SPIE. LASER DAMAGE

50th ANNIVERSARY

Laser Damage 2018

TECHNICAL PROGRAM/ ABSTRACT BOOK

ANNUAL SYMPOSIUM ON OPTICAL MATERIALS FOR HIGH-POWER LASERS

23–26 September 2018

Millennium Harvest House Boulder Hotel
Boulder, Colorado, USA

www.spie.org/LD

TECHNICAL PROGRAM/ABSTRACT BOOK

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Welcome

Welcome to the 50th Anniversary of the annual SPIE Laser Damage Symposium also known as the Symposium on Optical Materials for High Power Lasers, is the leading forum for the exchange of information on the physics/technology of materials for high-power/high-energy lasers. The conference proceedings series has grown to be a comprehensive source of information on optics for lasers and includes topics on laser-induced damage mechanisms, materials and thin film preparation, durability, properties modeling, testing, and component fabrication.

Celebrating 50 years of successful work for the international research community in those fields. The conference starts with a kick-off event – Sunday Evening Tutorial, and is hosting the featured Mini-Symposium, the Thin-Film Laser-Damage Competition, and includes both poster and oral presentations with no parallel sessions.

Distinguished international researchers in the field of optics for high-power/high-energy lasers will present invited talks. We have planned 3.5 days of information, networking, and enjoyment.

Take time to enjoy beautiful Boulder and its surroundings. We welcome you to Boulder!

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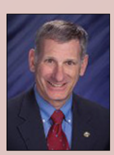
Christopher Wren Carr
Lawrence Livermore National Lab. (USA)

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



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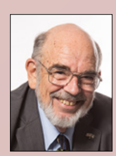

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Laser Damage 2018

ANNUAL SYMPOSIUM ON OPTICAL MATERIALS FOR HIGH-POWER LASERS

23–26 September 2018

Millennium Harvest House Boulder Hotel
Boulder, Colorado, USA

Welcome to Boulder

CELEBRATING 50 YEARS

50th ANNIVERSARY

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SPIE. LASER DAMAGE

23–26 September 2018
Millennium Harvest House Boulder Hotel
Boulder, Colorado, USA

Join your peers in Boulder for Laser Damage, where scientists and engineers present the latest research on high-power/high-energy lasers as well as materials and thin films, durability, properties modeling, testing, and component fabrication.

TUTORIAL and DISCUSSION

Laser Beam Characterization

Sunday 23 September 2018
6:00 to 7:00 pm
Location: Grand Ballroom
Registration and Badge Pick-up opens at 5:00 pm

CHAIRED BY

Bernd Eppich
Ferdinand-Braun-Institut, Leibniz-Institut für Höchstfrequenztechnik (Germany)

This tutorial is focused on overview of principles, approaches, and methods of characterization of later beams. Measurements of beam quality, diameter of laser spot on target surface, and other laser-beam parameters are inevitable for accurate measurements of laser-damage thresholds. The tutorial covers those topics to educate the next generation of the laser-damage research community.

FOLLOWED BY:

Welcome and Social Mixer
7:00 to 8:30 pm (See page 7 for details)

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GENERAL INFORMATION

ONSITE INFORMATION

Onsite Registration Hours / Badge Pick-Up

Sunday 23 September . . . . 5:00 pm to 7:30 pm
Monday 24 September . . . . 7:30 am to 4:00 pm
Tuesday 25 September . . . . 7:30 am to 4:00 pm
Wednesday 26 September . . . . 7:30 am to 3:00 pm

Refund Information

There is a $50 service charge for processing refunds. Requests for refunds must be received by 14 September 2018; all registration fees will be forfeited after this date. Membership dues, SPIE Digital Library subscriptions, or Special Events purchased are not refundable.

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U.S. Government credit card users: have your purchasing officer contact the credit card company and get prior authorization before attempting to register. Advise your purchasing agent that SPIE is considered a 5968 company for authorization purposes.

Car Rental

Hertz Car Rental has been selected as the official car rental agency for this event. To reserve a car, identify yourself as 2018 SPIE Laser Damage Symposium attendee using the Hertz Meeting Code CV# 029B0023. Discount rates apply for roundtrip rentals up to one week prior through one week after the conference dates. Note: When booking from International Hertz locations, the CV# must be entered with the letters CV before the number, i.e. CV029B0023.

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Contents

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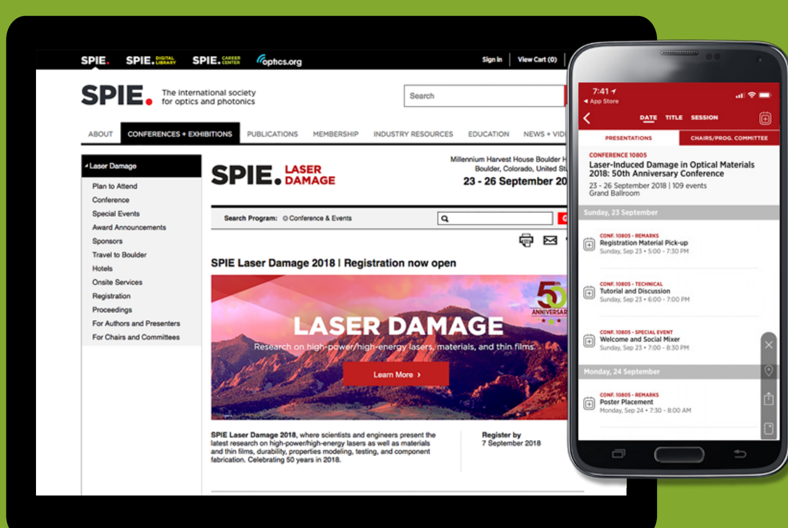

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COURTESY OF SPIE.

SUNDAY 23 September	MONDAY 24 September	TUESDAY 25 September	WEDNESDAY 26 September
SPIE LASER DAMAGE 2018			
REGISTRATION MATERIAL PICK-UP, 5:00 pm to 7:30 pm	**REGISTRATION MATERIAL PICK-UP,** 7:30 am to 4:00 pm	**REGISTRATION MATERIAL PICK-UP,** 7:30 am to 4:00 pm	**REGISTRATION MATERIAL PICK-UP,** 7:30 am to 3:00 pm
TUTORIAL AND DISCUSSION **Laser Beam Characterization,** 6:00 to 7:00 pm, p. 3	**Poster Placement,** 7:40 to 8:00 am, p. 8	**Poster Placement,** 7:30 to 8:00 am, p. 10	
Welcome and Social Mixer 7:00 to 8:30 pm, p. 7 *Registration Material Pick-up continues until 7:30 pm*	**Opening Remarks and 2017 Award Presentations** 8:00 to 8:40 am, p. 8 **Alexander Glass Best Oral Presentation, Arthur Guenther Best Poster Presentation, and MJ Soileau Best Student Paper Award**	**SESSION 5** **Mini-Symposium: 50th Anniversary Conference Overview II,** 8:00 to 9:40 am, p. 10	**SESSION 9** **Thin Films II,** 8:00 to 10:20 am, p.12
	**SESSION 1** **Mini-Symposium: 50th Anniversary Conference Overview I,** 8:40 to 10:20 am, p. 9		**Refreshment Break,** 10:20 to 10:50 am
	Monday Poster Overview, 10:20 to 10:50 am, p. 9	**Tuesday Poster Overview,** 9:40 to 10:10 am, p. 10	**SESSION 10** **Thin Films III,** 10:50 am to 12:50 pm, p.13
	Poster Viewing and Refreshment Break, 10:50 to 11:40 am, p. 9	**Poster Viewing and Refreshment Break,** 10:10 to 11:00 am, p. 10	
	SESSION 2 **Materials and Measurements I,** 11:40 am to 1:00 pm, p. 9	**SESSION 6** **Fundamental Mechanisms I,** 11:00 am to 1:00 pm, p.11	
	Lunch Break 1:00 to 2:10 pm	**Lunch Break** 1:00 to 2:20 pm	**Lunch Break** 12:50 to 2:00 pm
	SESSION 3 **Materials and Measurements II,** 2:10 to 3:50 pm, p. 10	**SESSION 7** **Fundamental Mechanisms II,** 2:20 to 3:40 pm, p.11	**SESSION 11** **Surface, Mirrors, and Contamination I,** 2:00 to 4:20 pm, p.13
	Poster Viewing and Refreshment Break, 3:50 to 4:40 pm, p. 10	**Poster Viewing and Refreshment Break,** 3:40 to 4:30 pm, p.11	**Refreshment Break,** 4:20 to 4:50 pm
	SESSION 4 **Materials and Measurements III,** 4:40 to 6:20 pm, p.10	**SESSION 8** **Thin Films I,** 4:30 to 5:30 pm, p.12	**SESSION 12** **Surface, Mirrors, and Contamination II,** 4:50 to 6:50 pm, p.13
	Closing Remarks, 6:20 to 6:30 pm, p.10	**Closing Remarks,** 5:30 to 5:40 pm, p.12	**Closing Remarks,** 6:50 to 7:00 pm, p.13
	OPEN HOUSE AND RECEPTION, 7:00 to 8:30 pm, p. 7	**WINE AND CHEESE TASTING RECEPTION,** 6:30 to 8:30 pm, p. 7	

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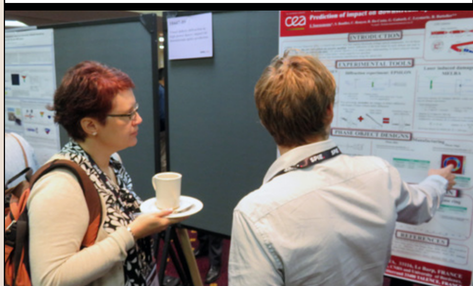

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Sunday • 23 September

TUTORIAL AND DISCUSSION

Laser Beam Characterization

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

Chaired by **Bernd Eppich**, Ferdinand-Braun-Institut, Leibniz-Institut für Höchstfrequenztechnik (Germany)

This tutorial is focused on overview of principles, approaches, and methods of characterization of later beams. Measurements of beam quality, diameter of laser spot on target surface, and other laser-beam parameters are inevitable for accurate measurements of laser-damage thresholds. The tutorial covers those topics to educate the next generation of the laser-damage research community.

Welcome and Social Mixer

7:00 to 8:30 pm
Location: The Millenium Garden

Join your colleagues for light refreshments and mingling.

Registration Material Pick-up continues until 7:30 pm, Sunshine Room, Across from Grand Ballroom

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Monday • 24 September

Poster Overviews—Monday

10:20 to 10:50 am • Location: Grand Ballroom

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

Poster Viewing and Refreshment Breaks-Monday

10:50 to 11:40 am and again from 3:50 to 4:40 pm
Location: Century Room

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

Open House and Reception

7:00 to 8:30 pm • Location: Advanced Thin Films

Come, relax, and join your colleagues at Advanced Thin Films for an enjoyable evening of refreshments, appetizers, and facility tour. Invitation and driving instructions will be included in your Registration Packet.

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Tuesday • 25 September

Poster Overviews—Tuesday

9:40 to 10:10 am • Location: Grand Ballroom

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

Poster Viewing and Refreshment Breaks-Tuesday

10:10 to 11:00 am and again from 3:40 to 4:30 pm
Location: Century Room

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

Wine and Cheese Tasting Reception

6:30 to 8:30 pm • Location: NCAR

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

SPONSORED BY: **SPIE** and **the Conference Co-Chairs of the 50th annual Laser Damage**

RECEPTION LOCATED AT:

NCAR-National Center for Atmospheric Research

1850 Table Mesa Dr., Boulder, Colorado

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CONFERENCE 10805

LOCATION: GRAND BALLROOM

Sunday–Wednesday 23–26 September 2018 • Proceedings of SPIE Vol. 10805

Laser-Induced Damage in Optical Materials 2018: 50th Anniversary Conference

Conference Chairs: **Christopher Wren Carr,** Lawrence Livermore National Lab. (USA); **Gregory J. Exarhos,** Pacific Northwest National Lab. (USA); **Vitaly E. Gruzdev,** The Univ. of New Mexico (USA); **Detlev Ristau,** Laser Zentrum Hannover e.V. (Germany); **M.J. Soileau,** CREOL, The College of Optics and Photonics, Univ. of Central Florida (USA)

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 (USA); **Enam A. Chowdhury,** The Ohio State Univ. (USA); **Stavros G. Demos,** Univ. of Rochester (USA); **Leonid B. Glebov,** CREOL, The College of Optics and Photonics, Univ. of Central Florida (USA); **Takahisa Jitsuno,** Osaka Univ. (Japan); **Klaus Mann,** Laser-Lab. Göttingen e.V. (Germany); **Andrius Melninkaitis,** Vilnius Univ. (Lithuania); **Carmen S. Menoni,** Colorado State Univ. (USA); **Masataka Murahara,** Tokai Univ. (Japan); **Jean-Yves Natoli,** Institut Fresnel (France); **Raluca A. Negres,** Lawrence Livermore National Lab. (USA); **Jérôme Néauport,** Commissariat à l'Énergie Atomique (France); **Semyon Papernov,** Univ. of Rochester (USA); **Wolfgang Rudolph,** The Univ. of New Mexico (USA); **Jianda Shao,** Shanghai Institute of Optics and Fine Mechanics (China); **Christopher J. Stolz,** Lawrence Livermore National Lab. (USA)

SUNDAY 23 SEPTEMBER

REGISTRATION MATERIAL PICK-UP

LOCATION: SUNSHINE ROOM . . . . 5:00 PM TO 7:30 PM

TUTORIAL AND DISCUSSION

LOCATION: GRAND BALLROOM . . . . 6:00 PM TO 7:00 PM

Laser Beam Characterization

Session Chair: **Bernd Eppich,** Ferdinand-Braun-Institut, Leibniz-Institut für Höchstfrequenztechnik (Germany)

This tutorial is focused on overview of principles, approaches, and methods of characterization of later beams. Measurements of beam quality, diameter of laser spot on target surface, and other laser-beam parameters are inevitable for accurate measurements of laser-damage thresholds. The tutorial covers those topics to educate the next generation of the laser-damage research community.

