dr. Glebov has been at CREOL/UCF as a Research Professor. He is a founder and VP for R&D of OptiGrate Corp. He is a coauthor of a book, more than 300 papers in scientific journals and 10 patents. He is a fellow of ACerS, OSA, SPIE, and NAI. He is a recipient of Gabor award in holography. The main directions of research are optical properties of glasses, holographic optical elements, and lasers controlled by volume Bragg gratings.

ABSTRACT TEXT: This presentation summarizes the results of volume holographic elements development for high power laser applications that were performed by research teams Photoinduced Processing Laboratory at CREOL/UCF and OptiGrate. The main types of holographic optical elements recorded in photo-thermo-refractive (PTR) glass are described: reflecting and transmitting volume Bragg gratings (VBGs), longitudinal and transverse chirped Bragg gratings (CBGs), tunable and achromatic holographic phase masks (HPMs), and distributed Bragg reflector (DBR) and distributed feedback (DFB) monolithic solid state lasers. No optical bleaching of holograms in PTR glass was detected for any type of CW or pulsed laser radiation. The main effects caused by high power CW radiation are shift of Bragg wavelength and induced lensing caused by thermal expansion of PTR glass resulted from absorption of laser radiation. The methods of heat management enabling operations at multikilowatt CW regimes are described. Bulk laser damage by pulsed laser radiation is caused by absorbing micro-inclusions that are byproducts of PTR glass fabrication and self-focusing. Nonlinear refractive index for PTR glass is the same as for fused silica. Exposure of PTR holographic optical elements to extremely high power femtosecond pulses results in self-phase modulation and supercontinuum generation. Examples of the use of PTR holographic optical elements in high power laser systems are presented. Limitations of the use of PTR holographic optical elements in high power pulsed laser systems are given.

Keywords: *Photo-thermo-refractive glass, Volume Bragg gratings, Holographic optical elements, Laser induced damage, Laser induced thermal effects*

9632-13, SESSION 4

Dedicated contamination experiments in the Orion laser target chamber

James E. Andrew, AWE plc (United Kingdom)

SPEAKER BIOGRAPHY: James Andrew is a principal scientist in the Plasma Physics Group at AWE plc.

ABSTRACT TEXT: The use of solid targets irradiated in a vacuum target chamber by focussed high energy, high power laser beams to study the properties of matter at high densities, pressures and temperatures are well known. An undesirable side effect of these interactions is the generation of plumes of solid, liquid and gaseous matter which move away from the target and coat or physically damage surfaces within the target chamber. The largest aperture surfaces in these chambers are usually the large, high specification optical components [i.e. large aperture off axis parabolas, aspheric lenses X ray optics and planar debris shields] used to produce the extreme conditions being studied. In order to study these plumes and the effects that they produce a set of dedicated experiments were performed to evaluate target by product coating distributions and particle velocities by a combined diagnostic instrument that utilised metal witness plates, polymer witness plates, fibre velocimetry and low density foam particle catchers.

Keywords: *aluminum, coating, contamination, copper, debris, gold, Orion, shrapnel*

9632-14, SESSION 5

Study of laser-induced damage at 1064nm in fused silica samples in vacuum environment

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

ABSTRACT TEXT: Ring patterns surrounding laser damage sites at the exit surface of fused silica are systematically observed when initiated by multiple longitudinal mode nanosecond laser pulses at 1064 nm in air environment. It has been shown in previous works that these patterns are the consequence of plasma dynamics and ablation processes. Indeed, a laser-driven ionization front supported by air develops while hot electrons activate the surface. Experiments have been performed in vacuum environment with multiple longitudinal modes pulses so as to corroborate the importance of air in the formation of ring patterns. In this configuration, the speed of appearance of the rings and the induced diameters are completely different than the ones observed in air environment. These observations imply that the mechanisms of formation of the rings are different when withdrawing the air. The investigation of laser-induced damage in vacuum environment has then been possible thanks to multiple longitudinal mode pulses.

Keywords: *nanosecond laser-induced damage, fused silica, vacuum environment, plasma dynamics, ring patterns*

9632-15, SESSION 5

Laser-induced damage of fused silica on high-power laser: beam intensity modulation, optics imperfection, contamination

Dongfeng Zhao, Shanghai Institute of Optics and Fine Mechanics (China)

ABSTRACT TEXT: Last October, one of the SG-II U facility's eight beams shots 3ω laser to target chamber about 19 shots. Beam energies at 3ω for these shots range from 3 to 5KJ, and pulse shapes are flat in time about 2.8ns. The wedged focus lens, one of the final optics assembly's optics, focuses the 351 nm beam onto target and separates the residual 1053 and 527 nm light with 351 nm light. After the experiment, it has about 42 damage-filaments in body at particular area. The damage-filaments almost start 20mm under the front-surface of wedged focus lens and extend to back-surface. The diameter of damage-filaments is about 20μm. And, the tail of damage-filaments, these damages are bulk spots and range form φ50 to 300μm.

The result shows that there are three reasons to induce theses damages when laser beam irradiates the fused silica. As the final optical assembly, these reasons are beam intensity modulation, optics imperfection and contamination. The 3ω beam intensity modulation is 100% with science camera to measure the whole beam diameter when the 1ωbeam is frequency conversion to 3ω beam by a pair of KDP crystals. And the optics imperfection can lower initial damage threshold and increase the 3ω beam intensity modulation because of diffraction. But the effect maybe neglect to laser energy fluence $<4J/cm^2$ because of the front subsurface of the optics processing with HF-based etching under ultrasonic. The contamination includes dust, metal and sio_2. These contaminations, the same to subsurface, can increase the beam intensity modulation because of diffraction. Therefore, the 3ω beam intensity modulation is the mostly import factor to induce damage. The n2 nonlinear coefficient can lead to small-scale self-focusing filament because of optics thickness and beam intensity. And some damage-filaments' tails are bulk damage spots because there are subsurface scratches or metal contaminations.

Keywords: *high power laser, laser damage, fused silica, final optics assembly, beam intensity, contamination, nonlinear, HF etching*

9632-16, SESSION 5

Laser-induced shallow pits on silica output surfaces: formation and resulting light scattering

Eyal Feigenbaum, Rajesh N. Raman, Norman D. Nielsen, Manyalibo J. Matthews, Lawrence Livermore National Lab. (United States)

ABSTRACT TEXT: A substantial effort has been spent in the last decade on mitigating damage sites initiation in high power lasers optics and on the suppression of their shot-to-shot growth [1-5]. These growing damage sites can be characterized by their complex fracture-dominated morphologies and while only a few tens of microns in depth have the potential to limit optics lifetime. On the other hand, much shallower laser-induced pits (i.e., sub-micron) that are free of fracture and appear on optics in greater densities are the subject of fewer studies since they do not change morphology under subsequent laser pulses (i.e. no growth), and do not lead to direct optics lifetime limitations. However, in this study we show that these shallow pits can be traced to certain types of particulate contamination and will ultimately lead to laser power scattering and performance degradation. These laser-induced shallow pits (LSPs) could be found on the exit surface of silica parts and are highly axisymmetric with Gaussian-like profile. We will discuss the formation of these LSPs and present relatively simple analytical relations between the observed morphology of the LSPs and the power scattering at the far-field. We note that these expressions could also be utilized for a carefully designed beam shaping optic based on LSP clusters.

We characterize the formation of LSP ensembles as a result of the exposure of fused silica slabs having particulates on their exit surface to different incident fluences. We use a set of fused silica substrates and sprinkle their exit surface with similar size and material particles and use confocal microscopy to characterize the morphology. We find that the size of the resulting LSP is correlated to the incident fluence, and that the width and the depth of the LSP increase proportionally. A morphology deviation from a Gaussian shape is detected as the incident fluence is increased.

Based on the Gaussian-like shape of the LSPs we derive closed form expressions for the total power scattering in the far-field and for its angular distribution. We validate the paraxial approximation usage for the pit shapes observed experimentally using Finite-Difference Time-Domain (FDTD) numerical simulations of Maxwell's equations. Expressions for the far-field scattering angle and the total scattered power are rigorously derived based on a Fraunhofer propagation representation. It is found that the scattered power is proportional to the square of the pit width and approximately also to the square of the pit depth, with the proportionality factor scaling with pit shape. As a result, the power scattered from shallow pitted optics is expected to be substantially lower than assuming complete scattering from the total visible footprint of the pits. The net scattering from an ensemble of LSPs is studied as a function of different mix ratios in a bi-modal population, showing substantial dominance to the wider pits. The closed form expressions are validated also for other observed pit morphologies (e.g. HF etching pits) which deviate from a Gaussian shape.

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9632-17, SESSION 5

Sub-wavelength microstructures for high-power laser application on fused silica

Ye Xin, Jin Huang, Ruifang Ni, Laixi Sun, Xiaodong Jiang, Wanguo Zheng, China Academy of Engineering Physics (China)

ABSTRACT TEXT: Light reflection occurs at the interface between two materials with different refractive index. The subwavelength microstructures (SWSs) built on the surfaces of an optic or window, which have a period sufficiently smaller than the wavelength of light, are an effective replacement for thin-film coatings in antireflection (AR) applications. AR SWSs exhibit particularly noteworthy performance where an average reflection loss of less than 1% over a broad wavelength range (500-1100nm) has been demonstrated. Recently, it has been shown that the LIDT of the AR SWSs is much approaching to the fused silica without the AR coating. The development of AR SWSs for use in high-power laser applications is presented. Scanning electron microscope (SEM) analysis, reflection measurement, and LIDT testing, are used to analyze the characteristic of AR SWSs fabricated in fused silica. The results of LIDT testing at wavelength of 1064nm confirm the initial result that AR SWSs can operate at pulsed laser power levels at least higher than that of untreated fused silica.

Keywords: *subwavelength structure, antireflection, reactive ion etching, laser induce damage threshold*

9632-18, SESSION 5

Effect of reaction ion etching process on laser-damage performance of fused silica optics

Laixi Sun, Hongjie Liu, Jin Huang, Xin Ye, Xiaodong Jiang, Weidong Wu, China Academy of Engineering Physics (China)

ABSTRACT TEXT: Laser induced damage of fused silica optics occurs primarily at surface or subsurface defects produced during polishing/grinding process. Many kinds of surface treatment processes are explored for improving laser damage resistance of fused silica. In this study, Reaction ion etching with CHF3-Ar mixture gas was used to experimentally investigate the influence of the etching process on defects distribution of fused silica optics. The influence of etching depth on laser damage performance was investigated and the impurities contamination, SSD, and stoichiometry were characterized by time-of-flight secondary ion mass spectrometry, confocal fluorescence microscopy and X-ray photoelectron spectroscopy respectively. The results show that RIE can efficiently eliminate the mental impurities defects in the redeposition layer and the fluorescence defects in the subsurface layer, which are associated with the damage performance of fused silica. Damage test reveals the damage performance of etched fused silica samples is enhanced dramatically. The results ulteriorly clarify laser induced damage mechanism and are beneficial for improving damage resistance of fused silica under UV pulse laser irradiation.