WELCOME AND SOCIAL MIXER

LOCATION: MILLENNIUM GARDENS . . . . 7:00 PM TO 8:30 PM

Join your colleagues for light refreshments and mingling.

Guest tickets are available onsite for $40.

Registration Material Pick-up continues until 7:30 pm

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MONDAY 24 SEPTEMBER

REGISTRATION MATERIAL PICK-UP

LOCATION: SUNSHINE ROOM . . . . .7:30 AM TO 4:00 PM

POSTER PLACEMENT

LOCATION: CENTURY ROOM . . . . 7:30 AM TO 8:00 AM

OPENING REMARKS OPENING REMARKS

LOCATION: GRAND BALLROOM . . . . 8:00 AM TO 8:40 AM

Session Chair: **M.J. Soileau,** CREOL, The College of Optics and Photonics, Univ. of Central Florida (USA)

AWARD WINNERS FOR LASER DAMAGE 2017

The Alexander Glass Best Oral Presentation Award

1st Place Best Oral Presentation

Revealing the relative contribution of photo- and impact-ionization in ultrashort pulse laser-induced damage in solid dielectrics . . . [10447-21]
Peter Jürgens, Anton Husakou, Mikhail Ivanov, Marc J.J. Vrakking, Alexandre Mermillod-Blondin, Max-Born-Institut für Nichtineare Optik und Kuzzeitspektroskopie (Germany)

The Arthur Guenther Best Poster Award

1st Place Best Poster Presentation

A method for the determination of the defect density distribution from standard damage frequency measurements. . . . . [10447-66]
Jonathan Arenberg, Northrop Grumman Aerospace Systems (USA); Carmen S. Menoni, Colorado State Univ. (USA)

The MJ Soileau Best Student Paper Award

1st Place Best Student Presentation

Time-resolved investigations of laser-dielectric interaction mechanisms . . . . (10447-27)
Allan Bildé, Stéphane Guizard, Ecole Polytechnique (France); Sergei M. Klimentov, A. M. Prohorov General Physics Institute of the Russian Academy of Sciences (Russian Federation); Andrius Melninkaitis, Julius Vaicenavicius, Balys Momgaudis, Vilnius Univ. (Lithuania); Alexandros Mouskeftaras, Ecole Polytechnique Fédérale de Lausanne (Switzerland)

Tribute to Joan Guenther

SESSION 1

LOCATION: GRAND BALLROOM . . . . MON 8:40 AM TO 10:20 AM

Mini-Symposium: 50th Anniversary Conference Overview I

Session Chairs: **M.J. Soileau,** CREOL, The College of Optics and Photonics, Univ. of Central Florida (USA);
Detlev Ristau, Laser Zentrum Hannover e.V. (Germany)

8:40 am: **Damage Phenomena in High-power Lasers: Early Studies** *(Plenary Presentation)*, Alexander J. Glass, KineMed, Inc. (USA) . . . . [10805-1]

9:05 am: **The Laser Damage Meeting: Early Years** *(Plenary Presentation)*, C. Martin Stickley, Retired from (D)ARPA/US-AFCRL, BDM, UCF/CREOL (USA) . . . . [10805-2]

9:30 am: **When Everything Damaged and We Didn't Know Why** *(Plenary Presentation)*, Michael A. Bass, CREOL, The College of Optics and Photonics, Univ. of Central Florida (USA) . . . . [10805-3]

9:55 am: **Test Methods for Laser-induced Damage Threshold of Medical Laser Delivery and Applications Systems** *(Plenary Presentation)*, Hans-Peter Berlien, Evangelische Elisabeth Klinik (Germany) . . . . [10805-4]

MONDAY POSTER OVERVIEWS

LOCATION: GRAND BALLROOM . . . . 10:20 AM TO 10:50 AM

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

POSTER VIEWING AND REFRESHMENT BREAK-MONDAY AM

LOCATION: CENTURY ROOM . . . . 10:50 AM TO 11:40 AM

Posters will be displayed for viewing during refreshment breaks on Monday from 10:50 am to 11:40 am, and again from 3:50 pm to 4:40 pm.

POSTER SESSION

LOCATION: CENTURY ROOM . . . . MON 10:50 AM TO 11:40 AM

Thin Films

Nanopits and catastrophic damage, Sebastian Paschel, Istvan Balasa, Lars O. Jensen, Laser Zentrum Hannover e.V. (Germany); Detlev Ristau, Laser Zentrum Hannover e.V. (Germany) and Leibniz Univ. Hannover (Germany); Xinbin Cheng, Zhanshan Wang, Tongji Univ. (China) . . . . [10805-57]

Particle mitigation during ion-beam sputtering towards enhanced damage threshold of high-power laser optics, Thimotheus Alig, Istvan Balasa, Laser Zentrum Hannover e.V. (Germany); Nils Bartels, Helmut Schröder, Paul Allenspacher, Deutsches Zentrum für Luft- und Raumfahrt e.V. (Germany); Lars O. Jensen, Detlev Ristau, Laser Zentrum Hannover e.V. (Germany)[10805-58]

Robust optimization of the laser-induced damage threshold of dielectric mirrors for high-power lasers, Marine Chorel, Thomas Lanternier, Éric Lavastre, CEA-Cesta (France); Nicolas Bonod, Institut Fresnel (France); Bruno Bousquet, Univ. de Bordeaux (France); Jérôme Néauport, CEA-Cesta (France). . . [10805-59]

Laser conditioning of UV anti-reflective optical coatings for applications in aerospace, Nils Bartels, Paul Allenspacher, Wolfgang Riede, Deutsches Zentrum für Luft- und Raumfahrt e.V. (Germany) . . . . [10805-60]

A comparison of LIDT behavior of AR-coated yttrium-aluminum-garnet substrates with respect to thin-film design and coating technology, Stepan Uxa, Václav Škoda, CRYTUR spol s.r.o. (Czech Republic); Jan Vanda, Mihai-George Muresan, HiLASE Ctr. (Czech Republic) . . . . [10805-61]

High-reflectance mirror using a porous MgF2 coating, Takahisa Jitsuno, Hidetsugu Yoshida, Junji Kawanaka, Noriaki Miyanaga, Osaka Univ. (Japan); Shinji Motokoshi, Institute for Laser Technology (Japan) and Osaka Univ. (Japan); Takayuki Okamoto, Takuya Mikami, Kunio Yoshida, Okamoto Optics Works, Inc. (Japan). . . . . [10805-62]

The impact of contamination and aging effects on the long-term laser-damage resistance of SiO_2/HfO_2/TiO_2 high-reflection coatings for 1054nm, Ella S. Field, Damon Kletecka, Sandia National Labs. (USA) . . . . [10805-63]

Laser-induced damage testing of high-efficiency reflectors for the MTW-OPAL beamline, Noah Talisa, The Ohio State Univ. (USA); Kyle Kafka, Univ. of Rochester (USA); Kevin Werner, The Ohio State Univ. (USA); Brittany N. Hoffman, Jim Oliver, Jake Bromage, Univ. of Rochester (USA); Enam A. Chowdhury, The Ohio State Univ. (USA) . . . . [10805-64]

Laser-induced damage threshold of porous single-layer ALD antireflective coatings, Thomas Gischkat, Rhysearch (Switzerland); Roelene Botha, Rhysearch (Switzerland) and NTB Interstaatliche Hochschule für Technik Buchs (Switzerland); Igor Stevanovic, Andreas Bächli, Rhysearch (Switzerland); Adriana Szeghalmi, Friedrich-Schiller-Univ. Jena (Germany) and Fraunhofer-Institut für Angewandte Optik und Feinmechanik (Germany); Lilit Ghazaryan, Friedrich-Schiller-Univ. Jena (Germany) . . . . [10805-65]

Femtosecond laser-induced modifications of frequency tripling mirrors (FTMs), Amir Khabbazi Oskouei, Luke A. Emmert, Wolfgang Rudolph, The Univ. of New Mexico (USA) . . . . [10805-66]

Continuous detection of particles on a rotating substrate during thin film deposition, Anna Karoline Rüsseler, Istvan Balasa, Lars O. Jensen, Laser Zentrum Hannover e.V. (Germany); Detlev Ristau, Laser Zentrum Hannover e.V. (Germany) and Leibniz Univ. Hannover (Germany) . . . . [10805-67]

Surfaces, Mirrors, and Contamination

Enhancement of fused silica laser-damage resistance using magnetic field-assisted finishing, Yusuke Funamoto, Daithi Shima, Yuji Umeda, Tomosumi Kamimura, Osaka Institute of Technology (Japan); Daniel Ross, Mikayla Lamb, Hitomi Yamaguchi, Univ. of Florida (USA). . . . . [10805-68]

Experimental study of growth on exit surface of various transmissive materials at 1053nm and 351nm, Mary A. Norton, Christopher W. Carr, Jeffrey D. Bude, Christopher F. Miller, William A. Steele, Ronald L. Luthi, John Honig, Lawrence Livermore National Lab. (USA) . . . . [10805-70]

Overview of laser damage performance of the third-harmonic frequency conversion crystals on the National Ignition Facility, Raluca A. Negres, Zhi M. Liao, David A. Cross, John J. Adams, Mary A. Norton, Christopher W. Carr, Lawrence Livermore National Lab. (USA) . . . . [10805-71]

SESSION 2

LOCATION: GRAND BALLROOM . . . . MON 11:40 AM TO 1:00 PM

Materials and Measurements I

Session Chairs: **Christopher J. Stolz,** Lawrence Livermore National Lab. (USA); **Enam A. Chowdhury,** The Ohio State Univ. (USA)

11:40 am: **Standardisation in optics characterisation** *(Keynote Presentation)*, Detlev Ristau, Laser Zentrum Hannover e.V. (Germany) and Leibniz Univ. Hannover (Germany); Istvan Balasa, Lars Jensen, Laser Zentrum Hannover e.V. (Germany) . . . . [10805-5]

12:20 pm: **U.S. National Committee proposed revision to the ISO Laser Damage Standard: 2018 Progress Report**, Jonathan W. Arenberg, Donna Howland, Northrop Grumman Aerospace Systems (USA); Michael D. Thomas, Spica Technologies, Inc. (USA); Trey Turner, Research Electro-Optics, Inc. (USA); Allen Krisiloff, Triptar Lens Co., Inc. (USA) . . . . [10805-6]

12:40 pm: **An analytic model to specify visual defects with regards to "hot spots" generation in a laser beam**, Florian Tournemenne, Stéphane Bouillet, Claude Rouyer, CEA-Cesta (France); Baptiste Battelier, Lab. Photonique, Numérique et Nanosciences (France) and Institut d'Optique Graduate School (France) and Univ. de Bordeaux (France) . . . . [10805-7]

Lunch Break . . . . Mon 1:00 pm to 2:10 pm

SESSION 3

LOCATION: GRAND BALLROOM . . . . MON 2:10 PM TO 3:50 PM

Materials and Measurements II

Session Chairs: **Meiping Zhu,** Shanghai Institute of Optics and Fine Mechanics (China); **Jean-Yves Natoli,** Institut Fresnel (France)

2:10 pm: **Absorption calibration of coatings with proxy pump**, Alexei L. Alexandrovski, Stanford Photo-Thermal Solutions (USA) . . . . . [10805-8]

2:30 pm: **Laser-induced damage measurements of crystalline coatings**, Garrett D. Cole, David Follman, Paula Heu, Gar-Wing Truong, Crystalline Mirror Solutions, LLC (USA); Christoph Deutsch, Crystalline Mirror Solutions GmbH (Austria); Chris Franz, Alexei L. Alexandrovski, Stanford Photo-Thermal Solutions (USA); Bin Ma, Xinbin Cheng, Tongji Univ. (China) . . . . [10805-9]

2:50 pm: **Multiple pulse nanosecond laser-induced damage threshold on AR coated YAG crystals**, Jan Vanda, Mihai-George Muresan, Vojtech Bilek, Pavel Cech, Antonio Lucianetti, Tomá? Mocek, Danijela Rostohar, Institute of Physics of the CAS, v.v.i. (Czech Republic); Václav ?koda, Stepan Uxa, CRYTUR spol s.r.o. (Czech Republic) . . . . [10805-10]

3:10 pm: **Investigation into Yb:YAG gain medium manufacturing and processing techniques for high-energy, high-average-power laser systems**, P. Jonathan Phillips, Mariastefania De Vido, Klaus Ertel, Saumyabrata Banerjee, Jodie Smith, Thomas Butcher, Chris Edwards, Cristina Hernandez-Gomez, John Collier, STFC Rutherford Appleton Lab. (United Kingdom); David Meissner, Stephanie Meissner, Onyx Optics Inc. (USA); Michael Walsh, Sean Kirkpatrick, Richard Svrluga, Exogenesis Corp. (USA); Paul Mason, STFC Rutherford Appleton Lab. (United Kingdom). . . . . [10805-11]

3:30 pm: **Laser-induced damage and defect analysis of calcium fluoride window caused by high pulse repetition rate ArF excimer laser radiation**, Takahito Kumazaki, Daisuke Tei, Masakazu Hattori, Junichi Fujimoto, Yasutsugu Usami, Hakaru Mizoguchi, Gigaphoton Inc. (Japan). . . . . [10805-12]

POSTER VIEWING AND REFRESHMENT BREAK-MONDAY PM

LOCATION: CENTURY ROOM . . . . 3:50 PM TO 4:40 PM

Posters will be displayed for viewing during refreshment breaks on Monday from 10:50 am to 11:40 am, and again from 3:50 to 4:40 pm.