Keywords: *damage, defects, fused silica, surface, reaction ion etching, characterization, subsurface, contamination*

9632-64, SESSION PSTUE

Direct absorption measurements in thin rods and optical fibers

Christian Mühlig, Simon Bublitz, Martin Lorenz, Leibniz-Institut für Photonische Technologien e.V. (Germany)

SPEAKER BIOGRAPHY: Christian Mühlig received his MS degree from Essex University, Colchester, England, in 1995, and his Diploma and PhD degrees in physics from Friedrich-Schiller University, Jena, Germany, in 1997 and 2005. He is currently a senior scientist in the work group Laser Diagnostics of the Department of Microscopy at Leibniz Institute of Photonic Technology, Jena, Germany. His research interests include laser based characterization of optical materials and coatings as well as modeling laser-induced absorption phenomena.

ABSTRACT TEXT: We report on the first realization of direct absorption measurements in thin rods and optical fibers using the laser induced deflection (LID) technique. Typically, along the fiber processing chain more or less technology steps are able to introduce additional losses to the starting material. After the final processing, the fibers are commonly characterized regarding losses using the so-called cut-back technique in combination with spectrometers. This, however, only serves for a total loss determination. For optimization of the fiber processing, it would be of great interest to not only distinguish between different loss mechanisms but also have a better understanding of possible causes.

For measuring the absorption losses along the fiber processing, a particular concept for the LID technique is introduced and requirements, calibration procedure as well as first results are presented. It allows to measure thin rods, e.g. during preform manufacturing, as well as optical fibers. In addition, the results show the prospects to also apply the new concept to topics like characterizing unwanted absorption after fiber splicing or Bragg grating inscription. In combination with other established concepts, the LID technique now covers the absorption characterization from the starting material to the final optical fiber.

Keywords: *absorption, optical fibers, fiber technology, photothermal technique, direct absorption measurement*

9632-65, SESSION PSTUE

Bulk damage and absorption in fused silica due to high-power laser applications

Frank Nuernberg, Heraeus Quarzglas GmbH & Co. KG (Germany)

ABSTRACT TEXT: Laser fusion projects are heading for IR optics with high broadband transmission, high shock and temperature resistance, long laser durability, and best purity. For this application, fused silica is an excellent choice. The energy density threshold on IR laser optics is mainly influenced by the purity and homogeneity of the fused silica. Heraeus Quarzglas developed the material grades Suprasil 3002/3001/300 especially for the infrared spectrum where performance must be optimized.

The absorption behavior regarding the hydroxyl content was studied for various synthetic fused silica grades. The main absorption influenced by OH vibrational excitation leads to different IR attenuations for OH-rich and low-OH fused silica [1]. The attenuation depends on the wavelength. Three wavelengths 946 nm, 1064 nm and 1319 nm were analyzed, which are typically used for laser diodes, pumping, material processing, Nd-doped lasers and medical purposes [2-4]. The measurements show two clear dependencies: OH-content and purity. In region with low vibrational excitations, materials with a low impurity level have a lower absorption. And for the same impurity level, materials with lower OH-content show lower absorption.

Industrial laser systems aim for the maximum energy extraction possible. Heraeus developed an Yb-doped fused silica fiber to support this growing market [7]. But the performance of laser welding and cutting systems is fundamentally limited by beam quality and stability of focus. Since absorption in the optical components of optical system has a detrimental effect on the laser focus shift, the beam energy loss and the resulting heating has to be minimized both in the bulk materials and at the coated surfaces. In collaboration with a laser research institute, an optical finisher and end users, photothermal absorption measurements on coated samples of different fused silica grades were performed to investigate the influence of basic material properties on the absorption level [5,6]. The low OH materials Suprasil 3002/3001/300 finally led to the lowest absorption results.

High purity, synthetic fused silica is as well the material of choice for optical components designed for DUV applications (wavelength range 160 nm - 260 nm). With the advent of the DUV microlithography stepper generation, the importance of fused silica as optical material has increased still further.

For higher light intensities, e.g. provided by excimer lasers, an interaction between the UV radiation and the optical material has to be taken into account. The UV photons may generate defect centers that effect the optical properties during usage, resulting in an aging of the optical components (UV radiation damage). Most important are additional absorption (induced absorption), induced refractive index change (compaction), and laser induced fluorescence.

Powerful excimer lasers require optical materials that can withstand photon energy close to the bandgap and the high intensity of the short pulse length. We concentrate on the induced absorption effect in fused silica caused by ArF and KrF laser radiation (193 nm and 248 nm). This absorption is restricted to the DUV wavelength range below 300 nm and consists of three different absorption bands centered at 165 nm (peroxy radicals), 215 nm (E'-center), and 265 nm (non-bridging oxygen hole center (NBOH)), which change the transmission behavior of material [8].

However, this induced absorption is transient in molecular hydrogen containing quartz glass types, meaning that it disappears when the laser is switched off. The defect centers that cause this absorption relax into a non-absorbing state with a time constant of about 120 s [9].

REFERENCES

[1] O. Humbach et al., J. Non Crystalline Solids, 203 (1996)
[2] Dr. Mühlig, private communications, Institut für Photonische Technolgien (IPHT), Jena, Germany (2008)
[3] Dr. Kondilenko, private communications, Stanford University (Ginzton Lab), USA (2003, 2005)
[4] Dr. Pinard, private communications, Laboratoire des Matériaux Avancés, Lyon, France (2006)
[5] D.T. Carpenter et al., Proc. of SPIE Vol. 8239 82390Y-3 (2012)
[6] ZIM cooperation project KF2411810DF2 on "Compensation of thermal lensing in laser optics", 2012.
[7] A. Langner et al., Proc. SPIE 8237, Fiber Lasers IX: Technology, Systems, and Applications, 82370F (February 9, 2012)
[8] St. Thomas et al., Proceedings of SPIE Vol. 2966 (1997) 56-64
[9] B. Kühn, SPIE's OE Magazine, April (2003) 40

Keywords: *fused silica, optical material, absorption, radiation damage*

9632-66, SESSION PSTUE

Refined metrology of spatio-temporal dynamics of nanosecond laser pulses: application to nonlinear Kerr effect and its influence on the measurement of laser-induced surface damage in thick fused silica window

Romain Diaz, Roger Courchinoux, Jacques Luce, Claude Rouyer, Jean-Luc Rullier, Jean-Michel Sajer, Commissariat à l'Énergie Atomique (France); **Jean-Yves Natoli,** Institut Fresnel (France); **Laurent Lamaignère,** Commissariat à l'Énergie Atomique (France)

ABSTRACT TEXT: The nonlinear optical Kerr effect and its influence on the beam propagation in fused silica have widely been investigated for few decades. Here, thanks to a resolved metrology of the beam characteristics, we propose an original interpretation of laser-induced damage experiments on the exit surface of thick fused silica samples. These latters have been performed by means of a Q-switched Nd:YAG laser without injection seeding operation. The spectral broadening of the laser pulses is then sufficient in reducing considerably the Stimulated Brillouin Scattering while propagating within thick fused silica samples of a few centimeters. Nevertheless, the induced statistical spectral fluctuations in the Multiple Longitudinal Modes configuration engender strong variations of the magnitude of the temporal spikes from one pulse to another. An accurate metrology of the spatio-temporal displacements of the beam by means of a streak camera and the use of a propagation code have allowed us to apprehend the Kerr effect in fused silica windows.

Keywords: *nanosecond laser-induced damage, fused silica thick window, nonlinear Kerr effect, metrology, modeling, spatio-temporal dynamics*

9632-67, SESSION PSTUE

Synchrotron micro-XRF study of metal inclusions distribution and variation in potassium dihydrogen phosphate (KH2PO4) induced by ultraviolet laser pulses

Zhiqiang Cao, Xin Ju, Chunyan Yan, Chang Liu, Univ. of Science and Technology Beijing (China)

ABSTRACT TEXT: Metal inclusions play critical roles in laser-induced damage of large potassium dihydrogen phosphate optics. In this paper, we have studied the distribution and variation of copper, zinc, iron, aluminum and cerium in prepared samples by synchrotron X-ray fluorescence spectrometry microprobe system at BL15U1 beam line in Shanghai Synchrotron Radiation Facility. The spatial resolution of the elemental map is up to 5μm. The results indicates that copper, zinc and iron play key roles in the damage procedure, and with the crater growing larger, they reduced quickly. However the content of aluminum and cerium do not change. We use the distribution of potassium to describe the size of each crater and found that an observable damage crater was formed by a major damage spot and some smaller spots. And the radius of major spot is about 30μm.

Keywords: *Synchrotron micro-XRF, laser induced damage, Potassium dihydrogen phosphate, metal inclusions*

9632-68, SESSION PSTUE

Optimization of the concentration of populations of an optical fiber doped with erbium

Ghoumazi Mehdi, Nacer-Eddine Demagh, Azzedine Adouane, Badreddine Boubir, Abdel Kader Daoui, Ctr. de Développement des Téchnologies Avancées (Algeria)

ABSTRACT TEXT: The erbium trivalent ions(Er+3) were played an important role in the development of optical telecommunications technology in recent years. The emission of ions Er+3 is crucial at 1.53µm for the optical telecommunications because this emission belong to the minimum of attenuation of silica fibers used to transport information. In this work we study and we optimize the populations of the ion states erbium in optical fiber in function of experimental spectroscopic parameter. This study is based on modeling of the effects of doping based on the strength of the signal and the pump used. Indeed, we simulate the transient behavior of the different levels of erbium energy, N1, N2, and N3 respectively by using MATLAB code.

Keywords: *Fiber doped erbium (EDFA), Optical amplifiers, Rare earth, Fiber doped*

9632-69, SESSION PSTUE

Nano-Kelvin calorimeter for optical absorption spectroscopy at the level of parts per billion

Behshad Roshanzadeh, S. T. P. Boyd, Wolfgang Rudolph, The Univ. of New Mexico (United States)

ABSTRACT TEXT: Optical absorption is widely used to characterize purity and associated quality of optical materials. Instruments based on photo-thermal methods have been developed in several laboratories that have sensitivities of a few ten parts per billion. Such sensitivity requires laser pump sources of a few Watts of average power, which are typically available only at selected wavelengths. To study the physical origin of absorption in high-quality dielectric materials it is desirable to combine sensitive absorption measurements with spectral resolution over an extended range. Tunable light sources exist now that emit from 170 nm to 1700 nm with an average spectral power density of 10 μW/nm. Absorption spectroscopy with, for example, 5-nm spectral resolution and 0.1 parts per million (ppm) sensitivity would be equivalent to a photo-thermal device capable of 0.5 parts per trillion (ppt) with a 10-W pump laser. This exceeds the demonstrated sensitivity of photo-thermal measurements by a factor of about 1000.

We describe a calorimeter that operates at 4 K. The low-temperature is of advantage for two reasons. (1) the heat capacity of optical materials is much lower at these temperatures leading to a larger temperature change for given absorption and (2) high resolution paramagnetic thermometers with Superconducting Quantum Interference Device (SQUID) readout can be applied. The calorimeter is fiber coupled to the tunable light source. Special emphasis has been given to mitigate problems associated with scattering and luminescence. Our measurements indicate sensitivities as high as 1 ppt may be achievable with this technique.

Keywords: *Optical calorimeter, Absorption spectroscopy*

9632-70, SESSION PSTUE

Defects characterization of optical materials by photothermal microscopy and optical scattering microscopy

Jingtao Dong, Bingbing Li, Jian Chen, Zhouling Wu, ZC Optoelectronic Technologies, Ltd. (China)

ABSTRACT TEXT: It is believed that the highly localized absorption of laser energy by defects in optical materials results in damage. Therefore, to identify the defects is very important for preparing high quality optics for high power laser applications. In this paper, we present our recent progress on characterization of defects in optical materials by using photothermal microscopy and optical scattering microscopy. The combination of photothermal response and scattering response provides more comprehensive information about the defects in optical materials. Difference between defect sites and regular sites of optical materials under laser irradiation is also investigated. It will be very helpful for better understanding of the laser damage mechanisms.

Keywords: *defects, photothermal microscopy, optical scattering microscopy, laser damage*

9632-73, SESSION PSTUE

Improving laser-damage resistance of optics by optimizing the interface structure

Xiaodong Jiang, China Academy of Engineering Physics (China)

ABSTRACT TEXT: Although there are many reasons for surface damage of optics during laser irradiation, but the damage Almost all display as Mechanical fragmentation, This proves that the damage was the result of the mechanical shock driven by laser. Similar to the explosion damage, the shock wave and light propagation affected by the interface properties of glass / air , There were significant refractive index and density variation on the interface, This will lead to energy deposition on the surface of glass. in other words, the slighter gradient of Optical and Acoustic at interface, the higher damage threshold of the optics. In addition to surface defect, the interface properties of glass / air was probably the most important factor for laser-induced damage of optics. we developed the model to simulate the propagation of optical and acoustic at the interface, and the thick film adhere to surface is optimally designed, we research on production of laser-induced blast shock wave and its propagation rule, and It is shown that the properties of film is close to glass, the interface gradient of film/glass is insignificant, the damage will occur in film/air interface, this interface structure could protect the glass surface against laser damage. The correctness of theoretical analysis is validated by experiments.

Keywords: *laser-induced damage, Optical and Acoustic gradient, Mechanical fragmentation, thick film*

9632-74, SESSION PSTUE

Improved laser damage threshold performance of calcium fluoride optical surfaces via accelerated neutral atom beam (ANAB) processing

Michael J. Walsh Jr., Sean Kirkpatrick, Richard Svrluga, Exogenesis Corp. (United States); **Michael D. Thomas,** Spica Technologies, Inc. (United States)

ABSTRACT TEXT: Optics are not keeping up with the pace of laser advancements. The laser industry is rapidly increasing its power capabilities and reducing wavelengths which have exposed the optics as a weak link in lifetime failures for these advanced systems. Nanometer sized surface defects (scratches, pits, bumps and residual particles) on the surface of optics are a significant limiting factor to high end performance. Angstrom level smoothing of materials such as calcium fluoride, spinel, magnesium fluoride, zinc sulfide, LBO and others presents a unique challenge for traditional polishing techniques. Exogenesis Corporation, using its new and proprietary Accelerated Neutral Atom Beam (ANAB) technology, is able to remove nano-scale surface damage and particle contamination leaving many material surfaces with roughness typically around one Angstrom. This surface defect mitigation via ANAB processing can be shown to increase performance properties of high intensity optical materials. This paper describes the ANAB technology and summarizes smoothing results for calcium fluoride laser windows. It further correlates laser damage threshold improvements with the smoothing produced by ANAB surface treatment. All ANAB processing was performed at Exogenesis Corporation using an nAccel100TM Accelerated Particle Beam processing tool. All surface measurement data for the paper was produced via AFM analysis on a Park Model XE70 AFM, and all laser damage testing was performed at Spica Technologies, Inc.

Exogenesis Corporation's ANAB processing technology is a new and unique surface modification technique that has demonstrated to be highly effective at correcting nano-scale surface defects. ANAB is a non-contact vacuum process comprised of an intense beam of accelerated, electrically neutral gas atoms with average energies of a few tens of electron volts. The ANAB process does not apply mechanical forces associated with traditional polishing techniques. ANAB efficiently removes surface contaminants, nano-scale scratches, bumps, particles and other asperities under low energy physical sputtering conditions. ANAB may be used to remove a precisely controlled, uniform thickness of material without any increase of surface roughness, regardless of the total amount of material removed. The ANAB process does not involve the use of slurries or other abrasive polishing compounds and therefore does not require any post process cleaning. ANAB can be integrated as an in-situ surface preparation method for other process steps in the uninterrupted fabrication of optical devices.

Keywords: *super-polish technique, accelerated neutral atom beam, ANAB, lateral sputtering, laser damage, Exogenesis, Angstrom,* CaF_2

9632-75, SESSION PSTUE

Scaling of laser-induced contamination growth at 266nm and 355nm

Matthias Ließmann, Lars O. Jensen, Istvan Balasa, Michael Hunnekuhl, Alexander Büttner, Peter Wessels, Jörg Neumann, Detlev Ristau, Laser Zentrum Hannover e.V. (Germany)

ABSTRACT TEXT: The growth of laser-induced contamination (LIC) on optical components in extraterrestrial missions is a known issue especially for the UV spectral region. The Laser Zentrum Hannover e.V. is responsible for the development of a pulsed laser-system operating at a wavelength of 266 nm for the ExoMars mission. In this context, toluene is utilized which is an often used model contaminant in LIC studies. Test cycles based on the application of the two UV wavelengths 355 nm and 266 nm on optical coatings are conducted and the observed contamination effects are compared. The well-known LIC characteristics at 355 nm serve as reference. This scaling allows a rough estimate of the destructive influence of LIC on space optics degradation at 266 nm. From this outcome, selected polymers will be qualified concerning their versatility for the construction of the ExoMars laser set-up.

Keywords: *laser-induced contamination, space optics, UV laser*

9632-77, SESSION PSTUE

Enhancement of surface-damage resistance by removing a polishing contamination in CaF_2 crystal

Keita Kawasaki, Yoshizumi Inagaki, Ryoya Ota, Tomosumi Kamimura, Osaka Institute of Technology (Japan)

ABSTRACT TEXT: Calcium fluoride (CaF_2) is one of the important materials for ArF excimer laser components and for chromatic aberration correction for stepper lens system. The developments of ultra-high purity CaF_2 single-crystal which resists the damage by deep UV laser are strongly required. The laser-induced damage threshold (LIDT) of polished surfaces is much lower than the damage threshold of its bulk. It is well known that contaminations of the polished surfaces are one of the causes of low LIDT. Particularly, polishing contamination used in optical polishing processes is embedded inside the surface layer, and cannot be removed by conventional cleaning methods. For enhancement of surface damage resistance, several surface treatments have been applied to the removal of embedded polishing compound at the CaF_2 surface.

In this study, by using ion beam etching, the outer surface of 60 nm was removed without changing surface roughness. However, the absorption in the UV region occurred due to the damage induced from irradiated ion. Therefore, the damaged surface was removed by using an additional surface treatment. The surface roughness of CaF_2 was kept through all the surface treatment processes. At the wavelength of 266 nm, the surface damage threshold was increased by about 2 times compared with that of polished CaF_2 surface. The LIDT of CaF_2 after the surface treatment was approximately 5 times of LIDT of the as-polished fused silica surface.

Keywords: *surface-damage resistance, polishing contamination, CaF_2, surface treatments*

9632-78, SESSION PSTUE

Retrieval of defect densities from STEREO-LID (spatio-temporally resolved optical laser induced damage) data and comparison with traditional damage tests

Yejia Xu, Luke A. Emmert, Wolfgang Rudolph, The Univ. of New Mexico (United States)

ABSTRACT TEXT: It is well established that long pulse (ns and longer) damage is mostly controlled by localized defects of largely unknown physical origin [1]. The characterization of these distributions is therefore a key issue in improving the performance of optical coatings and surfaces for high-power laser applications.

The recently developed STEREO-LID (Spatio-Temporally Resolved Optical Laser Induced Damage) method [2] is able to determine the damage fluence and intensity locally in one test event. N test sites and proper binning of the fluence axis produce a distribution P(F)DF that represents the probability that a damage fluence F ± $^{1}/_{2}$DF is observed.

We present a straightforward algorithm to retrieve defect density functions ρ – (F), an area density of defects that damage at incident fluence F, from P(F) [3].

We use Monte-Carlo simulations to compare STEREO-LID to the traditional damage tests. The new technique is superior with respect to the amount of information gained and precision. STEREO-LID using comparatively small number of test sites performs particularly well in characterizing distributions of defects that fail at low fluences, which is important for practical applications. Using a suitable number of test sites, incident fluences and spot sizes STEREO-LID can provide a rather comprehensive picture of defects on surfaces and in films that control the laser damage and ablation behavior.

REFERENCES

1. J.-Y. Natoli, L. Gallais, H. Akhouayri, and C. Amra, "Laser-induced damage of materials in bulk, thin-film, and liquid forms," Appl. Opt. 41, 3156–3166 (2002).
2. Yejia Xu, Luke A. Emmert, and Wolfgang Rudolph, "Spatio-TEmporally REsolved Optical laser Induced Damage (STEREO LID) Technique for Material Characterization," submitted to Applied Physics Letters.
3. Yejia Xu, Luke A. Emmert, and Wolfgang Rudolph, "Determination of defect densities from STEREO-LID (Spatio-TEmporally REsolved Optical Laser Induced Damage) measurements," submitted to Applied Optics.