SESSION 4

LOCATION: GRAND BALLROOM . . . . MON 4:40 PM TO 6:20 PM

Materials and Measurements III

Session Chairs: **Jonathan W. Arenberg,** Northrop Grumman Aerospace Systems (USA); **Semyon Papernov,** Univ. of Rochester (USA)

4:40 pm: **Why most attempts to predict fatigue-induced laser damage fail?**, Andrius Melninkaitis, Robertas Grigutis, Povilas Grigas, Linas Smalakys, Erikas Švažas, Vilnius Univ. (Lithuania); Mindaugas Šciuka, LIDARIS Ltd. (Lithuania); Urte Kimbaraite, Vilnius Univ. (Lithuania); Gintare Batavičiute, LIDARIS Ltd. (Lithuania) . . . . [10805-13]

5:00 pm: **Experimental measurement of material fatigue properties of x-ray optics by using laser pulses**, Xianchao Cheng, Lin Zhang, Stefan Droste, Lance Lee, Eric Flint Cunningham, Alan R. Fry, SLAC National Accelerator Lab. (USA) . . . . [10805-14]

5:20 pm: **Laser-Induced damage thresholds of nematic liquid crystals at 1 ns and multiple wavelengths**, Tanya Z. Kosc, Semyon Papernov, Alexei A. Kozlov, Stavros G. Demos, Kenneth L. Marshall, Univ. of Rochester (USA) . . . . [10805-15]

5:40 pm: **Automated repair of laser damage on National Ignition Facility optics using machine learning**, Scott Trummer, Glenn R. Larkin, Laura Mascio-Kegelmeyer, Mike C. Nostrand, Constantine Karkazis, David Martin, Raymond E. Aboud, Tayyab Suratwala, Lawrence Livermore National Lab. (USA) . . . . [10805-16]

6:00 pm: **Multimode silica-based fiber-optic delivery system for pulsed Nd-YAG lasers in UV region**, Karl-Friedrich Klein, Technische Hochschule Mittelhessen (Germany); Philipp Raithel, TransMIT GmbH (Germany) and WPI GmbH (Germany); Rahul Yadav, Technische Hochschule Mittelhessen (Germany); John Shannon, Rick Timmerman, Polymicro Technologies (USA); Bodo Kuehn, Heraeus Quarzglas GmbH & Co. KG (Germany). . . . . [10805-17]

CLOSING REMARKS

LOCATION: GRAND BALLROOM . . . . .6:20 PM TO 6:30 PM

Open House and Reception

MON 7:00 PM TO 8:30 PM

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TUESDAY 25 SEPTEMBER

REGISTRATION MATERIAL PICK-UP

LOCATION: SUNSHINE ROOM . . . . 7:30 AM TO 4:00 PM

POSTER PLACEMENT

LOCATION: CENTURY ROOM . . . . 7:30 AM TO 8:00 AM

SESSION 5

LOCATION: GRAND BALLROOM . . . . .TUE 8:00 AM TO 9:40 AM

Mini-Symposium: 50th Anniversary Conference Overview II

Session Chairs: **Detlev Ristau,** Laser Zentrum Hannover e.V. (Germany); **Christopher Wren Carr,** Lawrence Livermore National Lab. (USA)

8:00 am: **Early Laser Damage Research at State Optical Institute in Leningrad** *(Plenary Presentation)*, Leonid B. Glebov, CREOL, The College of Optics and Photonics, Univ. of Central Florida (USA); Vladimir L. Komolov, ITMO Univ. (Russian Federation) . . . . [10805-18]

8:25 am: **Highlights from the 2nd and 3rd Decades of the Laser Damage Symposia** *(Plenary Presentation)*, Brian E. Newnam, Los Alamos National Lab. (USA) . . . . [10805-19]

8:50 am: **Trends Observed in Ten Years of the BDS Thin Film Laser Damage Competition** *(Plenary Presentation)*, Christopher J. Stolz, Raluca A. Negres, Lawrence Livermore National Lab. (USA) . . . . [10805-20]

9:15 am: **The History and Presence of High-resolution Laser Spectroscopy and its Applications** *(Plenary Presentation)*, Scott A. Diddams, National Institute of Standards and Technology (USA). . . . . [10805-21]

TUESDAY POSTER OVERVIEWS

LOCATION: GRAND BALLROOM . . . . 9:40 AM TO 10:10 AM

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

POSTER VIEWING AND REFRESHMENT BREAK-TUESDAY AM

LOCATION: CENTURY ROOM . . . . 10:10 AM TO 11:00 AM

Posters will be displayed for viewing during refreshment breaks on Tuesday from 10:10 am to 11:00 am, and again from 3:40 pm to 4:30 pm.

CONFERENCE 10805

POSTER SESSION

LOCATION: CENTURY ROOM . . . . TUE 10:10 AM TO 11:00 AM

Fundamental Mechanisms

The structure of retired components and irradiated KDP crystals with different fluences, Xiangcao Li, Xin Ju, Baoan Liu, Univ. of Science and Technology Beijing (China) . . . . [10805-72]

Free-carrier heating in wide-band-gap crystals: high-collision-rate Drude model versus low-collision-rate approximation, Vitaly E. Gruzdev, Olga Sergaeva, Univ. of Missouri (USA); Enam A. Chowdhury, The Ohio State Univ. (USA) . . . . [10805-73]

Materials and Measurements

Laser damage size analysis (DSA) for efficient lifetime damage threshold measurements, Selim Elhadj, Jae Hyuck Yoo, Lawrence Livermore National Lab. (USA) . . . . [10805-74]

The nonlinear refractive index of thin films and substrates at various wavelengths and pulse durations, Morten Steinecke, Tarik Kellermann, Marco Jupé, Lars O. Jensen, Laser Zentrum Hannover e.V. (Germany); Detlev Ristau, Laser Zentrum Hannover e.V. (Germany) and Leibniz Univ. Hannover (Germany) . . . . [10805-75]

Time-resolved analysis of resist removal phenomenon without causing laser damage, Yuji Umeda, Daithi Shima, Hayato Tsukamoto, Sora Aikawa, Yusuke Funamoto, Kosuke Nuno, Hiroyuki Kuramae, Osaka Institute of Technology (Japan); Ryousuke Nakamura, Osaka Univ. (Japan); Hideo Horibe, Osaka City Univ. (Japan); Tomosumi Kamimura, Osaka Institute of Technology (Japan). . . . . [10805-76]

Accelerated testing of high fluence protective coated optics, Saptaparna Das, John Melchior, Eric Mason, Cymer LLC (USA) . . . . [10805-77]

Photothermal absorption characterization of fused silica laser-induced damage dependence on laser fluence, the number of shots and pulse repetition frequencies, Chunyan Yan, Xin Ju, Baoan Liu, Univ. of Science and Technology Beijing (China) . . . . [10805-78]

Absorption investigations in optical fibers, Christian Muehlig, Simon Bublitz, Martin Lorenz, Martin Leich, Leibniz-Institut für Photonische Technologien e.V. (Germany) . . . . [10805-79]

Laser durability evaluations of silica glass at 1064 and 213 nm, Reina Kashiwagi, Nikon Corp. (Japan) . . . . [10805-80]

Laser-induced damage in optical glasses using nanosecond pulses at 1030nm, Mihai Muresan, Pavel Cech, Vojtech Bilek, HiLASE Ctr. (Czech Republic); Petra Horodyska, Institute of Plasma Physics of the CAS, v.v.i. (Czech Republic); Danijela Rostohar, Antonio Lucianetti, Tomá? Mocek, HiLASE Ctr. (Czech Republic) . . . . [10805-81]

Application of image processing and machine learning for classification of laser-induced damage morphology, Linas Smalakys, Erikas Švažas, Robertas Grigutis, Andrius Melninkaitis, Vilnius Univ. (Lithuania), LIDARIS Ltd. (Lithuania) . . . . [10805-82]

Determination of the laser-induced damage threshold of polymer optical fibers, Kevin Kiedrowski, Istvan Balasa, Dietmar Kracht, Detlev Ristau, Laser Zentrum Hannover e.V. (Germany) . . . . [10805-83]

Investigation and characterization of optical signatures in multilayer dielectric gratings to improve cleanliness, Brittany N. Hoffman, Semyon Papernov, Stavros G. Demos, Univ. of Rochester (USA) . . . . [10805-84]

VIS-to-NIR absorption spectroscopy of magneto-optical materials for high-power laser applications, Tobias Trendle, Jens Kiessling, Jachin Kunz, Frank Kühnemann, Fraunhofer-Institut für Physikalische Messtechnik (Germany) . . . . [10805-86]

Spectrally resolved wavefront measurements on broad-band dielectric coatings, Klaus Mann, Jennifer Ahrens, Bernd Schäfer, Laser-Lab. Göttingen e.V. (Germany); Michael Vergöhl, Chris Britze, Stefan Bruns, Fraunhofer-Institut für Schicht- und Oberflächentechnik (Germany); Volker Kirschner, European Space Research and Technology Ctr. (Netherlands) . . . . [10805-87]

Online detection of hot image in the large aperture near field of the final optics assembly, Zhaoyang Jiao, Mingying Sun, Jianqiang Zhu, Shanghai Institute of Optics and Fine Mechanics (China). . . . . [10805-88]

Study of the role of interface on the defect density in HfO_2 films using STEREO-LID (Spatio-TEmporally REsolved Optical Laser-Induced Damage), Luke A. Emmert, Sebastian Töpfer, The Univ. of New Mexico (USA); Thomas Willemsen, Marco Jupé, Detlev Ristau, Laser Zentrum Hannover e.V. (Germany); Wolfgang Rudolph, The Univ. of New Mexico (USA) . . . . . . [10805-89]

Distribution of the laser damage threshold: extreme value statistical analysis, Jonathan W. Arenberg, Northrop Grumman Aerospace Systems (USA) [10805-90]

SESSION 6

LOCATION: GRAND BALLROOM . . . . TUE 11:00 AM TO 1:00 PM

Fundamental Mechanisms I

Session Chairs: **Andrius Melninkaitis,** Vilnius Univ. (Lithuania); **Amy L. Rigatti,** Univ. of Rochester (USA)

11:00 am: **Shaping nonlinear ultrafast laser interactions: gateway to novel bulk glass and intra-film devices** *(Keynote Presentation)*, Peter R. Herman, Stephen Ho, Ehsan Alimohammadian, Erden Ertorer, Sifan Liu, Jianzhao Li, Univ. of Toronto (Canada) . . . . [10805-22]

11:40 am: **Laser-induced periodic structures on optical materials**, M.J. Soileau, Yingjie Chai, CREOL, The College of Optics and Photonics, Univ. of Central Florida (USA). . . . . [10805-23]

12:00 pm: **Revisiting of the laser-induced filamentation damage conditions in fused silica for energetic laser systems**, Eyal Feigenbaum, Wade H. Williams, Raluca A. Negres, Mary A. Norton, Christopher F. Miller, Gabriel Mennerat, Clay Widmayer, Christopher W. Carr, Jean-Michel G. Di Nicola, Jeffrey D. Bude, Lawrence Livermore National Lab. (USA) . . . . [10805-24]

12:20 pm: **Laser-induced-damage mechanisms under nanosecond laser irradiation in absorbing glasses**, Stavros G. Demos, Brittany N. Hoffman, Univ. of Rochester (USA); Christopher W. Carr, Jeffrey D. Bude, David A. Cross, Lawrence Livermore National Lab. (USA) . . . . [10805-25]

12:40 pm: **Damage morphology at pulse-lengths near the transition from intrinsic to defect-driven initiation in hafnia-silica high reflectors**, Alexei A. Kozlov, Brittany N. Hoffman, James B. Oliver, Stavros G. Demos, Univ. of Rochester (USA) . . . . [10805-26]

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

SESSION 7

LOCATION: GRAND BALLROOM . . . . TUE 2:20 PM TO 3:40 PM

Fundamental Mechanisms II

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

2:20 pm: **Towards quantification of laser-induced damage phenomena: experimental assessment of absorbed pulse energy via time-resolved digital holography**, Balys Momgaudis, Robertas Grigutis, Viaceslav Kudriašov, Mikas Vengris, Andrius Melninkaitis, Vilnius Univ. (Lithuania) . . . . [10805-27]

2:40 pm: **Few-cycle pulse single shot laser ablation of single layer TiO_2 thin films**, Noah Talisa, Kevin Werner, Enam A. Chowdhury, The Ohio State Univ. (USA) . . . . [10805-28]

3:00 pm: **Changes of the nonlinear absorption in crystals under irradiation with trains of high-repetition rate femtosecond pulses**, Valdas Sirutkaitis, Karolis Bagocius, Mantas Sirutavicius, Simas Butkus, Julius Vengelis, Ieva Pipinyte, Vygandas Jarutis, Vilnius Univ. (Lithuania) . . . . [10805-29]

3:20 pm: **First principles simulation of near- and mid-infrared ultrashort pulse laser damage using the particle-in-cell method**, Alex Russell, Douglass Schumacher, The Ohio State Univ. (USA). . . . . [10805-30]

POSTER VIEWING AND REFRESHMENT BREAK-TUESDAY PM

LOCATION: CENTURY ROOM . . . . 3:40 PM TO 4:30 PM

Posters will be displayed for viewing during refreshment breaks on Tuesday from 10:10 am to 11:00 am, and again from 3:40 pm to 4:30 pm.