Keywords: *laser-induced damage, defect density, Monte Carlo simulations, retrieval algorithm*

9632-19, SESSION 6

Optical coatings excited by femtosecond lasers near the damage threshold: challenges and opportunities

Luke A. Emmert, Cristina Rodriguez, Zhanliang Sun, Wolfgang Rudolph, The Univ. of New Mexico (United States)

ABSTRACT TEXT: Broadband stacks of optical coatings are widely used as mirrors, polarizers and filters for femtosecond laser pulses. Special emphasis has been given to tailor the phase response to a desired dispersive behavior for dealing with few-cycle pulses. We will review the current understanding of femtosecond laser damage of individual coatings and stacks and open questions. Stacks of dielectric films also provide unique opportunities to design the nonlinear optical behavior at irradiances below the LID threshold. An extension of the optical matrix algorithm to include third-harmonic generation allows one to predict the frequency conversion and design structures with large conversion efficiencies. A complementary understanding of these stack properties can be gained by treating the film stacks as a 1D photonic crystals. Realistic nonlinear optical frequency converters based on coating stacks are on the horizon, but require careful balancing of nonlinearities and LIDT.

Keywords: *optical multilayers, femtosecond pulse, dispersion control, laser-induced damage, critical electron density, nonlinear frequency conversion*

9632-20, SESSION 6

Analysis of energy deposition and damage mechanisms in single layers of HfO_2 and Nb_2O_5 submitted to 500fs pulses

Dam-Bé L. Douti, Mhamad Chrayteh, Serge Monneret, Mireille Commandre, Laurent Gallais, Institut Fresnel (France)

ABSTRACT TEXT: Laser damage of optical interference coatings is a main limitation for the development of femtosecond laser systems and applications. The ability to model physical mechanisms leading to the degradation of thin film materials is essential for better understanding of damage behavior in coatings and gives some feedback on design and manufacturing of these components (material selection, structure optimization for increased optical resistance ...). Such models have been supported by experiments to assess their validity. A commonly used approach is the measurement of Laser-Induced Damage Threshold as a function of different irradiation parameters (pulse duration, wavelength). Following this approach we compare in this work LIDT measurements to simulations of laser material interactions in optical thin films.

The model used in this study is based on the Single Rate Equation for calculations of the evolution of the free electron density generation during the pulse. Excitations process by photoionization with the Keldysh model and impact ionization with a Drude model are employed. The interference effects and the transient optical properties of the dielectric materials under considerations are taken into account in the simulations, in order to obtain an accurate description of spatio-temporal energy deposition in the film.

Experiments are conducted on single layers of Hafnia and Niobia with different thicknesses, deposited by Magnetron Sputtering on fused silica substrates. The samples were tested in 1on1 mode at 1030nm and 343nm, with 500fs to determine their LIDT. Furthermore irradiations at different fluences above the LIDT were systematically conducted to analyze the damage morphologies as a function on the irradiation conditions, the measurements being done by in situ phase imaging and ex situ Atomic Force Microscopy, Optical Profilometry and Scanning Electron Microscopy.

The comparison of experiments to theoretical results has been done on the basis of different damage criterion: density of free electrons to generate a critical plasma or absorbed energy density above a physical limit. Our results suggest that only a critical absorbed energy give consistent results both with the measured LIDT and the damage morphologies observed above the LIDT.

9632-21, SESSION 6

Ultrafast pre-damage dynamics in ultraviolet reflector

Juan Du, Zehan Li, Shanghai Institute of Optics and Fine Mechanics (China); **Bing Xue, Takayoshi Kobayashi,** The Univ. of Electro-Communications (Japan); **Yuanan Zhao, Yuxin Leng,** Shanghai Institute of Optics and Fine Mechanics (China)

ABSTRACT TEXT: Because of the high absorption at wavelengths near to the material electronic band-gap, only limited UV-transparent materials such as metal oxides and SiO_2 combinations, large bandgap fluoride combinations, and metal oxide/fluoride combinations can be selected for the manufacture of interference coatings in the UV spectral range [1]. Moreover, the damage of optical materials displays highly deterministic damage performance in the ultrashort pulse regime. In the present study, UV femtosecond laser pulses with the pulse duration of 70 fs are used to study the instinctive laser-induced response dynamics inside the Al_3O_2/SiO_2 reflector, which is promising for understanding the origin and mechanism of laser-induced damage threshold (LIDT) and hence improving the LIDT in UV HR coatings [2].

Using laser energy lower than the LIDT, the multiphoton ionization is easy realized and reflectivity decrease has been observed. The decrease could be assigned to the photon absorption by the free electrons in the conduction band of the reflector. As studied by typical crater morphologies, laser damage occurred first in the Al_3O_2 layer, which suggested that the laser induced absorption dynamics is mostly due to the free electron there. Spectral shift between two different laser-induced reflectivity decrease bands is observed. The former one centered at 406 nm undergo a fast decay of ~2.6 ps and a longer one of ~15 ps. Accompanied with this decay, another reflectivity decrease band centered at 396 nm grew around ~2.8 ps after the laser excitation. The probable reason is that a defect state below the conduction band exists, and it has an absorption peak at 396 nm. The free carrier in the Al_3O_2 conduction band is trapped into this defect state at a time scale of ~2.8 ps. Since the defect state has much longer lifetime than the initial generated free carriers in the conductive band, probably under the condition of ultrafast high-frequency pulsed UV laser exposure, the incubation effect will decrease the laser damage threshold of the subsequent laser pulses.

REFERENCES

[1] N. Kaiser, H. Uhlig, U. B. Schallenberg, B. Anton, U. Kaiser, K. Mann, and E. Eva, Thin Solid Films, 260, 86–92 (1995).

[2] A. Mouskeftaras, S. Guizard, N. Fedorov, S. Klimentov, Appl. Phys. A, 110, 709–715(2013).

Keywords: *ultrafast laser spectroscopy, laser induced damage threshold, ultraviolet reflector, reflectivity, defect state, free electron, conduction band*

9632-22, SESSION 6

Laser-damage resistance of optical components in sub-picosecond regime in the infrared

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

ABSTRACT TEXT: While considering long pulse or short pulse high power laser facilities, optical components performances and in particular laser damage resistance are always factors limiting the overall system performances. A common practice is to use large beams and therefore large optical components in order to reduce the energy density. Consequently, getting a detailed understanding of the behavior of these optical components under irradiations with large beam in short pulse range is of major importance. A rasterscan procedure adapted to the sub-picosecond is set to determine laser-induced damage densities as function of fluence. This procedure is used to determine laser-induced damage densities in sub-picosecond regime of high-reflective coatings operating at 1053nm and manufactured with different processes. Whereas laser-induced damage is usually considered deterministic in this regime, damage events occur on these structures for fluences lower than their intrinsic Laser-Induced Damage Threshold (LIDT). These densities are found to be high even for fluences as low as 20% of the intrinsic LIDT and they can increase catastrophically with the fluence. Scanning Electron Microscope observations of these "under threshold" damage sites evidence ejections of defects, embedded in the dielectric stack. Since their evolutions cannot be correlated with the intrinsic LIDT of the structures, it brings a new viewpoint for the qualification of optical components and their optimization for high damage resistance in sub-picosecond regime. To complete the study, we conducted additional experiments (growth after initiation, different pulse durations tests...) to enable a better prediction of the optics life time in operating condition.

Keywords: *laser damage, short pulse, coatings, damage density*

9632-23, SESSION 7

What time-resolved measurements tell us about femtosecond laser damage? *(Keynote Presentation)*

Andrius Melninkaitis, Vilnius Univ. (Lithuania) and LIDARIS Ltd. (Lithuania); **Nerijus Šiaulys, Balys Momgaudis, Julius Vaicenavicius, Simona Barkauskaite, Valdas Sirutkaitis,** Vilnius Univ. (Lithuania); **Laurent Gallais,** Ecole Centrale Marseille (France); **Stéphane Guizard,** Commissariat à l'Énergie Atomique (France) and Ctr. National de la Recherche Scientifique (France) and Ecole Polytechnique (France)

ABSTRACT TEXT: There exist several approaches of experimenting focused towards the understanding the nature of the laser-induced damage phenomena. On one hand post mortem consequences of damage process (such as laser-induced damage threshold, morphology or material modification products) could be analyzed as a function of laser, environmental or engineered material parameters. On the other hand, damage process could be investigated in situ by using time-resolved techniques with appropriate observation method and resolution. Both ways complement each other and some day they probably will merge into unified theory; however, to this end there exist a gap between those two approaches. In this presentation a short overview of time-resolved techniques will be made. Recent advances of time-resolved digital holographic probing of damage process of thin films will be reported. The obtained results reveal fundamental differences between the so-called 1-on-1 and S-on-1 testing regimes. New concepts of damage threshold measurement without reaching catastrophic damage, exploring the nonlinear properties of optical thin films as well as single shot observation of coherent phonon generation will be introduced.

Keywords: *time resolved, digital holography, laser damage, thin films, Kerr effect*

9632-24, SESSION 7

Laser damage threshold: useful idea or dangerous misconception?

Jonathan W. Arenberg, Northrop Grumman Aerospace Systems (United States)

SPEAKER BIOGRAPHY: Jonathan W Arenberg has been working as an optical and systems engineer for over 30 years. His work experience has included tactical and high-power laser components and systems and major space astronomical projects such as Chandra and the James Webb Space Telescope. He holds degrees in physics and engineering from the University of California, Los Angeles and currently the Chief Engineer for Northrop Grumman Aerospace Systems on the James Webb Space Telescope. Dr. Arenberg is an SPIE fellow.

ABSTRACT TEXT: The concept of a laser damage threshold is ubiquitous, useful and confounding. This paper seeks to examine and discuss the power of the concept of a laser damage threshold, identifying the good and the danger in its use. This paper will trace the history of the definition and concept of the laser damage threshold from the earliest days of the conference through to the present day. As an analytic framework, the expression for the distribution of the weakest site on an optic will be derived. This derivation will be analyzed for the properties that affect the weakest site on an optic and how this affects the definition of laser damage threshold. The discussion concludes with the conditions under which blind application of the concept of a laser damage threshold can be useful or dangerously misleading.

Keywords: *laser damage threshold, distribution, probability of damage, blasphemy*

9632-25, SESSION 7

Characterization of laser-induced structural modification in bulk of broken-down dielectrics

Karol A. Janulewicz, Zia U. Rehman, Yavor V. Grigorov, Khoa A. Tran, Le T. Na, Vinh H. Nguyen, Gwangju Institute of Science and Technology (Korea, Republic of)

SPEAKER BIOGRAPHY: he is since 2008 with the Department of Physics and Photon Science at the Gwangju Institute of Science and Technology, as Assoc. Professor. Main scientific interests include intense laser-matter interaction, plasma physics, high-energy density physics and short-wavelength sources and their applications.

ABSTRACT TEXT: Localized energy deposition by tightly focused laser beam in a bulk of transparent material, results in high temperature and high pressure. This leads to optical breakdown (rapid increase in the number of free electrons) and finally optical damage in the form of irreversible structural changes in the deposition area and its vicinity. Phase transitions belong to the fundamental phenomena at the heart of many structural changes occurring in the material. Transformation accompanying the optical breakdown is specific, as it results from the extreme conditions driving rapid changes in the thermodynamic state of the irradiated matter.

In this study, an ultra-short laser pulse (duration from nano- to femtoseconds) was tightly focused in bulk of transparent glasses. The fast changes in temperature and pressure occurring within the confined geometry of the deposition area triggered shock and rarefaction waves. These were followed by cavitation and material densification (compression factor 1.17) in a thin layer surrounding the void, and called shell. Cavitation scale observed in the experiment suggested softening of the material before or during the compression. Change of refractive index in the shell was connected with a phase transformation caused, in turn, by rearrangement of the lattice structure. More detailed inspection of the apparently homogeneous shell revealed existence of gradual phase transition from the amorphous phase to crystallization. The shell showed significant content of localized nanocrystals embedded in the amorphous matrix. This is the first demonstration of nano-crystallization under extreme conditions generated by a single laser pulse. The temperature gradient associated with the shock wave, being considered as the dominating factor in the process was well reflected in changes of nanocrystal parameters in the radial direction. Features of crystallites investigated mainly by HRTEM (high resolution transmission electron microscopy) will be discussed in detail. The transparent glasses with precipitation of nanocrystals (glass ceramics) used to attract considerable interest due to their applications in optical devices, such as optical amplifier, nonlinear optical devices, optical storage, 3D display etc.

Keywords: *energy deposition, high-energy density, shock wave, phase transitions, nano-crystallization*

9632-26, SESSION 7

Single-shot femtosecond laser ablation of copper: experiment versus simulation

Enam Chowdhury, Kyle R. P. Kafka, Robert A. Mitchell III, Kevin Werner, Noah Talisa, Hui Li, Allen Yi, Douglass W. Schumacher, The Ohio State Univ. (United States)

SPEAKER BIOGRAPHY: A leading expert in the field of high power short pulse lasers, ultra-intense and high energy density laser matter interaction, Research Assistant Professor at OSU Physics, Dr. Enam Chowdhury currently leads Femtosecond Solid Dynamics Laboratory, a program dedicated to studying fundamentals of laser solid interactions near material damage threshold, including ionization, ablation, multi-pulse effects, laser induced periodic surface structures. He is also active in the area of laser plasma based MeV electron and ion acceleration. Dr. Chowdhury has authored over 50 articles in peer reviewed journals and conference proceedings in physics and engineering.

ABSTRACT TEXT: Introduction: Femtosecond laser ablation of solids is a rich topic in non-linear light matter interaction, because it incorporates non-thermal excitation of electrons, initially bound in a many body system, in intense light field, electron coupling energy into lattice via various pathways and finally irreversible surface modification due to melting/vaporization of atoms from lattice. It is also very interesting from application point of view, as femtosecond laser pulses can produce nm-scale features in metals and non-metals due to extreme spatio-temporal localization of pulse energy preventing heat diffusion in surrounding volume [1]. Although a large body of experimental work on this topic exists, to the best of authors' knowledge, single shot damage threshold of single crystal Cu has not been published previously. Published works by Nolte et al.[1], Hashida et al. [2] and Colombier et al. [3] extrapolated poly-crystalline Cu single shot fluence threshold from laser ablation craters formed by 10-100,000 pulses and dividing ablation depth by number of pulses. Extrapolating femtosecond single shot ablation threshold from multi-pulse measurement is unreliable, because each pulse can induce defect states and surface roughness for subsequent pulses to absorb more energy, and thus lowering the threshold. Because of its non-perturbative nature, and long time scale from femtosecond to nano-seconds or longer, simulating femtosecond laser ablation with realistic spatial scale and benchmarking against experiments had not been possible previously. Recently, Mitchell et. al. demonstrated such a simulation effort based on Particle-In-Cell (PIC) framework [4,5], which renders experimental benchmarking against simulation possible. In current work, we present for the first time, experimental efforts to benchmark single pulse femtosecond laser ablation of Cu against simulation results.

Experimental setup: The experiments were performed using a home built 3 mJ/pulse, 35 fs Ti:Sapphire laser with center wavelength of 773 nm operating at 500 Hz. An external Pockel's cell with a high contrast polarizer was used to select single pulses. The pulse energy was attenuated first using reflections off of two uncoated surfaces of a pair of prisms, and the resultant pulse energy on target was controlled via a wave plate and polarizer combo and monitored via a calibrated photodiode. The laser pulses were focused onto a 10 mm x 10 mm single crystal Cu target (MTI) using a high performance infinity conjugate Reflx objective (Edmund Optics) producing a diffraction limited spot with exp(-2) diameter of 2 μm. The target was positioned with 0.5 um accuracy, using a five axis positioning system and imaged in situ with a co-propagating HeNe laser. The focal spot was characterized by an infinity conjugate 20x objective (Edmund Optic).

Results: The average fluence on target varied from 0.4 – 40 J/cm^2, resulting in crater depths from 5-800 nm. Crater profiles were studied using Wyko NT9100 optical profiler and SEM. The single shot ablation threshold fluence determination using crater depth, width and damage probability at 15 degree AOI yielded values between 0.7-0.9 J/cm^2 (average fluence), which is higher than published LDT values extrapolated from multi-pulse measurements [1-3]. Comparison of crater widths and depths obtained from simulation and experiments will be presented.

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REFERENCES:

[1] S. Nolte, C. Momma, H. Jacobs, A. Tu, B. N. Chichkov, B. Wellegehausen, and H. Welling, J. Opt. Soc. Am. B 14, 2716 (1997).
[2] M. Hashida, a. . Semerok, O. Gobert, G. Petite, Y. Izawa, and J. .- Wagner, Appl. Surf. Sci. 197-198, 862 (2002).
[3] J. Colombier, P. Combis, F. Bonneau, R. Le Harzic, and E. Audouard, Phys. Rev. B 71, 165406 (2005).
[4] R. a. Mitchell, D. Schumacher, and E. A. Chowdhury, Opt. Eng. 53, 122507 (2014).
[5] R. a. Mitchell, Douglass W. Schumacher, and E. A. Chowdhury, arXiv 1502.07722 (2015).

Keywords: *laser ablation, laser damage threshold, femtosecond laser, Particle-in-cell*

9632-27, SESSION 8

Probing the properties of laser super-heated fused silica following exit surface damage

Stavros G. Demos, Raluca A. Negres, Rajesh N. Raman, Michael D. Feit, Kenneth R. Manes, Alexander M. Rubenchik, Lawrence Livermore National Lab. (United States)

SPEAKER BIOGRAPHY: Stavros G. Demos is an experimental physicist and has been involved in the field of Laser Damage since he 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 110 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: Laser induced damage (breakdown) initiated on the exit surface of transparent dielectric materials using nanosecond pulses creates a volume of superheated material reaching localized temperatures on the order of 1 eV and pressures on the order of 10 GPa or larger. The volume of this superheated material depends largely on laser parameters such as fluence and pulse duration. It is well established that this leads to material ejection and the formation of a crater. The bottom of the crater also contains evidence of previously melted material and fibers. However, there is arguably very little known about the state and dynamics of the superheated material, including the relaxation pathways.

To elucidate the material behaviors involved, we utilized two approaches. The first was to understand the exact timeline of particle ejection from the superheated volume. As the ejected particles preserve the instantaneous internal energy of the superheated material at the time of separation, the pressure energy is translated into kinetic energy of the ejected particles (or pressure to kinetic energy density). This approach captures the pressure change during the relaxation process. The second approach was to examine the morphologies of the ejected superheated material particles. After devising a method to capture these particles, their examination revealed distinctive morphologies; we hypothesize that these morphologies arise from the difference in the structure and physical properties (such as the dynamic viscosity and presence of instabilities) of the superheated material (while it relaxes) at the time of individual particle ejection. Some of the ejected particles are on the order of 1 μm and appear as "droplets". Another subgroup appears to have stretched, foam-like structure that can be described as material globules interconnected via smaller diameter columns. Such particles often contain nanometer sized fibers attached on their surface. Another subgroup appears to have preserved only the globules, suggesting that may be associated with a collapsed foam structure under pressure as it traverses in air. These distinct features may exemplify the structure of the superheated material during volume boiling just prior to the ejection of these particles. It is worth noting that the particles produced by the superheated material have strong similarities to micro-tektites. The latter are natural glassy materials that are believed to have formed by the ejection of superheated near-surface material at meteorite impact locations.

This study provides direct information regarding the state of the superheated material during its relaxation phase. It also shows the morphologies of the produced debris that may inadvertently deposit on adjacent optics following exit surface damage (or damage growth) in ICF class laser systems.

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Keywords: *no keywords*

9632-28, SESSION 8

Gigashot optical degradation in silica optics at 351 nm

Sonny S. Ly, Lawrence Livermore National Lab. (United States)

ABSTRACT TEXT: As applications of lasers demand higher average powers, higher repetition rates, and longer operation times, optics will need to perform well under unprecedented conditions. We investigate the optical degradation of fused silica surfaces at 351 nm for up to 109 pulses with pulse fluences up to 12 J/cm^2. The central result is that the transmission loss from defect generation is a function of the pulse intensity, Ip, and total integrated fluence, ?T, and is influenced by oxygen partial pressure. In 10-6 Torr vacuum, at low Ip, a transmission loss is observed that increases monotonically as a function of number of pulses. As the pulse intensity increases above 13 MW/cm^2, the observed transmission losses decrease, and are not measureable for 130 MW/cm^2. A physical model which supports the experimental data is presented to describe the suppression of transmission loss at high pulse intensity. Similar phenomena are observed in anti-reflective sol-gel coated optics. Absorption, not scattering, is the primary mechanism leading to transmission loss. In 2.5 Torr air, no transmission loss was detected under any pulse intensity used. We find that the absorption layer that leads to transmission loss is less than 1 nm in thickness, and results from a laser-activated chemical process involving photo-reduction of silica within a few monolayers of the surface. The competition between photo-reduction and photo-oxidation explains the measured data: transmission loss is reduced when either the light intensity or the O2 concentration is high. These degradation processes are further investigated at different wavelengths and for different optical materials.