CONFERENCE 10805

SESSION 8

LOCATION: GRAND BALLROOM . . . . TUE 4:30 PM TO 5:30 PM

Thin Films I

4:30 pm: **Recent advances on light-matter interaction in layered media** *(Keynote Presentation)*, Michel Lequime, Institut Fresnel (France) [10805-31]

5:10 pm: **Effects of film stress in laser-induced damage**, Lars O. Jensen, Tammo Boentgen, Laser Zentrum Hannover e.V. (Germany); Helmut Kessler, Manx Precision Optics Ltd. (Isle of Man); Detlev Ristau, Laser Zentrum Hannover e.V. (Germany). . . . . [10805-32]

CLOSING REMARKS

LOCATION: GRAND BALLROOM . . . . .5:30 PM TO 5:40 PM

Wine and Cheese Tasting Reception

TUE 6:30 PM TO 8:30 PM

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REGISTRATION MATERIALS PICK-UP

LOCATION: SUNSHINE ROOM . . . . .7:30 AM TO 3:00 PM

SESSION 9

LOCATION: GRAND BALLROOM . . . . WED 8:00 AM TO 10:20 AM

Thin Films II

Session Chairs: **James E. Andrew,** AWE plc (United Kingdom); **Vitaly E. Gruzdev,** Univ. of Missouri (USA)

2018 DAMAGE COMPETITION

8:00 am: **1064-nm Mirror Thin Film Damage Competition**, Raluca A. Negres, Christopher J. Stolz, Lawrence Livermore National Lab. (USA); Andrew J. Griffin, Michael D. Thomas, Spica Technologies, Inc. (USA) . . . . [10805-33]

8:20 am: **Extensive time-resolved investigation of laser-induced damage fatigue of single layer dielectric coatings**, Linas Smalakys, Balys Momgaudis, Mikas Vengris, Robertas Grigutis, Andrius Melninkaitis, Vilnius Univ. (Lithuania) . . . . [10805-34]

8:40 am: **Predictions of electric-field–limited laser damage for multilayer coatings**, James B. Oliver, Brian Charles, David Coates, Stavros G. Demos, Brittany N. Hoffman, Kyle Kafka, Alexei A. Kozlov, Sara MacNally, Thomas J. Noll, Semyon Papernov, Amy L. Rigatti, Daniel Sadowski, Chris Smith, Univ. of Rochester (USA) . . . . [10805-35]

9:00 am: **Production of high laser-induced damage threshold (LIDT) mirror coatings using plasma assisted evaporation (PAD), plasma assisted reactive magnetron sputtering (PARMS) and ion beam sputtering (IBS)**, Alex Ribeaud, Harro Hagedorn, Jürgen Pistner, Bühler Alzenau GmbH (Germany); Matthew Brophy, Pete Kupinski, Jon Watson, Robert Hand, Optimax Systems, Inc. (USA) . . . . [10805-36]

9:20 am: **Laser-induced pits in optical coatings**, Yuan'an Zhao, Shanghai Institute of Optics and Fine Mechanics (China); Cheng Li, Shanghai Institute of Optics and Fine Mechanics (China) and Univ. of Chinese Academy of Sciences (China); Yun Cui, Meiping Zhu, Jianda Shao, Shanghai Institute of Optics and Fine Mechanics (China). . . . . [10805-37]

9:40 am: **Development of adaptively mixed thin film (AMTF) deposited by a dielectric material and a plastic**, Kunio Yoshida, Osaka Univ. (Japan) and Okamoto Optics Works, Inc. (Japan); Takayuki Okamoto, Takuya Mikami, Okamoto Optics Works, Inc. (Japan); Hidetsugu Yoshida, Junji Kawanaka, Noriaki Miyanaga, Osaka Univ. (Japan); Shinji Motokoshi, Institute for Laser Technology (Japan); Takahisa Jitsuno, Osaka Univ. (Japan) . . . . [10805-38]

10:00 am: **Laser damage of Yb:YAG active mirrors under atmospheric, vacuum, and cryogenic conditions**, Hanchen Wang, Alexander Meadows, Elzbieta Jankowska, Brendan A. Reagan, Jorge J. Rocca, Carmen S. Menoni, Colorado State Univ. (USA). . . . . [10805-39]

Coffee Break . . . . Wed 10:20 am to 10:50 am

SESSION 10

LOCATION: GRAND BALLROOM . . . . WED 10:50 AM TO 12:50 PM

Thin Films III

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

10:50 am: **Effect of water vapor on the properties of coatings deposited by electron-beam evaporation**, Meiping Zhu, Tingting Zeng, Shanghai Institute of Optics and Fine Mechanics (China); Yingjie Chai, Univ. of Central Florida (USA); Chaoyi Yin, Nuo Xu, Jianda Shao, Shanghai Institute of Optics and Fine Mechanics (China). . . . . [10805-40]

11:10 am: **The role of entrapped Argon on laser performance of hafnia coatings under nanosecond UV laser exposure**, Colin Harthcock, S. Roger Qiu, Raluca A. Negres, Alexander M. Rubenchik, Gabe Guss, Marlon G. Menor, Tommaso Pardini, Luis A. Zepeda-Ruiz, Christopher J. Stolz, Paul B. Mirkarimi, Lawrence Livermore National Lab. (USA); Gourav Bhowmik, Mengbing Huang, Univ. at Albany (USA) . . . . [10805-41]

11:30 am: **Damage thresholds in hafnia and silica monolayers and correlation to optical signatures**, Marine Chorel, Thomas Lanternier, Éric Lavastre, Laurent Lamaignère, CEA-Cesta (France); Brittany N. Hoffman, Alexei A. Kozlov, James B. Oliver, Semyon Papernov, Stavros G. Demos, Univ. of Rochester (USA); Bruno Bousquet, Univ. de Bordeaux (France); Jérôme Néauport, CEA-Cesta (France) . . . . [10805-42]

11:50 am: **The role of interfacial roughness on laser performance of silica/hafnia multilayer coatings under nanosecond UV laser exposure**, S. Roger Qiu, Eyal Feigenbaum, Colin Harthcock, Raluca A. Negres, Ted A. Laurence, Gabe Guss, Marlon G. Menor, Tommaso Pardini, Sonny Ly, Christopher J. Stolz, Hoang T. Nguyen, Paul B. Mirkarimi, Lawrence Livermore National Lab. (USA); Gourav Bhowmik, Mengbing Huang, SUNY CNSE/SUNYIT (USA) . . . . [10805-43]

12:10 pm: **Laser damage property of the ultra-steep edge filter**, Jinlong Zhang, Hongfei Jiao, Bin Ma, Chun Xie, Xinbin Cheng, Zhanshan Wang, Tongji Univ. (China) . . . . [10805-44]

12:30 pm: **LIDT measurements and contamination mitigation techniques of optical coatings at ELI beamlines facility**, Praveen Kumar Velpula, Michal Durák, Daniel Kramer, Bedrich Rus, ELI Beamlines (Czech Republic) . . . . [10805-45]

Lunch Break . . . . Wed 12:50 pm to 2:00 pm

SESSION 11

LOCATION: GRAND BALLROOM . . . . WED 2:00 PM TO 4:20 PM

Surface, Mirrors, and Contamination I

Session Chairs: **Raluca A. Negres,** Lawrence Livermore National Lab. (USA); **Jianda Shao,** Shanghai Institute of Optics and Fine Mechanics (China)

2:00 pm: **Getting a high-power UV laser into space: the story of the Aladin laser development for the European Space Agency's Aeolus Satellite** *(Keynote Presentation)*, Denny Wernham, European Space Research and Technology Ctr. (Netherlands); Wolfgang Riede, Deutsches Zentrum für Luft- und Raumfahrt e.V. (Germany). . . . . [10805-46]

2:40 pm: **Novel AMP surface treatment for improving optical fiber strength and laser gain**, Diana VanBlarcom, Derrek R. Drachenberg, Marcus V. Monticelli, Gabriel E. Davalos, Steve R. Davis, Nick Schenkel, Matthew J. Cook, Robert P. Crist, Michael J. Messerly, Jay W. Dawson, Lawrence Livermore National Lab. (USA). . . . . [10805-69]

3:00 pm: **A system to identify small damage sites (<50 µm) to increase the lifetime of recycled fused silica optics**, Christopher F. Miller, Laura Kegelmeyer, Mike C. Nostrand, Rajesh N. Raman, David A. Cross, Zhi M. Liao, Raminder Garcha, Christopher W. Carr, Lawrence Livermore National Lab. (USA) [10805-47]

3:20 pm: **Pulsed LiDT of transversely resonant nano-structure array high reflectors at 1064nm**, Douglas S. Hobbs, Bruce D. MacLeod, Anthony D. Manni, Stephen M. Consoles, TelAztec LLC (USA) . . . . [10805-48]

3:40 pm: **Cleaning process to improve the laser-induced damage threshold of anti-reflection subwavelength structures in near-infrared region**, Fei Liu, Jinlong Zhang, Hongfei Jiao, Bin Ma, Zhanshan Wang, Chun Xie, Xinbin Cheng, Tongji Univ. (China) . . . . [10805-49]

4:00 pm: **Novel etching fluids for water-sensitive optical crystals**, Salmaan H. Baxamusa, Paul Ehrmann, Jemi Ong, Ted A. Laurence, Steven A. Hawks, John J. Adams, Kathleen Schaffers, Lawrence Livermore National Lab. (USA) . [10805-50]

Coffee Break . . . . Wed 4:20 pm to 4:50 pm

SESSION 12

LOCATION: GRAND BALLROOM . . . . WED 4:50 PM TO 6:50 PM

Surfaces, Mirrors, and Contamination II

Session Chairs: **Gregory J. Exarhos,** Pacific Northwest National Lab. (USA); **Klaus Mann,** Laser-Lab. Göttingen e.V. (Germany)

4:50 pm: **Damage performance and developments of final optics system for UV nanosecond high-power laser systems**, Mingying Sun, Zhaoyang Jiao, Yajing Guo, Chong Liu, Rong Wu, Lei Ren, Ping Shao, Jianqiang Zhu, Zunqi Lin, Shanghai Institute of Optics and Fine Mechanics (China) . . . . [10805-51]

5:10 pm: **Mitigation of a novel phase-defect-induced laser damage mechanism on NIF final optics**, Michael C. Nostrand, Phil Miller, Pamela K. Whitman, Christopher W. Carr, David A. Cross, Aaron Peer, Rajesh N. Raman, Tayyab Suratwala, Lawrence Livermore National Lab. (USA) . . . . [10805-52]

5:30 pm: **Fragment plume evaluations from high-energy density laser target interactions**, James E. Andrew, AWE plc (United Kingdom) . . . . [10805-53]

5:50 pm: **Study of the first stages of laser-induced contamination**, Georges Gebrayel El Reaidy, Frank R. Wagner, Jean-Yves Natoli, Institut Fresnel (France); Delphine Faye, Ctr. National d'Études Spatiales (France) . . . . [10805-54]

6:10 pm: **Stochastic nature of interaction between nanosecond-pulsed 351nm laser and glass contaminants on fused silica exit surface**, Rajesh N. Raman, Christopher F. Miller, Raminder Garcha, Mary Norton, Christopher W. Carr, Lawrence Livermore National Lab. (USA) . . . . [10805-55]

6:30 pm: **Removal of particle contaminations on dielectric pulse-compressor gratings by laser cleaning and the effect on laser-damage threshold**, Jingxuan Wang, China Academy of Engineering Physics (China) . . . . . [10805-56]

CLOSING REMARKS

LOCATION: GRAND BALLROOM . . . . .6:50 PM TO 7:00 PM

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TECHNICAL ABSTRACTS

ABSTRACTS

10805-1, SESSION 1

Damage Phenomena in High-power Lasers: Early Studies

Alexander J. Glass, KineMed, Inc. (USA)

No Abstract Available

10805-2, SESSION 1

The Laser Damage Meeting: Early Years

C. Martin Stickley, Retired from (D)ARPA/US-AFCRL, BDM, UCF/CREOL (USA)

ABSTRACT TEXT: This talk will cover my personal recollections about the early years of lasers and the laser damage situation in the 60s: the persons involved, the lasers used in damage experiments, the companies involved, funding agencies involved, personal interactions in those days, the nature of the papers in 1968 , and the unique style of management and conduct of the first and later meetings by Art Guenther and Alex Glass, a co-invited speaker with me at this 50th anniversary meeting.

10805-3, SESSION 1

When Everything Damaged and We Didn't Know Why

Michael A. Bass, CREOL, The College of Optics and Photonics, Univ. of Central Florida (USA)

ABSTRACT TEXT: As lasers approached their 10th birthday it was clear that before high power lasers would damage a target they would most likely damage themselves. If the cause was to ever be understood the properties of the laser beam and the surface or material irradiated had to be specified in a reproducible manner. Experiments had to be performed so that another experimenter could confirm or not the earlier work. This meant no reports of damage caused by multimode laser beams. These by definition are not reproducible even one pulse to the next. The pulse waveform and duration had to be given along with the bandwidth of the detection system. It was also necessary to specify how the pulse energy was measured. Then came the vexing problem of measuring the distribution and diameter of the laser light incident on the target. In fact, a reproducible definition of when damage had taken place had to be given. Understanding and dealing with all of these problems did not happen at once but over time more careful experimental techniques made it possible to gain a better understanding of laser damage to optical components. Early efforts to deal with these problems, techniques developed to make proper measurements and concepts expressed for when damage took place will be discussed.

10805-4, SESSION 1

Test Methods for Laser-induced Damage Threshold of Medical Laser Delivery and Applications Systems

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ABSTRACT TEXT: Fire in an operating room is the most dangerous situation for patient and staff. Besides electrosurgical devices and endoscopic light sources, even surgical lasers can be ignition sources for drapes, gowns and tracheal tubes. This risk was identified very early and several ISO standards for laser proof materials have been published. The medical beam delivery system itself, however, was out of focus. Due to the increasing market on the one hand and necessity for cost reduction in health care on the other hand fibres have come into the market with a risk of self-ignition of the core or cladding material. Furthermore with reinvention of fibre-applicator-systems for contact application or integrated diffusor systems they have an increased risk for self-ignition due to high absorption. So it is important to perform quality requirements for companies suppliers and hospitals. At this time there is no existing work or standard to this topic. This project elaborates reproducible test parameters for medical beam delivery systems.

Because the problem of ignition and damage due to laser transmission is not limited only to medical devices but even e.g. in communication systems and fiber laser system the work was started in close cooperation with WG1 SC9 to avoid any duplication. The presented draft follows the structure, terminology and test procedure the existing standards for surgical drapes ISO11810 and Endotracheal tubes ISO11990 to avoid inconsistency in these standards

10805-57, SESSION PS1

Nanopits and catastrophic damage

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ABSTRACT TEXT: Previous studies have shown that nanometer scale defects can lead to the formation of submicrometer craters if located in coatings with a relatively small thickness[1,2]. Due to the small size, such damages are challenging to detect in the online and offline damage detection and may therefore lead to an overestimation of the LIDT for the tested optical component. Especially for thin anti-reflective (AR) coatings the formation of pits with submicrometer sizes was observed at significantly lower fluences compared to the needed fluence for catastrophic damage[2]. However, the influence of these nanopits on the optical properties and the impact on the initiation of the catastrophic damage was not investigated in detail in the past. In order to study the correlation between nanopits, optical properties and catastrophic damage, samples with an AR-coating were fabricated by means of ion beam sputtering (IBS) and tested for their laser resistance by LIDT raster scans in the nanosecond regime at 355nm. The generation and morphology changes of the nanopits were monitored for different pulse numbers and in dependence of the starting fluence. Additionally to the inspection with an optical microscope in differential interference contrast (DIC) mode as prescribed by ISO 21254, alternative inspection methods, for example

dark field microscopy and scanning electron microscopy (SEM), were used to detect the nanopits.

REFERENCES

[1] S. Papernov, A. W. Schmid, "High-spatial-resolution studies of UV-laser-damage morphology in SiO_2 thin films with artificial defects," Proc. SPIE 5647, Laser-Induced Damage in Optical Materials: 2004, (21 February 2005)

[2] Z. Song, X. Cheng, H. Ma, J. Zhang, B. Ma, H. Jiao, and Z. Wang, "Influence of coating thickness on laser-induced damage characteristics of anti-reflection coatings irradiated by 1064-nm nanosecond laser pulses," Appl. Opt. 56, C188-C192 (2017)

10805-58, SESSION PS1

Particle mitigation during ion-beam sputtering towards enhanced damage threshold of high-power laser optics

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ABSTRACT TEXT: In future earth explorer mission with satellites, LIDAR systems with high power laser optics will enable advanced understanding of tropical dynamics and processes relevant to climate change. However, nano-scaled particles originating from sample preparation or film deposition processes reduce the optic's laser-induced damage threshold by heating of the defect to extremely high temperatures[1,2]. Therefore, successful missions require thorough investigations of all optical components. Taking the film deposition process to a level, where the formation of these particular defects is prevented, will increase the safety margin of these missions significantly.

To eliminate the damage precursors, high energetic ion bombardment during layer growth is studied. Within the corresponding optimization steps, gas types and incident angles of the ion bombardment are varied. High damage thresholds in vacuum and low defect concentrations qualify reactive ion beam sputtering as a suitable deposition method[3]. In order to eliminate less tightly bound surface defects, preferential resputtering during the growth process is utilized. For high power applications, ultraviolet antireflective coatings combining aluminum oxide and silicon dioxide layers are deposited on super polished substrates.

To verify the impact on the defect mitigation, laser-induced damage threshold tests according to ISO 21254-2 in an S-on-1 protocol are conducted. Furthermore, raster scan methods cover a large portion of the optical surface in order to trigger even smallest densities of remaining layer defects. Insusceptibility with respect to laser-induced contamination is the second important criteria for reliability in space applications. Therefore additional investigations in controlled environment are conducted.

KEYWORDS: Particle mitigation; Laser-induced damage threshold; Dual ion beam sputtering; Anti-reflective coating; Aluminum oxide; Silicon dioxide

REFERENCES:

[1] L. G. DeShazer, B. E. Newnam, and K. M. Leung "Role of coating defects in laser induced damage to dielectric thin films", Appl. Phys. Lett. 23, 607 (1973)

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[2] I. Balasa; M. Hippler, H. Schröder, L. Jensen, M. Gauch, D. Ristau and W. Riede “Enhancement of contamination growth and damage by absorption centers under UV irradiation”, Proc. SPIE 9237, Laser-Induced Damage in Optical Materials: 2014, 92372A (November 4, 2014)
[3] L. Jensen, M. Jupé, H. Mädebach, H. Ehlers, K. Starke, D. Ristau, W. Riede, P. Allenspacher and H. Schroeder „Damage threshold investigations of high-power laser optics under atmospheric and vacuum conditions”, Proc. SPIE. 6403, Laser-Induced Damage in Optical Materials: 2006, 64030U. (October 11, 2006)

10805-59, SESSION PS1

Robust optimization of the laser-induced damage threshold of dielectric mirrors for high-power lasers

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ABSTRACT TEXT: We report on a numerical optimization of the laser induced damage threshold of multi-dielectric high reflection mirrors in the sub-picosecond regime. We highlight the interplay between the electric field distribution, refractive index and intrinsic laser induced damage threshold of the materials on the overall laser induced damage threshold (LIDT) of the multilayer. We describe an optimization method of the multilayer that minimizes the field enhancement in high refractive index materials while preserving a near perfect reflectivity. This method yields a significant improvement of the damage resistance since a maximum increase of 40% can be achieved on the overall LIDT of the multilayer.

KEYWORDS: thin films; optical properties; deposition and fabrication; multilayer design; ultrafast optics; laser damage

10805-60, SESSION PS1

Laser conditioning of UV anti-reflective optical coatings for applications in aerospace

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SPEAKER BIOGRAPHY: Nils Bartels received his PhD from the University of Göttingen (Germany) in 2015 working on fundamental physics of energy transfer between gas phase molecules and metal surfaces. His current research focuses on the investigation of laser optics (laser-induced molecular contamination as well as laser-induced damage thresholds) for applications in the aerospace.

ABSTRACT TEXT: In this work we study the effect of laser conditioning on laser-induced damage of ion-beam sputtered, anti-reflection coated laser optics with ns-pulsed laser radiation at a wavelength of 355 nm. With respect to applications in aerospace, measurements were performed under high vacuum. At laser fluences below 20 J/cm^2, laser-induced damage appears as pin-point damage (small explosion pits with sizes in the range of 1 µm), sometimes referred to as “grey haze”. We compare two different protocols of laser conditioning (below-threshold versus ramped laser conditioning) and systematically analyze their effect on mitigating laser-induced damage. We find that ramped laser conditioning is far superior to below-threshold laser conditioning and greatly reduces the density as well as the average crater size of pin-point damages. We discuss our results in the framework of the small absorber model for damage crater formation.

KEYWORDS: Laser conditioning; Ion-beam sputtering; Anti-reflection coating; Aerospace; Crater formation

10805-61, SESSION PS1

A comparison of LIDT behavior of AR-coated yttrium-aluminium-garnet substrates with respect to thin-film design and coating technology

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SPEAKER BIOGRAPHY: Stepan Uxa received his PhD degree in Physics from the Charles University in Prague, Faculty of Mathematics and Physics in 2015. He has been working as optical coating researcher in the coating department in Crytur Ltd. in Turnov, Czech Republic since 2012.

ABSTRACT TEXT: Laser-induced damage threshold (LIDT) of anti-reflection (AR) coated substrates prepared from Czochralski-grown yttrium-aluminium-garget (YAG) single crystal was measured at the wavelength of 1030 nm, 10 ns pulse duration with repetition rate of 10 Hz in s-on-1 mode according to the ISO 21254 standard. Induced damage was detected by both the online scattered light diagnostics and the offline inspection using confocal microscopy. Surface of the substrates was visually inspected for the presence of scratches and digs and the micro-roughness was measured by white-light interferometry (WLI) prior to deposition. Both narrow-band (V-shape) and broad-band (W-shape) AR dielectric coatings were designed for normal incidence at lasing/pumping wavelengths of Nd:YAG and Yb:YAG lasers with respect for their applicability to laser crystals. The samples were coated in high-vacuum cryo-pumped chamber using either reactive or ion-assisted e-beam deposition technology. A comparison of measured values of LIDT is presented.

KEYWORDS: LIDT; thin films; AR coatings; dielectric coatings; YAG; laser crystals

10805-62, SESSION PS1

High-reflectance mirror using a porous MgF_2 coating

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ABSTRACT TEXT: In the stack of QWOT layers of the form substrate-HL-n which uses in laser system, SiO_2 material is mainly used.

However, the SiO_2 has a strong absorption band at the wavelength of 1.3, 2.2,and 2.7 µm. The transmission of MgF_2 material is transparent over the wide wavelength range, but the usage of the MgF_2 material is very difficult because of the crazing generation due to strong tensile stress. On the contrary, the tensile stress of the porous MgF_2 thin film is less than 20. This porous coating forms a mixed thin film with MgF_2 material and plastic, and the transmission is transparent in the ultraviolet to near-infrared regions. This porous MgF_2 thin film is promising for making the multilayer coatings.

KEYWORDS: High reflection coating; Multi-layer coating; Porous coating; MgF_2

10805-63, SESSION PS1

The impact of contamination and aging effects on the long-term laser-damage resistance of SiO_2/HfO_2/TiO_2 high-reflection coatings for 1054nm

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SPEAKER BIOGRAPHY: Ella Field is an engineer at Sandia National Laboratories in Albuquerque, New Mexico. She manages operations at the Optical Support Facility and develops optical coatings for the Z-Backlighter Laser. She received bachelor's degrees in mechanical engineering and Asian languages and literature from the University of Minnesota in 2009, and received a master's degree in mechanical engineering from the Massachusetts Institute of Technology in 2011.

ABSTRACT TEXT: The laser damage thresholds of optical coatings can suffer degradation over time. Optical coatings deposited using electron beam evaporation are particularly susceptible to degradation due to their porous structure, which collects contamination. In earlier work we tried to determine whether these coatings also develop intrinsic aging effects that promote degradation. The study showed that a thin film aging effect is likely responsible for reduced laser damage resistance, although contamination in these aged coatings was also suspected. The coatings in question were high reflectors for 1054 nm that contained SiO_2 and HfO_2 and/or TiO_2 layers. They were deposited in 2013 and the laser damage threshold of each coating was then measured at 3.5 ns as a baseline. In 2017, the laser damage thresholds were measured again, and most of the coatings exhibited lower intrinsic damage thresholds, leading us to believe that an aging effect was responsible. However, to better understand the role of contamination in these results, the coatings were recleaned and the laser damage thresholds were measured again in 2018. The results of these tests are presented in this study, along with suggestions of how to maintain the quality of porous optical coatings over time.

KEYWORDS: Contamination; Aging; Laser Damage; Degradation; Optical Coatings; Hafnia; Silica; Titania

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10805-64, SESSION PS1

Laser-induced damage testing of high-fficiency reflectors for the MTW-OPAL beamline

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ABSTRACT TEXT: Introduction: The development of the Multi-Terawatt Optical Parametric Amplifier Line (MTW-OPAL) at the laser facility at the Laboratory for Laser Energetics (LLE) will enhance the high energy density physics (HEDP) research capabilities of the laser facility, and will form a solid foundation for the development of the OMEGA EP OPAL system. The MTW-OPAL system is intended to output 15 fs pulses with 7.5 J, achieving 0.5 PW peak power and intensities around 1021 W/cm^2[1]. This performance necessitates, among other challenges, the design of high efficiency optics with a high laser-induced damage threshold (LIDT). In this work, the LIDTs of a broadband enhanced metal reflector (BEMR) and a multi-layer dielectric reflector (MLD), both designed and manufactured at LLE [2], are determined in a test station designed to mimic the operational environment of the optics in the MTW-OPAL system.

Experimental setup: Laser pulses with a duration of 15 ±1 fs and nominal central wavelength ~760 nm are generated with a hollow-core fiber and chirped mirror compressor setup (Kaleidoscope, Spectra Physics), pumped by 0.5 mJ pulses from a home-built 3 mJ/pulse, 35 fs Ti:Sapphire laser operating at 500 Hz. The pulse duration was measured with a home-built dispersionless scanning autocorrelator. The optical path length to the autocorrelator was carefully matched to the path length leading to the sample so that the measured duration accurately represents the pulses that hit the sample. The bandwidth and dispersion of the pulses were carefully tuned by adjusting the Ar pressure in the hollow core fiber and separation of a glass wedge pair in order to achieve bandwidth limited pulses with the same pulse duration as the MTW-OPAL beamline. The laser focus was characterized in situ by image relaying onto a camera for fluence calibration, and the energy of each pulse was measured with a pickoff followed by a calibrated photodiode. Test mirrors were irradiated at 45° angle of incidence in rough vacuum (<1 mbar) with p- or s-polarization, depending on the mirror design. Single shot, R-on-1, and multi-shot damage threshold fluences were determined by post analysis with optical- and atomic force-microscopy (AFM).

Results: In the first round of testing, a single MLD was compared with two BEMR's from the same coating run. A significant discrepancy between the measured threshold fluences for s-polarized pulses of the two BEMR's led to a second round of testing, which involved testing the same two mirrors with p-polarized pulses and then testing three other BEMR's with the same design with s-polarization. One of the 5 BEMR's tested showed a large difference in LIDT fluence between s- and p- pol pulses, whereas the other 4 had the same threshold within experimental error and showed no significant difference between s- and p-pol thresholds. Further investigation into what caused the discrepancy of LIDT of two reflectors from the same coating run will be discussed, and could provide insight into how thin film coating conditions can affect the LIDT. Overall, the LIDT of the MLD was significantly higher than that of the BEMR design. The damage morphologies of the two reflectors were studied using AFM, can provide information about how the layer design can affect laser-induced damage.