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9632-29, SESSION 8

In situ study of irradiation effects on fused silica induced by high-repetitive laser pulses at 355 nm

Jian Chen, Jingtao Dong, Bingbing Li, Zhouling Wu, ZC Optoelectronic Technologies Ltd. (China)

ABSTRACT TEXT: In this paper, we present our recent progress on investigation of damage processes on fused silica induced by a pulsed 355 nm laser with high repetition rate. By using a system based on photothermal effect, we have realized in-situ monitoring of laser-material-interaction dynamics through measuring the laser-induced absorption evolution. The results demonstrate that the initiation of laser-induced damage process occur far before any physical damage observable using high-resolution optical microscopes. The damage processes typically are long term accumulation effects of laser-induced increase in absorption that is dependent on the irradiation fluence.

Keywords: *absorption, fused silica, laser irradiation, photothermal, 355 nm*

9632-30, SESSION 9

Energetic laser cleaning of metallic particles and surface damage on silica optics: Investigation of the underlying governing mechanisms

Nan Shen, Stavros G. Demos, Raluca A. Negres, Alexander M. Rubenchik, Candace D. Harris, Manyalibo J. Matthews, Lawrence Livermore National Lab. (United States)

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 Optics Materials and Target Science Group at the National Ignition Facility, and focuses her works on identifying damage precursors in fused silica optics and developing mitigation strategies.

ABSTRACT TEXT: Surface particulate contamination on optics originated from processing and handling or other means can lead to enhanced localized laser absorption and hence, laser-induced damage. This is particularly important for contamination on the exit surface due to the subsequent higher damage growth rate compared to that on the input surface. There is a need to understand the fundamental mechanisms that lead to damage initiation by metal contaminants. On the other hand, possible pathways in which laser pulses can be used to benignly remove the potent contaminants can be explored and is sometimes referred to as "dry laser cleaning". In this study, spherical particles were deposited on the exit surface of fused silica substrate as a model system for exploring the interaction between the laser beam, particle and substrate. Our approach was two-fold. We employed a toolset of experimental techniques involving plasma spectroscopy and imaging, time resolved imaging and post irradiation microscopy to capture the dynamics of the complex interaction. We also applied theoretical principles to model all fundamental interactions and compared with experiments to evaluate their relative contribution.

Using time-resolved shadowgraph microscopy, we image the dynamic process of ejecting ~30 μm stainless steel (316L) particles from the exit surface of a fused silica substrate irradiated with 1064 nm, 10 ns and 355 nm, 8 ns laser pulses at varying pulse energy. The experimental results were compared with theoretical modeling to estimate the contribution from possible physical mechanisms such as thermal expansion, propulsion from material ejection and plasma pressure at and near the particle-substrate interface. Spectral information of the plasma emission during ejection was also captured as a function of time and laser pulse energy using a gated intensified CCD camera. Both Si and Fe atomic species can be identified in the plasma emission and related to substrate and particle ablation, respectively. The estimated plasma temperature and electron number density of Si(II) appears higher than those derived from Fe(I) emission suggesting plasma confinement effect at the interface. The pits formed on the substrate surface from particle ejection were characterized using laser scanning confocal microscopy and appear consistent with both time-resolved microscopy data and theoretical predictions.

The results from this study provide a comprehensive picture of the mechanisms involved in laser ejection of metallic particle fused silica substrate and help understand the potential risks and possible methods to mitigate those risks. While the use of spherical particles may not always be representative of the actual contamination, the simple geometry facilitates a more direct interpretation of the experimental results. With proper expansion, these results can be applied to describe more general morphologies of the metal contaminants on the surface of optical components.

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9632-31, SESSION 9

Delay dependency of two-pulse femtosecond laser damage

Mark Gyamfi, Peter Juergens, Lars O. Jensen, Detlev Ristau, Laser Zentrum Hannover e.V. (Germany)

ABSTRACT TEXT: In the femtosecond regime laser damage thresholds are determined by the electric field distribution within the optical components. Especially, for radiation sources with integrated frequency conversion the simultaneous presence of photons with different frequencies introduces additional ionization channels in optical materials by cross excitation and other effects.

In this work we report on the pulse delay dependency of the LIDT of HR390/780nm mirrors under simultaneous exposure to fundamental and second harmonic femtosecond radiation. We perform Son1-tests according to the Standard ISO 21254 with the addition of a second harmonic pulse at different fixed pulse energies. To determine the influence of the cross excitation between fundamental and second harmonic radiation, these tests are repeated for different time delays between the two pulses. For the 1on1, single wavelength femtosecond LIDT testing, the Keldysh theory in combination with the Drude Model has been proven to reasonably describe the time dependent electron density in the conduction band, and hence the LIDT. We extend these approaches to the determination of the LIDT for the case of simultaneous interactions of photons with two wavelengths.

Keywords: *laser damage threshold, ultrashort pulse, dual pulse, multichromatic*

9632-32, SESSION 9

Self-consistent modeling of photoionization and the Kerr effect in bulk solids

Jeremy R. Gulley, Kennesaw State Univ. (United States)

SPEAKER BIOGRAPHY: Jeremy Gulley is an assistant professor of physics at Kennesaw State University near Atlanta, Georgia. His research is in theoretical applied physics and computational ultrafast optics. In particular, his research concentrates on simulating the propagation of high intensity ultrashort laser pulses through bulk nonlinear media. These simulations are used to investigate laser induced dielectric breakdown, pulse filamentation, and ultrafast laser-induced modifications to bulk solids.

ABSTRACT TEXT: In calculations of ultrafast laser-induced ionization the treatment of fundamental mechanisms such as photoionization and the Kerr effect are treated in isolation using monochromatic perturbative approaches. Such approaches are often questionable for pulses of ultrashort duration and multi-chromatic spectra. In this work we address this issue by solving the quantum optical Bloch equations in a 3D quasi-momentum space and couple this model to ultrashort pulse propagation in dielectrics. This approach self-consistently couples a quantum calculation of the photoionization yield, the photoionization current, and the current from free-carriers with the traditional Kerr effect (self-focusing and self phase modulation) without resort to a perturbative treatment. The material band structure is taken in the tight binding limit and is periodic in the crystal momentum space. As this model makes no assumption about the pulse spectrum, we examine the laser-material interaction of strongly chirped pulses and multi-color multi-pulse schemes of laser-induced material modification. These results are compared to those predicted by standard treatments, such as the Keldysh model of photoionization, for pulses of ultrashort duration.

Keywords: *Ultrashort laser pulse propagation, Kerr effect, Photoionization, Self-focusing, Laser-induced ionization, Multi-chromatic pulse, Optical Bloch equations*

9632-33, SESSION 9

First principles simulations of laser-induced periodic surface structure using the particle-in-cell method

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

ABSTRACT TEXT: Laser-induced periodic surface structure (LIPSS) forms under a broad range of conditions and materials when an intense, short-pulse laser is incident on a target surface. This process is of fundamental interest in the study of the interaction of intense light with matter but has also found significant application in materials processing and machining. However, there is no broad agreement on the formation mechanisms which must cover metals, semi-conductors and insulators, multi-shot or few-shot excitation, and low and high spatial frequency regimes. We have recently developed a new approach to modeling surface modification by a laser based on the particle-in-cell method that operates at the level of the fundamental interactions between the laser and the target and between particles with no tunable parameters [1]. In these simulations, macroscopic damage and surface modification occurs due to the accumulation of the microscopic interactions while still being able to treat realistic laser profiles and structure formation.

PIC simulations integrate the Maxwell and Lorentz equations of motion for “macroparticles”, each 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, but the basic PIC approach does not resolve particle-particle interactions within a grid cell. If important, the effect of any such interactions must be added to the PIC integration cycle. At the heart of our simulations is the implementation of a Lennard-Jones pair potential model (LJPPM) for PIC codes. The use of PIC facilitates ab initio treatment of realistic target sizes while the LJPPM allows a PIC code to treat a system of particles as a medium which can ablate, melt, and resolidify. The resulting algorithm retains the strengths of PIC including self-consistent treatment of the laser-particle interaction and subsequent generation of plasma waves and electron heating. Our work was performed using the PIC code LSP [2], but our LJPPM should be compatible with any PIC code.

In this work, we treat the case of an intense laser incident on a copper target with an initial surface deformation such as a 0.5 μm deep semi-circular scratch for varying laser parameters. The work was performed in 2D3V where the particle positions can only vary in 2D, but other vector quantities such as the electric and magnetic fields and currents are represented as 3D vectors. This effectively treats the laser focus as a line focus. The interaction was modeled by three sequential simulations treating the fs-laser interaction using PIC, the ps-thermalization using the two temperature model and the ns-target evolution using PIC with LJPPM. Target grid, cell size and time-step were adjusted appropriately for each phase. Careful treatment of within-cell collisions between charged particles during the laser interaction was crucial. Electron-ion rates were obtained using the Lee-More-Desjarlais model, a polynomial-interpolation method between known cold-metal and plasma states was used for electron-electron rates, and ion-ion rates were determined self-consistently with the LJPPM. We obtain robust LIPSS formation which can then be subsequently analyzed. In particular, we find clear indication of formation via surface plasmon polaritons (SPP). After the laser interaction, SPP fields are apparent and correlated with regions of electron heating.

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

REFERENCES

1. R. A. Mitchell, D. W. Schumacher, and E. A. Chowdhury, “Using Particle-In-Cell simulations to model femtosecond pulse laser damage,” Laser-Induced Damage in Optical Materials: 2014, Proc. SPIE 9237, 92370X (2014).
2. D. R. Welch, D. V. Rose, M. E. Cuneo, R. B. Campbell and T. A. Mehlhorn, Physics of Plasmas 13, 063105 (2006).

Keywords: *laser-induced periodic surface structure, LIPSS, laser-induced damage, femtosecond, ablation, modeling, particle-in-cell, short pulse*

9632-34, SESSION 9

Calculation of nonlinear optical damage from space-time-tailored pulses in dielectrics

Thomas E. Lanier, Jeremy R. Gulley, Kennesaw State Univ. (United States)

SPEAKER BIOGRAPHY: Thomas Lanier is a postdoctoral researcher working under Dr. Jeremy R. Gulley at Kennesaw State University under a grant from the Air Force Office of Scientific Research.

ABSTRACT TEXT: Control of the time duration of a laser pulse as it focuses spatially in a material provides a means for delaying the onset of nonlinear effects during propagation. We investigate simultaneous space-time focusing (SSTF) of femtosecond radially-chirped annular pulses in Kerr dielectrics. The energy and temporal chirp of pulses incident upon a grating-grating-lens system are varied in simulations that solve the unidirectional pulse propagation equation. This system is modeled by inserting transformations that act on the electric field obtained from propagation from one component to the next. The propagation is coupled to the time evolution of the free charge density as a function of space. The resulting "ionization tracks" are taken as a metric for predicting material modification and/or damage in bulk fused silica. As expected from linear-optical considerations, the temporal pre-chirp determines the overall pulse duration as the focusing annulus closes. We find in addition that, for a given pulse energy, the temporal pre-chirp also determines the on-axis intensity distribution as energy collapses onto the propagation axis. This effect determines how the local ionization-induced decrease in refractive index shifts energy in time relative to energy arriving on-axis from the spatially collapsing beam. The magnitude of the pre-chirp can thus control the spatial structure of ionization that may lead to material modification and/or damage.

Keywords: *ultrashort laser pulse, nonlinear propagation, ionization, pulse shaping, beam shaping, micromachining, material modification, bessel beam*

9632-35, SESSION 9

The photo-ionization and band structure of solids: non-evident interplay

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

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

ABSTRACT TEXT: Understanding of the fundamental mechanisms of laser-induced damage (LID) of transparent materials is still a significant challenge in spite of more than 40 decades of research in that area. The commonly accepted approach considers electron excitation from valence to conduction band of wide-band-gap dielectrics as the major mechanism of generation of electron-hole plasma and absorption that lead to LID [1-10]. Among the electron-excitation effects, the major contributions are attributed to the photo-ionization (i.e., inter-band electron transitions stimulated by simultaneous absorption of several photons under action of electric field of laser radiation) and to impact ionization (inter-band electron transitions due to energy transfer during collisions of valence electrons with high-energy conduction electrons). The photo-ionization rate is most frequently evaluated by the Keldysh formula [1], while the impact ionization is described by kinetic equations with certain collision integrals (or kinetic coefficients) [2-7]. The commonly accepted approach is to reduce the contribution of the photo-ionization to production of seed conduction electrons to initiate the impact ionization under the assumption about dominating input of the impact ionization to the total electron-hole plasma generation. However, contribution of each of those ionization mechanisms to the total ionization process is still a controversial point in the theory of the fundamental LID mechanisms. For example, the recent results on LID by ultrashort laser pulses suggest that the photo-ionization can be intensive enough to initiate LID without any significant contribution of the impact mechanisms [8-10].

Reliable judging on contributions of those two ionization mechanisms to initiation of LID can be done only based on reliable models of both the impact and the photo-ionization. In this talk we focus on the photo-ionization and note that the Keldysh formula is frequently applied to materials that do not meet the approximations utilized in the Keldysh derivations [11, 12]. Moreover, utilizing of the Keldysh formula for arbitrary materials does not allow uncovering the fundamental influence of band structure on the photo-ionization and LID. However, the previous results [12] suggest that the influence must be very pronounced. Following the Keldysh procedure [1], we derive several modifications of the Keldysh formula for dielectric crystals with cubic structure (e. g., simple cubic, face-centered cubic, and volume-centered cubic). All those materials have cosine bands, but details of their band structures differ. Obtained results show that scaling of the photo-ionization rate with laser parameters significantly depends on the details of band structure. In particular, volume-centered cubic crystals exhibit specific singularities of intensity scaling of the ionization rate while simple cubic lattice demonstrates the intensity scaling pretty similar to that of the Keldysh formula. Results obtained for alkali halides are in remarkable agreement with the experimental data on two- and three-photon absorption.

References

[1] Keldysh L. V. 1965. Sov. Phys.-JETP 20: 1307-1314.

[2] Arnold D., Cartier E., DiMaria D. J. 1992. Phys. Rev. B 45: 1477-1480.

[3] Stuart B. C., Feit M. D., Herman S., Rubenchik A. M., Shore B. W., Perry M. D. 1996. Phys. Rev. B 53: 1749-1761.

[4] Apostolova T., Hahn Y. 2000. J. Appl. Phys. 88: 1024-1034.

[5] Rethfeld B. 2004. Phys. Rev. Lett. 92: 187401.

[6] Starke K., Ristau D., Welling H., Amotchkina T. V., Trubetskov M., Tikhonravov A. A., Chirkin A. S. 2004. Proc. SPIE 5273: 501-514.

[7] Nikiforov A. M., Epifanov A. S., Garnov S. V. 2012. Opt. Eng. 51: 121813.

[8] Rethfeld B. 2006. Phys. Rev. B 73: 035101.

[9] Kaiser A., Rethfeld B., Vicanek M., Simon G. 2000. Phys. Rev. B 61: 11437-11450 .

[10] L. A. Emmert, W. Rudolph, in Laser-Induced Damage in Optical Materials, D. Ristau, ed (CRC Press/Taylor and Francis Group, New York, 2014) Chapter 5, 127-151.

[11] Gruzdev V. E. 2004. Journal of Optical Technology 71: 504-508.

[12] Gruzdev V. 2007. Phys. Rev. B 75: 205106.

Keywords: *laser damage, fundamental mechanisms of laser damage, photo-ionization of solids, transparent optical materials, Keldysh formula*

9632-36, SESSION 10

Characterization of extremely high-purity optical materials for solid state laser cooling *(Keynote Presentation)*

Mansoor Sheik-Bahae, Nathan Giannini, The Univ. of New Mexico (United States)

ABSTRACT TEXT: Since its first experimental observation in 1995, optical refrigeration has advanced immensely. Most recently, crystals doped with Yb ions have cooled by UNM group to an absolute temperature of about 90K starting from room temperature, with even lower temperatures possible. The key in attaining the recent results as well as advancing this technology further is the growth of extremely high purity host materials doped with rare-earth ions. In this talk, I will discuss the role of parasitic absorption in laser cooling materials, and the techniques to accurately measure and identify its physical origin in rare-earth doped crystals as well as in semiconductors.

Keywords: *optical refrigeration, laser cooling of solids, thermal lensing, rare-earth doped crystals, absorption measurement*

9632-37, SESSION 10

Laser-induced damage of rapid-grown KDP crystals

Yuanan Zhao, Yueliang Wang, Guohang Hu, Meiping Zhu, Weili Zhang, Xiaoyi Xie, Jianda Shao, Shanghai Institute of Optics and Fine Mechanics (China)

SPEAKER BIOGRAPHY: Yuanan Zhao received his PhD degree at the Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Sciences. His current research interests include laser-induced damage to optics and related metrologies.

ABSTRACT TEXT: Laser induced damage of rapid-grown KDP crystals were investigated. The performances of the KDP crystals grown with and without continuous filtrations, including scattering inclusions, laser damage resistance, transmission, were analyzed. Compared with the rapid-grown KDP without continuous filtration, the transmittance in the near-infrared was increased at least 2%. Two unique inclusions were captured by scattering technique and TEM. One is sparse distributed ~10μm order size inclusions and another is high density bubble like inclusions with ~10-100nm order size. The continuous filtration ruled out the existence of the ~10um order inclusions and decreased the submicron bubble like inclusions by about 90%. Laser damage testing showed the laser induced damage thresholds (LIDTs), as well as the consistence of the LIDTs from sample to sample, were improved greatly. Moreover, it identified that the large size defects were the low laser fluence damage precursors which initiated laser damage at relative lower laser fluence (4~6J/cm^2), and there were less correlations between smaller size scattering defects and laser damage initiations. The improvement of LIDTs consistence attributed to elimination of large size defects, and LIDT enhancement came from the decrease of absorption of KDP crystals.

Keywords: *Laser induced damage, KDP crystals, rapid growth, continuous filtration, inclusions*

9632-38, SESSION 10

Laser damage of calcium fluoride by ArF excimer laser irradiation

Minako Kashimoto, Eiichiro Nakahata, Nikon Corp. (Japan)

ABSTRACT TEXT: The artificially grown calcium fluoride is one of key materials for microlithography and is used as for excimer laser optics etc. Such calcium fluoride is required high laser durability and laser induced bulk damage threshold (LIDT). Mechanical properties of calcium fluoride are different according to the crystal axis, for example, hardness is the highest in {100}. Moreover, it is known to cleave in {111}. Therefore there is a possibility that the property that originates in such a crystal structure influences LIDT. In this study, we investigated the relation between crystal structure and laser durability and LIDT.

We examined the influence of the relation between the polarization plane of the ArF excimer laser and the crystal orientation of calcium fluoride on LIDT. We prepared samples that optical axes were <111>, <110> and <100> from the same crystal. The azimuth of the sample was measured by the reflection Laue method. The samples were rotated to the polarization plane of the ArF excimer laser, and the change in the number of irradiation pulses that damage entered was measured.

As a result, we found the position of the crystal orientation of the calcium fluoride and the polarization plane of the ArF excimer laser that LIDT becomes the maximum.

Keywords: *Calcium fluoride, ArF excimer laser, Laser durability, Laser induced bulk damage threshold (LIDT), Crystal orientation*

9632-39, SESSION 10

High-speed quantitative phase imaging of dynamic thermal deformation in laser irradiated films

Lucas N. Taylor, Joseph J. Talghader, Univ. of Minnesota, Twin Cities (United States)

SPEAKER BIOGRAPHY: I'm an Electrical Engineering Doctoral Candidate at the University of Minnesota. My thesis work has studied the relationship between film crystallinity and laser damage as well as imaging laser damage events. I am interested in the areas of optical system design, high-power laser systems, MEMS and thin films.

ABSTRACT TEXT: We present a technique for high-speed imaging of the dynamic thermal deformation of transparent substrates under high-power laser irradiation. Traditional thermal sensor arrays are not fast enough to capture thermal decay events. Our system adapts a Mach-Zender interferometer (MZI) along with a high-speed camera to capture phase images on sub-millisecond time-scales. These phase images are related to temperature by thermal expansion effects and by the change of refractive index with temperature. High power continuous-wave and long-pulse laser damage often hinges on thermal phenomena rather than the field-induced effects of ultra-short pulse lasers. Our system was able to measure such phenomena. We were able to record 2D videos of 1 ms thermal deformation waves, with 6 frames per wave, from a 100 ns, 10mJ Q-switched Nd:YAG laser incident on a yttria-coated glass slide. We recorded thermal deformation waves with peak temperatures on the order of 100 degrees Celsius during non-destructive testing.

Our phase imaging system consisted of a MZI operating with a 632.8 nm single-mode HeNe laser, along with a high-speed camera and high-power Nd:YAG pump laser. Our system allowed coaxial coupling of a Nd:YAG pump laser via dichroic mirror in the sample arm of the MZI. Interferograms were produced at the output of the second beamsplitter of the MZI, where the camera was placed. Our measurements were made at 11,800 fps and we were able to capture approximately 6 frames per thermal event.