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KEYWORDS: laser-induced damage threshold; MTW-OPAL; multi-layer dielectric; enhanced metal reflector; ultrashort; ultra-intense; test station; laser damage

REFERENCES:

[1] "MTW-OPAL: A Technology Development Platform for Ultra-Intense OPCPA Lasers and Applications," J. Bromage, S.-W. Bahk, I. A. Begishev, C. Dorrer, R. G. Roides, C. Mileham, J. B. Oliver, D. Weiner, D. Haberberger, C. Stoeckl, P. M. Nilson, D. H. Froula, and J. D. Zuegel, presented at IFSA 2015, Seattle, WA, 20–25 September 2015.

[2] J. B. Oliver, J. Bromage, C. Smith, D. Sadowski, C. Dorrer, and A. L. Rigatti, "Plasma-ion-assisted coatings for 15 femtosecond laser systems," Appl. Opt. 53, A221-A228 (2014)

10805-65, SESSION PS1

Laser-induced damage threshold of porous single-layer ALD antireflective coatings

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ABSTRACT TEXT: Atomic layer deposition (ALD) enables the coating of complex shaped substrates with excellent uniformity along the surface of the optic. Recently developed nanoporous SiO2 layers have been applied as single layer antireflection coatings on Suprasil 1 fused silica substrates at both 1064 nm and 532 nm wavelengths. The LIDT in the nanosecond regime at both 1064 nm and 532 nm of these nanoporous SiO2 coatings were investigated. The multiple pulse damage characteristic for 3000 shots showed no significant pulse dependence, with the 1064nm LIDT value (95 J/cm^2) approaching that of an uncoated substrate (109 J/cm^2). Furthermore, the stability of the coatings with respect to LIDT and optical properties has been evaluated under normal atmospheric conditions, dry air with relative humidity < 10% and Nitrogen atmosphere.

KEYWORDS: atomic layer deposition; ALD; laser damage; porous SiO_2

10805-66, SESSION PS1

Femtosecond laser-induced modifications of frequency tripling mirrors (FTMs)

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ABSTRACT TEXT: A Frequency Tripling Mirror (FTM) is a 1D stack of multilayer films. The thicknesses of alternating high and low

index dielectric coatings, for example hafnia and silica films, are dimensioned so that third-harmonic (TH) radiation in reflection is produced efficiently when femtosecond pulses are incident [1,2]. The relatively small nonlinear susceptibility of third-order that controls third-harmonic generation of amorphous wide-gap dielectric coatings is balanced by the large incident intensities that are possible before catastrophic laser induced damage (LID) occurs in these materials.

The mirrors were tested by focusing a train of pulses from a Ti:sapphire oscillator (791 nm central wavelength; 50 fs pulse duration; 110 MHz repetition rate; up to 7 nJ pulse energy; 6.5 μm beam waist at focus). Permanent material modifications (i.e. change to reflection/transmission and TH) are observed for below LID fluences as can be expected in materials like hafnia [3]. TH is a particularly sensitive measure of material modification because of its cubic dependence on the field enhancement in the multilayer stack. Such modifications can compromise the FTM's performance. Understanding their properties and origin is necessary to design and fabricate stable nonlinear components based on dielectric coatings.

The FTM under consideration consists of hafnia (with a small admixture of alumina) and silica layers. The mirror was exposed to linearly polarized fs pulses of high fluence below LID, with their central wavelength tuned for maximum TH generation. The experiment was then repeated with a circularly polarized laser and with the laser tuned off resonance. The induced material modification led to a drop of TH generation, which saturated at the level of a few ten percent of the initial value after about 20 min. The modified stack region was then probed by a weak test pulses to measure changes in transmission and reflection, and imaged using a microscope in transmission, reflection, and Nomarski modes.

The results show that

1. The laser must be tuned to the resonance wavelength of the FTM in order to observe material modification.
2. However, TH is not required as material modification was also observed after illuminating with a circularly polarized beam, which suppresses THG in isotropic materials.
3. The change of transmission and reflection can be explained, through modeling, by a change of the complex refractive index of the layer with high fundamental field intensity.
4. This model puts an upper limit on the relative increase to the real and imaginary parts of the refractive index at 1% and 23%, respectively.
5. Microscope images reveal that the radius of the modified spot is approximately equal to the beam waist.

KEYWORDS: nonlinear optics; third harmonic generation; multilayer dielectric coatings; material modification

REFERENCES:

1. C. Rodríguez and W. Rudolph, "Modeling third-harmonic generation from layered materials using nonlinear optical matrices," Opt. Express 22, 1678–1684 (2014).
2. C. Rodríguez, S. Günster, D. Ristau, and W. Rudolph, "Frequency tripling mirror," Opt. Express 23, 31594 (2015).
3. L. A. Emmert, M. Mero, and W. Rudolph, "Modeling the effect of native and laser-induced states on the dielectric breakdown of wide band gap optical materials by multiple subpicosecond laser pulses," J. Appl. Phys. 108, 043523 (2010).

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10805-67, SESSION PS1

Continuous detection of particles on a rotating substrate during thin film deposition

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SPEAKER BIOGRAPHY: Anna Karoline Rüsseler studied physics at the Gottfried Wilhelm Leibniz Universität in Hanover, Germany. She received the Master's degree in physics in 2016. Since 2017, she has been working as a research associate at Laser Zentrum Hannover e.V. in the Characterization Group of the Laser Components Department. Her current research interest includes the characterization of defects on optical thin films, especially the in situ particle detection during thin film deposition.

ABSTRACT TEXT: Particles which contaminate the surface of a thin film optic during the deposition process demand special attention in the field of high precision optics. The particles are embedded in the coating either cannot be removed or they are leaving a defect upon removal by standard cleaning procedures. As they are overcoated by thin film material, even small particles can initiate the formation of larger defects by nodular growth. Especially in the nanosecond regime, irradiated with high power laser light, defects can be considered as absorption centers, which lead to local heating and eventually to catastrophic damage of the optics. In addition, not only considering damage phenomena, a broad variety of deficiencies such as delamination, increased scatter losses, or wavefront distortions can be attributed to unwanted particle inclusions in the coating.

In this contribution, a camera based device for the detection of particles is presented which monitors the coating surface continuously during the deposition process. Dark field LED illumination is used to reach high sensitivity for the detection of small particles. A fully in-vacuum setup has been constructed and mounted on the substrate plate. It co-rotates with a transparent test substrate, viewing the coating surface through the substrate's volume.

The advantage of the presented monitoring system is that the camera images are taken without having to stop the substrate plate's rotation to prevent motion blur. Therefore, this detection concept minimizes the intervention in the actual coating process and is particularly interesting for production quality control.

Automated analysis of the camera images taken by this device is used to draw conclusions about the evolution of particle contamination on the substrate during the deposition of different materials. Thereby it is shown how the number of particles increases over the process time for different material combinations and in individual process steps. In addition, ex situ measurement results from a subsequent dark field microscopy of the coated samples are shown. Combining both, the time resolved data and ex situ characterization data with high spatial resolution, the first steps are taken towards an identification of particle sources in the coating process which is the basis for the development of particle mitigation strategies on production level in the future.

10805-68, SESSION PS2

Enhancement of fused silica laser-damage resistance using magnetic field-assisted finishing

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ABSTRACT TEXT: The laser-induced damage threshold (LIDT) of a fused silica polished surface is much lower than the dielectric breakdown threshold of bulk pure fused silica. Effect of polishing contamination and surface defects for the LIDT has already been extensively studied in transparent optics. In addition, subsurface damage is known to lower the LIDT of fused silica. These factors for the decrease in LIDT could be suppressed by a final finishing process after conventional optical polishing. The magnetic field-assisted finishing (MAF) technique has been shown to be successful in the fine finishing of optical components such as transparent Nd:YAG ceramics.

In this paper, the effects of the MAF technique for final finishing of fused silica surfaces were investigated. Fused silica substrates polished with CeO2 compounds were prepared as workpieces, and the surface roughness was about 0.3 nm Sq after optical polishing. MAF was performed for 20 minutes and for 40 minutes. Material removal occurred with the MAF process, however the final surface roughness did not change. Each processed surface was tested for laser damage at wavelengths of 266 nm. For surfaces processed for 40 minutes, the LIDT at a laser wavelength of 266 nm of processed surfaces was about 1.3 times higher than for the as-polished surface. The damage morphology will be discussed.

KEYWORDS: defects; particles; in situ monitoring; thin films; dark field microscopy; quality control; camera imaging; particle induced laser damage

10805-70, SESSION PS2

Experimental study of growth on exit surface of various transmissive materials at 1053nm and 351nm

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SPEAKER BIOGRAPHY: M. A. Norton received the A. B. degree in Physics from Emmanuel College in Boston, and an M. S. and a Ph. D. in Physics from the University of Arizona. After working at M. I. T. Lincoln Laboratory in adaptive optics, she joined Lawrence Livermore Laboratory in 1987 where her current research interests are laser damage and growth in solid state laser systems.

ABSTRACT TEXT: High-energy laser systems are limited by the onset and subsequent rate of damage growth on constituent optics. This phenomenon extensively studied for optics comprised of SiO2, but less so for other common optical materials. There are very few materials as well characterized as fused silica and, in this work, we explore the growth characteristics of other widely used optical materials with a range of physical parameters such as sapphire, potassium dihydrogen phosphate, phosphate glass, and others and compare them to SiO_2.

Since current understanding is that material fracture must be present before the fluences used in ns laser might be sufficient to cause the flaw location to grow, we have chosen to study flaws on the exit surfaces created with a Vickers indenter. A range of indenter forces were selected that would produce flaw sizes typical of those that have been seen in laser created damage flaws.

Samples with arrays of indents were tested in the in the Optical Science Laser (OSL), a master oscillator power amplifier system, with a front-end pulse shaping capability able to deliver relevant fluences with a large area beam. Samples were tested in vacuum at 351 nm and at atmosphere at 1053 nm with a single shot fired every 45 minutes exposing dozens of sites simultaneously. High resolution images of each flaw were taken after every shot to document any changes. Additional tests at 1064 nm were conducted of individual sites at a 60 Hz rep rate in the Gigashot Optical Laser Damage (GOLD) system. The thrust of these shots was to investigate the reliability of predicting lifetime from single shot data. The data from all these experiments will be presented and discussed.

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

KEYWORDS: laser damage growth; fused silica damage; indent laser growth

10805-71, SESSION PS2

Overview of laser damage performance of the third-harmonic frequency conversion crystals on the National Ignition Facility

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ABSTRACT TEXT: The National Ignition Facility (NIF) is a 192-beam, ICF-class laser system in operation at Lawrence Livermore National Laboratory which can deliver over 1.8 MJ of 351-nm light on target for extreme laser-matter interaction experiments. At its highest operating level, the final optics in the ultraviolet section of the laser are routinely exposed to 351-nm fluences as high as 9-10 J/cm^2, which is enough to initiate and grow damage. Damage is frequently monitored on all final optics using an elaborate in-situ damage inspection system and data processing software to track the status of the optics and allow for timely optics exchanges and subsequent repair/recycling of the optical components at a fraction of their original acquisition cost. For the past three years we have focused our efforts on better understanding the damage performance of the deuterated potassium dihydrogen phosphate (DKDP) third-harmonic frequency conversion crystals with emphasis on surface damage initiation and growth. We report on the methodologies for accurate calibration of the in-situ damage inspection system based on offline, full-aperture optics metrology and a preliminary assessment of damage initiation and growth rates on DKDP optics at the current NIF operational fluences.

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

KEYWORDS: surface damage; damage growth; DKDP; nanosecond laser pulses; third-harmonic frequency conversion crystals; ultraviolet light

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10805-5, SESSION 2, KEYNOTE PRESENTATION

Standardisation in optics characterisation

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SPEAKER BIOGRAPHY: Detlev Ristau finished his study of physics at the University of Hannover in 1982 and worked in the field of power handling capability of optical coatings in the thin film group of the Institut für Quantenoptik at the University of Hannover. After receiving a Ph.D. degree in 1988 he was responsible for the thin film group at the institute until 1992. Detlev Ristau is presently director of the Department of Laser Components at the Laser Zentrum Hannover. After receiving a state doctorate in 2008 he was appointed as a professor for Applied Physics at the Leibniz University in Hannover in 2010 and also assumed responsibility for a research group on Ultrahigh Quality Optical Layers. He is author or co-author of more than 300 technical papers as well as several book chapters, and he edited a book on “Laser induced damage in optical materials”.

ABSTRACT TEXT: An adapted quality management is a major prerequisite for the reliable production of optical components and coatings. Especially laser applications impose highest demands on modern optical systems and can be considered as a major pacemaker for the development of advanced quality management strategies. Therefore, most of the standardised concepts for the determination of the properties necessary for a comprehensive quality control, as for example losses and transfer functions as well as laser induced damage thresholds or defect densities of optical surfaces, are based on laser systems. This contribution is intended to offer a brief review on the present status of optics characterisation and the related standards often applied in the production of laser components. A selection of International Standards will be presented with focus on the determination of laser induced damage thresholds (ISO 21254), optical absorption (ISO 11551), total scattering (ISO 13696), losses (ISO 13142), und transfer functions. The corresponding measurement methods will be described and discussed before the background of typical applications in laser technology. Finally, some aspects of the future development and projects of the international standardization activities will be discussed.

KEYWORDS: International Standards ISO 21254, ISO 13696, ISO 11551, ISO 13142, ISO 15368, ISO 13697

10805-6, SESSION 2

U.S. National Committee proposed revision to the ISO Laser Damage Standard: 2018 Progress Report

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ABSTRACT TEXT: In previous years, this committee reported on the need for a US National Laser damage standard, addressing the needs of domestic industry. [1] Last year, a process was reported that connected the measurement of the active defect density in a small area, a, with the likely density of such defects over a larger area, A. This was presented as the basis of a Type 1, go/no-go test. The main issue as reported last year is that the proper flow of a standard is to start with the required properties of the larger area and design a robust test. The process presented in 2017 [2] is hard to implement in a way convenient for the non-expert user, which is nearly all. The main thrust of the work in 2018, is developing and evaluating options for implementing a useful workable standard.

KEYWORDS: Laser damage procedure; Standards; OEOSC TF7

REFERENCES

[1] “Periodic Review of ISO 21254: US National Committee Proposal for Revision”, Jonathan W. Arenberg, Donna J. Howland, Christopher Wren Carr, Michael D. Thomas, John C. Bellum, Trey Robinson and Jason Yager, Presented at SPIE Laser Damage, Boulder CO, 2016

[2] “U.S. National Committee proposed revision to the ISO Laser Damage Standard”, Jonathan W. Arenberg, Donna Howland, Michael Thomas, Trey Turner, John Bellum, Ella Field, C. Wren Carr, Gary Shaffer, Matthew Brophy, Allen Krisiloff, Proc. SPIE 10447, Laser-Induced Damage in Optical Materials 2017, 104471E (21 November 2017)

10805-7, SESSION 2

An analytic model to specify visual defects with regards to “hot spots” generation in a laser beam

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SPEAKER BIOGRAPHY: Florian Tournemenne graduated two year ago from the ENSEIRB-MATMECA engineering school. In 2016, he started his PhD at the CEA-CESTA. His main interest is the impact of “visual” defects on the propagation of a high power laser beam.

ABSTRACT TEXT: The optics used in the high-power laser facilities have to be well specified in order to maintain the wave quality. Indeed, a degraded wave will decrease the laser performances with regards to focal spot or laser induced damage. The wave imperfections can be whether global considerations like roughness or local defects like digs. In this paper, we focus on the local defects with regards to their impact on “hot spots” generation which increases the probability of downstream laser induced damage. The local defects are traditionally specified according to their transverse dimension and the specification is applied by using standards like ISO 10110-7 or MIL-PRF-13830B. We note two main issues. First, these standards are poorly justified and do not fit a high-power laser needs. Moreover, they are based on transverse dimensions only and they neglect the defects nature and structure. In order to address this issue, we developed an analytic model to identify the parameters responsible for “hot spots” formation downstream of a defect. The defect is modeled by concentric quasi-circular rings of different radii, transmissions and phase shifts fitted to the defect structure. In this paper, we investigate the light diffracted by typical defects like mitigations of laser damage sites or AR coating process defects. Confrontations are made between observed diffraction patterns downstream of real defects and what the model predicts, in terms of “hot spots” apparitions. We show that, even for defects with complex morphology, the knowledge of few parameters (in most cases transverse dimension and phase shift) is enough to estimate a safety area where downstream light modulations are low enough.

KEYWORDS: visual defects; metrology; diffraction; propagation; near field; laser damage; hot spot generation

10805-8, SESSION 3

Absorption calibration of coatings with proxy pump

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SPEAKER BIOGRAPHY: Alexei Alexandrovski, General Partner at Stanford Photo-Thermal Solutions (SPTS), obtained his PhD in Physics at Moscow State University in 1977. Until 1997 he worked in various positions in the research staff of the Moscow State in the field of crystal growth and nonlinear optics. From 1997 till 2009 he was a research scientist at the Ginzton Lab, Stanford University, where he introduced Photothermal Common-Path Interferometry for the measurement of low absorption in optical components. The technology was commercialized in the year 2003 with the foundation of SPTS. Dr. Alexandrovski has published more than 100 journal articles and conference proceedings.

ABSTRACT TEXT: Multilayer coatings may not respond as simple thin films, both optically and thermally, when tested with a photothermal technology. At infrared (IR) wavelengths and especially in the mid-IR, where thicknesses of layers are larger, individual calibration of every coating design is essential. We report on a new experimental approach, the “proxy pump” calibration technique, which is applied quickly and in situ for the efficient characterization of the photothermal response of high reflectivity (HR) GaAs/AlGaAs multilayers. For this work, the photothermal setup is equipped then with an additional, “proxy” pump having the same beam spot size as the main pump. The other requirement for this additional pump is known absorption in the coating.

The technique was implemented with a low power 532 nm pump for the HR GaAs/AlGaAs crystalline coatings with design wavelengths ranging from 1064 nm to 3800 nm. As the penetration depth is a fraction of a micron for GaAs at 532 nm, the proxy pump generates same thermal field in the coating and the substrate as the main IR pump, with the benefit of known absorbed power. Two different low-noise optical probes were used, including a red HeNe-laser and a 1310 nm single-frequency diode. Both green proxy pump and the red probe initially appear to be non-ideal choices because of the potential for free carriers generation in these GaAs-based coatings , giving rise to nonlinear absorption and non-thermal effects with these sources. We will show in detail, however, that the linear thermal effect of absorption in GaAs dominates for the green pump. A very weak, about 1 ppm in absorption scale, non-thermal effect had only been detected for the IR pump and for the red probe, while clearly separable from the thermal signal.

KEYWORDS: optical absorption; interference coatings; photothermal spectroscopy; aluminum gallium arsenide; near infrared; mid-infrared

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10805-9, SESSION 3

Laser-induced damage measurements of crystalline coatings

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SPEAKER BIOGRAPHY: Garrett D. Cole, Co-Founder of Crystalline Mirror Solutions, obtained his PhD in Materials from UCSB in 2005. Since completing his doctorate, he has held positions ranging from the first employee of a high-tech startup (Aerius Photonics LLC, now FLIR Electro-Optical Components), to a postdoctoral position at LLNL, a Marie Curie Fellow of the Austrian Academy of Sciences, and an assistant professor at the University of Vienna. Dr. Cole has authored 2 book chapters and published more than 50 journal articles and conference proceedings including papers in Science, Nature, Nature Physics, Nature Photonics, Nature Nanotechnology, Nature Communications, and the Proceedings of the National Academy of Sciences. Leveraging his expertise in microfabrication, tunable vertical-cavity surface-emitting lasers, and cavity optomechanics, Dr. Cole developed the proprietary substrate-transfer process at the heart of CMS and, along with Prof. Markus Aspelmeyer, co-founded the venture in late 2013.

ABSTRACT TEXT: Substrate-transferred crystalline coatings have emerged as a groundbreaking new concept in optical interference coatings. Building upon our initial demonstration of this technology in 2013, we have recently realized significant improvements in the optical performance of these novel single-crystal GaAs/AlGaAs multilayers. In the near-infrared, for center wavelengths spanning 1064 to 1560 nm, we have reduced the excess optical losses (scatter + absorption) to less than 5 ppm, with the direct measurement of sub-ppm optical absorption in these films, enabling the realization of a cavity finesse exceeding 600,000 at the telecom-relevant wavelength range near 1550 nm. In this presentation we outline preliminary measurements of the laser-induced damage threshold (LIDT) of these novel semiconductor-based interference coatings. For pulsed excitation (ns pulse durations at 1064 nm), the narrow bandgap of the constituent mirror materials limits the LIDT to 3-5 J/cm^2. Under these conditions, laser damage is driven by two-photon absorption (TPA) in the semiconductor multilayer, primarily the high-refractive-index GaAs films. Note that improved performance may be realized for illumination wavelengths >1740 nm, where TPA is eliminated. For continuous-wave (CW) illumination, the high thermal conductivity (~30 Wm-1K-1) and low intrinsic absorption yield the potential for excellent performance. Here we present preliminary CW damage measurements for a 10-ppm transmission quarter-wave GaAs/AlGaAs Bragg mirror transferred to super-polished fused silica, with only a 1.4 K temperature rise for an intensity of ~1.5 MW/cm^2. Further efforts will continue to push the limits of the structure with the aim of determining the maximum CW intensity that such mirrors can tolerate.

KEYWORDS: absorption; aluminum gallium arsenide; distributed Bragg reflectors; epitaxial layer transfer; interference coatings; laser damage; near infrared; semiconductors

10805-10, SESSION 3

Multiple pulse nanosecond laser-induced damage threshold on AR coated YAG crystals

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SPEAKER BIOGRAPHY: Jan Vanda received his PhD degree in Optoelectronics from the Technical University of Ostrava, Czech Republic. He gathered one-year experience as post-doc at FORTH-IESL Crete and then he joined Czech Office for Standards as a secretary at IEC, CEN and CENELEC. In 2011 he joined Institute of Physics CAS, where he participated at HiLASE project. At the present, he is in charge of LIDT group at HiLASE Centre, Czech Republic

ABSTRACT TEXT: Research and development of innovative materials and components, in particular optical coatings, is a key in achieving powerful, versatile and reliable laser systems. Yttrium Aluminum Garnet (YAG) crystals as a hosts doped by a proper elements are active media often used in solid-state lasers. Such components are under substantial pressure regarding energy handling capabilities, which is, in a case of optical elements, mostly represented by LIDT measured value. Indeed, optical components rarely serve in laser systems as bulk materials; common practice is to use various thin-film coatings on the surface in order to improve optical properties. It is obvious that accurate determination of LIDT of mentioned thin films is crucial for application of coated crystals in laser systems.

In our work, we used LIDT testing station developed at HiLASE Centre in accordance with ISO 21254 recommendations to test several variants of anti-reflective (AR) coatings prepared by reactive or ion-assisted e-beam deposition on Czochralski-grown YAG crystals. As source for tests was used diode-pumped solid state laser (DPSSL) “Bivoj” located at HiLASE Centre. This laser provides 10 ns pulses with repetition rate 10 Hz at wavelength 1030 nm and energy up to 5 J, delivered in square flat-top single-longitudinal mode beam to the experimental chamber. During the test, samples were continually observed by two online damage detection systems based on scattered light and online microscopy. Tested samples surface were both before and after the test inspected at laser scanning microscope. In following paper, we will describe process of LIDT testing of various coated YAG samples in order to compare their performance at pumping wavelength 1030 nm. Further, respective damage probability curves and LIDT craters morphology will be presented and discussed.

KEYWORDS: LIDT; YAG; thin film

10805-11, SESSION 3

Investigation into Yb:YAG gain medium manufacturing and processing techniques for high-energy, high-average-power laser systems

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ABSTRACT TEXT: Ytterbium-doped yttrium aluminium garnet (Yb:YAG) is one of the most widely used gain materials for high-energy, high average power diode-pumped lasers thanks to its superior thermo-mechanical and thermo-optical properties. The DiPOLE concept, developed at the STFC Rutherford Appleton Laboratory (UK), is based on cryogenically-cooled, multi-slab Yb:YAG amplifier technology and it has been successfully applied to the demonstration of nanosecond pulse amplifications to pulse energies above 100 J at a repetition rate of 10 Hz [1, 2]. Laser operation at higher output pulse energy require the development of Yb:YAG gain material slabs characterised by apertures well in the excess of 10 cm and by high resilience to high fluence laser irradiation to avoid laser-induced damage onset.

Currently, production of large-sized, high optical quality Yb:YAG is challenging both in terms of costs and of manufacturing process, thus imposing a limit to the size of the slabs. In this paper, we demonstrate that the adhesive-free bonding technique (AFB), developed by Onyx Optics, Inc. (USA), is a viable solution for producing large aperture gain medium slabs characterised by high mechanical strength and laser-induced damage threshold (LIDT) [3].

Additionally, we present the application of the gas cluster ion beam (GCIB) and of the accelerated neutral atom beam (ANAB) surface treatments, performed by Exogenesis Corporation (USA), to Yb:YAG [4]. We demonstrate that GCIB and ANAB allow accurate control of Yb:YAG surface characteristics and constitute an alternative to conventional surface finishing techniques. We show that the GCIB and the ANAB techniques allow meeting the requirements on resilience to laser irradiation at fluence levels characterising high-energy laser systems. Moreover, we show that surface nano-texturing improves the LIDT of coated samples, possibly through an improvement in the adherence of coatings to ceramic Yb:YAG substrates.

KEYWORDS: of Yb:YAG laser slabs ; laser-induced damage; adhesive-free bonding technique ; gas cluster ion beam ; accelerated neutral atom beam techniques ; fluence levels characterising high-energy, high average power laser systems

REFERENCES

[1] P. D. Mason, et al., “Scalable design for a high energy cryogenic gas cooled diode pumped laser amplifier,” Appl. Opt. 54(13), 4227–4238 (2015).

[2] P. D. Mason, et al., “Kilowatt average power 100 J-level diode pumped solid state laser,” Optica 4(4), 438-439 (2017).

[3] M. De Vido, et al., “Characterisation of adhesive-free bonded crystalline Yb:YAG for high energy laser applications,” Optical Materials Express 7(2), 425-432 (2017).

[4] M. De Vido, et al., “Impact of gas cluster ion and accelerated neutral atom beam surface treatments on the laser-induced damage threshold of ceramic Yb:YAG,” Optical Materials Express 7(9), 3303-3311 (2017).

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10805-12, SESSION 3

Laser-induced damage and defect analysis of calcium fluoride window caused by high pulse repetition rate ArF excimer laser radiation

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ABSTRACT TEXT: In the semiconductor industry, optical projection lithography is employed for the production of microchips. In this process ultraviolet radiation has been used to exposure of photoresists on silicon wafers. Light sources with shorter wavelength are needed to shrink the chip size due to the diffraction limit. Pulsed excimer lasers have been used since the middle of 1990s instead of mercury lamps. At first KrF lasers (248-nm) were adopted, then ArF lasers (193-nm) have been applied to satisfy tighter leading edge device requirements. Now almost 5,000 excimer lasers for lithography tools are being operated at the world-wide semiconductor fab with stable, its availability up to 99.8%. The latest ArF excimer laser can pulse 15mJ to 20mJ energy with 6-kHz repetition rate, its typical module lifetime which can be replaced is several dozen Billion pulses. The module lifetime are expected to expand to reduce the downtime to replace. In excimer laser system, the chamber filled with excimer gas (either krypton, fluorine and neon for KrF laser or argon, fluorine and neon for ArF) is applied to oscillate and amplify excimer light by discharge excitation. The calcium fluoride windows usually used to pass the light through the chamber are the one of the critical degradation parts even high grade crystals are adopted. To achieve longer lifetime of the chamber including windows, the detailed degradation mechanism of window especially its onset should be realized.