The high-power Nd:YAG Q-switched pump system operated at 1064 nm with a pulse length of 100 ns and repetition rate of 2 kHz. The beam was focused by the microscope objective to a beam width of 30 microns. The pulse energy was 10 mJ. Samples were irradiated with an average of 16 pulses and no damage was observed for our tests. Our samples were standard glass slides coated with 300 nm of yttrium-oxide deposited by electron-beam evaporation.

Interferograms were post-processed by a Hilbert-transform method. Our measurements were made relative to a background frame taken right before the test. Additionally, laboratory mechanical noise forced us to make phase measurements relative within each frame.

The phase images revealed interesting phenomenological information about the laser-sample interaction. We imaged a temperature distribution which decayed temporally, but not radially. This indicated a beam width larger than the thermal decay length. Phase images were approximately linearly related to temperature via thermal expansion and refractive index. Literature values for these parameters were both on the order of 1e-5 /K. The resulting peak temperatures were on the order of 100 degrees Celsius above ambient with decay times of 500 microseconds. Data was fit to thermal models which showed a thermal diffusivity of 0.3 mm2/s, which agrees well with standard glass values.

Keywords: *interferometry, high-speed imaging, laser heating, microscopy, laser damage, heat transfer, quantitative phase, thermal imaging*

9632-40, SESSION 11

Comparative STEREO-LID (spatio-temporally resolved optical laser-induced damage) studies of critical defect distributions in IBS, ALD, and electron-beam coated dielectric films

Yejia Xu, The Univ. of New Mexico (United States); **Drew D. Schiltz,** Colorado State Univ. (United States); **Luke A. Emmert,** The Univ. of New Mexico (United States); **Andrew K. Brown, Joseph J. Talghader,** Univ. of Minnesota, Twin Cities (United States); **Damon E. Kletecka, Ella S. Field, John C. Bellum,** Sandia National Labs. (United States); **Dinesh Patel, Carmen S. Menoni,** Colorado State Univ. (United States); **Wolfgang Rudolph,** The Univ. of New Mexico (United States)

ABSTRACT TEXT: Laser-induced damage in high-quality optical coatings by nanosecond laser pulses is controlled by statistically distributed defects of largely unknown physical origin. The defect distribution can be characterized by a distribution function $\rho^{-}(F)$,an area density of defects that damage at incident fluence F. The defect distribution in optical coatings have previously been characterized under simplifying conditions by modeling measurements of damage probability [1,2].

STEREO-LID (Spatio-Temporally Resolved Optical Laser Induced Damage) [3] is a technique that identifies the initiation of laser-induced damage of an optical coating or surface both spatially and temporally. This allows the determination of the critical fluence and intensity in a single-shot measurement unlike in a traditional damage test. An optical surface (bulk or film) is probed by repeated tests (N sample sites) at the same incident fluence F_0. The resulting N damage fluences (or intensities) are properly binned and a function P(F) is determined that represents the probability that a damage event at fluence F is observed for an incident peak fluence F0. This probability distribution can be related to the defect distribution in a straightforward manner with few assumptions [4].

The implementation and operation of STEREO-LID will be briefly reviewed. Its application to the characterization of dielectric films prepared by different coating methods (ion-beam sputtering, electron-beam evaporation, and atomic layer deposition) will be presented. The defect distributions of the films coated with different methods will be compared.

REFERENCES

1. J. O. Porteus and S. C. Seitel, "Absolute onset of optical surface damage using distributed defect ensembles," Appl. Opt. 23, 3796–3805 (1984).
2. J.-Y. Natoli, L. Gallais, H. Akhouayri, and C. Amra, "Laser-induced damage of materials in bulk, thin-film, and liquid forms," Appl. Opt. 41, 3156–3166 (2002).
3. Yejia Xu, Luke A. Emmert, and Wolfgang Rudolph, "Spatio-TEmporally REsolved Optical laser Induced Damage (STEREO LID) Technique for Material Characterization," submitted to Applied Physics Letters.
4. Yejia Xu, Luke A. Emmert, and Wolfgang Rudolph, "Determination of defect densities from STEREO-LID (Spatio-TEmporally REsolved Optical Laser Induced Damage) measurements," submitted to Applied Optics.

Keywords: *laser induced damage threshold, coating defects, nanosecond pulse, ion-beam sputtering, electron-beam evaporation, atomic layer deposition*

9632-41, SESSION 11

Heat treatment of fused silica optics repaired by CO_2 laser

Thomas Doualle, Laurent Gallais, Institut Fresnel (France); **Philippe Cormont, Jean-Luc Rullier,** Commissariat à l'Énergie Atomique (France)

ABSTRACT TEXT: In this work we study the effect of a heat treatment on silica samples in a furnace. The work is conducted both on the as-polished surface and on CO_2 laser mitigated sites. The effect of annealing is investigated on super-polished fused silica samples of type II (Suprasil) and III (Corning 7980), these 2 materials having different characteristic temperatures (annealing point, softening point). We compare before and after different annealing conditions the morphology of mitigated site, the evolution of residual stress and the laser-induced damage threshold measured at 355nm, 3ns. The results show that the initial laser damage probabilities were significantly improved after annealing at 1050°C for 12 hours. The results of isothermal annealing are compared to local annealing with a CO_2 laser that was previously successfully applied to enhance the laser damage resistance of the mitigated sites [1].

The results of these experiments are compared to finite element thermo mechanical simulations [2] allowing evaluation of the evolution of residual thermo-mechanical stresses and fictive temperature after local and global annealing.

REFERENCES

[1] P. Cormont et al, Optics Express 18, 26068 (2010).

[2] T. Doualle et al., Proc. SPIE 9237, 92371R (2014)

Keywords: *laser damage, laser damage mitigation, annealing, LIDT*

9632-42, SESSION 11

Damage growth analysis at the National Ignition Facility

Zhi M. Liao, Michael C. Nostrand, Pam K. Whitman, Jeffrey D. Bude, Lawrence Livermore National Lab. (United States)

SPEAKER BIOGRAPHY: Zhi 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. 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's working in developing models for predicting optic lifetime for NIF which he has authored/presented 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 crystal.

ABSTRACT TEXT: Optics damage growth modeling and analysis in the National Ignition Facility (NIF) has been performed on fused silica. We will show results of single shot growth comparisons, damage site lifetime comparisons as well as growth metric of each individual NIF beamline. These results help validate the consistency of the damage growth models and allow us to have confidence in our strategic planning in regards to projected optic usage.

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9632-43, SESSION 11

Alternate fitting methods for sensitivity measurements of laser damage behavior

Jonathan W. Arenberg, Northrop Grumman Aerospace Systems (United States);
Clemens Heese, European Space Research and Technology Ctr. (Netherlands)

SPEAKER BIOGRAPHY: Jonathan W Arenberg has been working as an optical and systems engineer for over 30 years. His work experience has included tactical and high-power laser components and systems and major space astronomical projects such as Chandra and the James Webb Space Telescope. He holds degrees in physics and engineering from the University of California, Los Angeles and currently the Chief Engineer for Northrop Grumman Aerospace Systems on the James Webb Space Telescope. Dr. Arenberg is an SPIE fellow.

ABSTRACT TEXT: This paper extends recent research into so-called sensitivity measurements of laser damage behavior. Previous efforts have concentrated on data collected from randomly selected fluence levels. This year's report will concentrate on the role of fluence selection protocols on the rate of convergence of the sensitivity method and the resulting uncertainty in model parameters. The role of damage probability models will also be discussed.

Keywords: *maximum likelihood methods, sensitivity tests, fluence selection, Test methods*

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Tunable laser source based on storage device using Bragg grating

Chinmayee V. Prabhu Dessai, I. V. Anudeep K. Reddy, P. Saidi Reddy, G. R. C. Reddy,
National Institute of Technology, Goa (India)

SPEAKER BIOGRAPHY: Dr.G.R.C.Reddy Graduated from Osmania University with majors in math, physics and chemistry. He obtained his MSc (Technology) in Engineering Physics and PhD.(Optical Information Processing) from Faculty of Engineering and Technology, NIT(REC) Warangal. He joined on the faculty of the then REC Warangal and now NIT Warangal in the year 1979 and became full professor in 1995 in the Department of Physics.

Dr. Reddy`s specialization is Photonics. He was an investigator in a number of research projects sanctioned by CSIR, MHRD, DRDO etc. He published over 80 research papers in various National and International journals / Conference proceedings. He is a specialist in Optical Information Processing. His present interests include Optics applications in Nano-Science and Technology and Non-Linear Optics.

Earlier he was Director of NIT Calicut during 2005-2010. Currently he is the Director of National Institute of Technology,Goa, which is one of the most prominent institutes of India

ABSTRACT TEXT: Data storage is a fundamental technique today. In the past 50 years many attempts were made to store data. Devices like Floppy disk, CD-ROM and flip-flops came into picture and they store data in the form of bits. Present day electronic storage devices use electrons as storage medium. An attempt has been made to replace these fundamental particles with photons, which are also called light particles. Photons have rest mass of zero and excel in terms of size and speed. They travel at speed of light and hence replacing storage medium will benefit in terms of speed and efficiency. Basic Fiber optic devices like fiber optic couplers, fiber optic circulator, Erbium Doped Fiber Amplifier and fiber Bragg grating have been used to make Optical Storage Device. The basic idea is to take the light signal in feedback and form a loop. Light signal cannot escape out because of loop and keeps on rotating in the loop. Light signal loses power constantly due to multiple rotations. To maintain the power of the signal in a loop an Optical Amplifier is used which constantly boosts the signal. Fiber Bragg grating (FBG) is used here to store a selected frequency of light signal. This light signal is analogous to bit. Presence of light signal is taken as 1 and its absence as 0. Using multiple fiber Bragg gratings of different wavelengths, one can store multiple bit data using this device. Bragg grating is Temperature and strain sensitive and has excellent linearity. They are generally used for making sensors that measure basic physical parameters. Using mechanical methods to vary these parameters will result into a Variable wavelength Tunable Laser Source.Power of the tunable Laser source can also be varied using Erbium Doped Fiber Amplifier. This laser source has precision of 0.1 nm and is stable.

Keywords: *Tunable Laser Source, Optical Storage Device, Fiber Bragg Grating*

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SPIE INTERNATIONAL HEADQUARTERS
PO Box 10
Bellingham, WA 98227-0010 USA
Tel: +1 360 676 3290
Fax: +1 360 647 1445
help@spie.org • www.SPIE.org

SPIE EUROPE OFFICES
2 Alexandra Gate
Ffordd Pengam, Cardiff, CF24 2SA UK
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