In this paper, the analysis of degraded calcium fluorides window used as laser chamber window of ArF excimer laser (193-nm wavelength, 30-ns pulse width, 10-mJ output energy, ~80-mJ/cm^2, 6-kHz and several dozen Billion pulses) will be reported. The results of analysis such as TEM-EDX, Raman spectroscopy, or slice & view measurements with SEM etc. will be shown. Also environmental condition dependence such as temperature of purge gas for window against laser-induced damage might be reported. Based on these results, the mechanism of the degradation of calcium fluoride would be assumed and the way to improve the durability against laser radiation would be discussed.

KEYWORDS: calcium fluoride; ArF excimer laser

10805-13, SESSION 4

Why most attempts to predict fatigue-induced laser damage fail?

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SPEAKER BIOGRAPHY: Dr. Andrius Melninkaitis is an associate professor at laser Research Center of Vilnius University. His main research interest cover areas of laser-induced damage metrology, time resolved holographic imaging, laser damage statistics, laser-matter physics. He is also co-founder and CEO of Lidaris company.

ABSTRACT TEXT: To quantify a multi-shot "fatigue effect" on the optical elements so-called S-on-1 test is often performed via standardized metrology process. As a result, characteristic damage curve is obtained. Such curve indicates the trend of laser-induced damage threshold (LIDT) with respect to (S) incident laser pulses. Exceeding the fluence of LIDT for given S has a meaning of non-zero chance that material will be irreversibly damaged. There were many attempts in the past to find a universal fitting function that could describe the trend of aging represented by characteristic damage curve. Ideally, the well-fitted data would allow the generalization of LIDT as well as extrapolation of the fit towards a higher number of laser pulses. If such approach could be validated it would also serve as a predictor of future. That is of course of great interest in many practical applications. In reality, however, it is already clear: there is no single function that could uniformly well fit all the experimental data and have a power of predictability at the same time. Thus, blind extrapolation of S-on-1 data with non-validated models is not able to satisfy practical needs of most laser system engineers. In this study, an attempt is made to find and exemplify potential blockers of good predictability. Firstly, we conducted an experimental investigation of fatigue effect in a set of most popular single-layer materials deposited by IBS process with repetitive femtosecond pulses. Then we performed fitting of data with known aging models from pertinent literature. Finally, we identified several potential thinking mistakes in that can lead to poor extrapolation accuracy and propose a re-framing of the problem.

KEYWORDS: fatigue effect; failure modes; S-on-1 test; characteristic damage curve

10805-14, SESSION 4

Experimental measurement of material fatigue properties of x-ray optics by using laser pulses

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SPEAKER BIOGRAPHY: Xianchao Cheng is an analysis mechanical engineer at the LCLS of SLAC National Accelerator Laboratory. He worked at the European Synchrotron as PhD student from Nov. 2011 to Oct. 2014. He received his PhD in Oct. 2014.

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

With the LCLS-II high-repetition-rate FEL, the number of pulses on the optics over ten years can reach 20 trillion. The thermal fatigue, damage and lifetime of the optics are important issues that should be addressed. Material fatigue properties of x-ray optics are essentially important for their lift-time prediction, optics optimization and opto-mechanical design. In this work, the fatigue properties of typical x-ray optics materials such as single-crystal silicon are experimentally measured by using laser pulses. The laser source can have an average power of 50 W at wavelength of 1.03 µm and repetition rate of 1 MHz

with pulse duration of ~300 fs. The SHG crytal is used to generate 514 nm laser beam for the test to get an equivilent absorption length to soft X-rays. The maximum single-pulse energy is more than 20 μJ. The numbers of pulses that the optics can survive are measured for different pulse energies.

Previous studies indicate that the material damage threshold depends on many parameters, including the material type, photon beam energy and intensity, angle of grazing incidence, the number of pulses, and the beam pulse duration. There are significant publications on ablation threshold with a limited number of photon beam pulses. However, for the X-ray optics, the definition of the damage should be the significant (for instance, 50%) reduction of reflectivity, which is premonitory of damage, and much more stringent than the ablation threshold.

We also propose combining theoretical modeling, experimental tests with laser beams and the FEL beam properties to develop a thermal fatigue model to predict the lifetime of X-ray optics and beam transport components. The outcome of this project will be a fatigue damage model predicting the lifetime of the key components used for high-repetition-rate X-ray FELs and also sample material under large number of laser pulses. This will be a major tool useful for SLAC, LCLS but also for the whole FEL community and potentially to semiconductor industry.

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

10805-15, SESSION 4

Laser-Induced damage thresholds of nematic liquid crystals at 1 ns and multiple wavelengths

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SPEAKER BIOGRAPHY: Dr. Tanya Kosc is a scientist in the Optical Materials Technology group at the Laboratory for Laser Energetics at the University of Rochester.

ABSTRACT TEXT: We report on the laser-induced–damage thresholds (LIDT's) of six nematic liquid crystal (LC) materials measured at 1053 nm, 527 nm, and 351 nm using a 1-ns laser pulse. These experiments explore the effect of varying degrees of -electron delocalization and electron density in saturated and unsaturated LC compounds at different wavelengths. Bulk measurements were performed using LC materials in the nematic phase with no long-range preferred molecular alignment direction. Damage detection relied on comparing pre-shot and post-shot images of the test site. A test site was considered damaged either upon the formation of gas bubbles or the detection of a permanent change in the site appearance.

The LIDT for saturated compounds was typically ~50% higher than for unsaturated materials in the near infrared. For green and blue wavelengths, there was an order of magnitude difference between the two materials classes.

The above results, in conjunction with previous measurements on the same materials focused on exploring the LIDT as a function on pulse length at 1053-nm light (using pulses between 600 fs and 1 ns), provide the underpinning for the development of a better understanding of the governing damage-initiation mechanisms.

Preliminary analysis suggests that the energy separation between the ground state and both the first excited state and the upper electronic states involved in excited state absorption have a major impact on the damage performance of each material as a function of pulse length

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and wavelength. Future work will include investigation of damage thresholds of aligned LC devices and detailed characterization of the performance of such devices under simulated operational conditions.

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KEYWORDS: liquid crystal; nematic; laser induced damage; 1-ns-pulse damage

10805-16, SESSION 4

Automated repair of laser damage on National Ignition Facility optics using machine learning

Scott Trummer, Glenn R. Larkin, Laura Mascio-Kegelmeyer, Mike C. Nostrand, Constantine Karkazis, David Martin, Raymond E. Aboud, Tayyab Suratwala, Lawrence Livermore National Lab. (USA)

SPEAKER BIOGRAPHY: Scott Trummer graduated with a B.S. in Applied Physics in 2014 from the University of California, Davis. He was hired as an operator in the Optics Mitigation Facility and currently works as a software engineer for the Optics and Materials Science & Technology group.

ABSTRACT TEXT: The National Ignition Facility (NIF) routinely operates at fluences above the onset of laser-induced optics damage. To do so, it is necessary to routinely recycle the NIF final optics, which involves removing an optic from a beamline, inspecting and repairing the laser-induced damage sites, and re-installing the optic. The inspection and repair takes place in our Optics Mitigation Facility (OMF), consisting of four identical processing stations for performing the repair protocols. Until recently, OMF has been a labor-intensive facility, requiring 10 skilled operators over two shifts to meet the throughput requirements. Here we report on the implementation of an automated control system—informed by machine learning—that significantly improves the throughput for recycling of NIF optics while reducing staffing requirements. Performance metrics for early 2018 show that while the staff has been reduced to four operators over two shifts, the number of repairs successfully applied meets or exceeds previous throughput records.

Computer keystrokes have been reduced from about 6000 per optic to under 300. This work was performed under the auspices of the U.S. Department of Energy by Lawrence

Livermore National Laboratory under Contract DE-AC52-07NA27344.

KEYWORDS: Machine Learning; Automation; Damage Repair; Laser Damage; Deep Learning

10805-17, SESSION 4

Multimode silica-based fiber-optic delivery system for pulsed Nd-YAG lasers in UV region

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ABSTRACT TEXT: Reductions of UV transmission in multimode silica-based fibers due to optically active UV defects have been extensively studied using low power broadband UV light sources or excimer lasers. In parallel, pulsed, frequency-multiplied Nd-YAG lasers at 355 and 266 nm were also used as UV light sources in the past.

In particular, laser damaging and spectral tests were carried out in two independent measuring arrangements. In addition to annealing processes in the fiber, the reproducibility of the same position due to the repeated use of the two arrangements can lead to measurement errors and misinterpretation, especially for the short-term behavior in generating and annealing of defects. Therefore, a combined set-up has been proposed and realized, with the main aim that the laser-induced damage can be measured in regard to wavelength from 190 up to 1000 nm without movement of the test fiber or fiber bundle. In addition, the damaging UV lasers should be easily changed and aligned.

The standard high-OH multi-mode UV fibers used in many UV applications for decades have been studied, mainly. However, few-mode fibers or low-OH fibers are interesting candidates for testing. On the other hand, pulsed Nd-YAG lasers in the UV-region has been used: from one company, compact lasers with the very interesting wavelengths 213, 266 and 355 nm were commercially available. The behavior at the three wavelengths are quite different. At 355 nm, the low attenuation level of these fibers lead to a nearly constant intensity within 10 m of fibers. Although the linear basic attenuation is dominant, the almost constant two-photon absorption along the fiber is responsible for a homogeneous distribution of UV defects. Within <2 days no UV-induced losses were observed at the laser wavelength. Using 266 and 213 nm lasers, the NBOHC and E'-centers can be generated by one photon, only: therefore, because of the attenuation of 0.3 dB/m or 0.6 dB/m, respectively, is higher, the intensity is reduced exponentially. However, at high power levels, two-photon-absorption can even increase the decay. In addition, photon energies bigger than the bandgap of silica are available. Therefore, the UV-defect concentration along the fiber is significantly higher than the well-known values during D2-lamp irradiation. First results at these wavelengths with currently available fibers will be shown and discussed.

KEYWORDS: Silica-based UV fibers; Step-index fibers; UV defects; Measurement set-up; Nd-YAG lasers and harmonics; Pulsed UV lasers

10805-18, SESSION 5

Early Laser Damage Research at State Optical Institute in Leningrad

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ABSTRACT TEXT: State Optical Institute (SOI) named after S.I. Vavilov was the major Federal research institute in the USSR responsible for research and development of optical materials, optical components and optical systems for wide range of applications. Creation of first high power pulsed lasers in ruby and Nd doped glasses in middle sixties resulted in damage of optical components used in those lasers. Therefore complex researches were triggered at SOI in several directions. The main attention was paid the role of different defects on damage of different materials. The leading research group in both theory and experiment was headed by Dr. Alexey Bonch-Bruevich while development of technology of materials with high resistance to laser radiation was managed by Dr. Gury Petrovskii. This presentation will provide a survey of results in theory and experimental study of mechanisms of laser induced damage.

10805-19, SESSION 5

Highlights from the 2nd and 3rd Decades of the Laser Damage Symposia

Brian E. Newnam, Los Alamos National Lab. (USA)

SPEAKER BIOGRAPHY: Dr. Newnam received his PhD in Electrical Engineering from the University of Southern California in November, 1972. His dissertation was entitled, “Laser-Induced Damage Phenomena in Dielectric Films, Solids,and Inorganic Liquids.” From 1972 to 2002, Dr. Newnam was employed as a technical staff member of Los Alamos National Laboratory. He contributed to the major LANL programs of laser fusion, laser isotope separation, free-electron lasers, accelerator-driven transmutation of nuclear waste, and high-temperature superconductors. From 2002 to 2012: Guest scientist, Los Alamos National Laboratory. From 2005 to 2015: Editor of the Journal of the Violin Society of America. From 1998 - present: Violinist and violist in the San Juan Symphony Orchestra

ABSTRACT TEXT: Having begun in 1969, the “Boulder” Laser Damage Symposium has reached its present 50th anniversary meeting due to continued keen interest of members of the laser and materials research communities. In this presentation, we take a look back at the symposia held during the years 1980 to 1995 to recall the topics that were of prominent interest and reported at those meetings.

KEYWORDS: Boulder; Laser; Damage; Symposium; Materials and measurements; Thin Films; Fundamental mechanisms; Surfaces, mirrors, and contamination

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ABSTRACTS

10805-20, SESSION 5

Trends Observed in Ten Years of the BDS Thin Film Laser Damage Competition

Christopher J. Stolz, Raluca A. Negres, Lawrence Livermore National Lab. (USA)

SPEAKER BIOGRAPHY: Christopher Stolz has been in the laser program at Lawrence Livermore National Laboratory (LLNL) since 1989 researching high-power laser coatings. He is currently responsible for the Optics Production group for the National Ignition Facility (NIF). Chris has served as a cochair or program chair for numerous conferences including Laser-Induced Damage in Optical Materials and Optical Interference Coatings. He has coauthored over 100 journal and proceeding articles and 2 book chapters.

ABSTRACT TEXT: The thin film damage competition series at the Boulder Damage Symposium provides an opportunity to observe general trends in laser damage behavior between different coating types (high reflector, anti-reflector, Polarizer, and Fabry-Perot filter), wavelength ranges (193 – 1064 nm), and pulse length ranges (40 fs – 18 ns). Additionally, the impact of deposition process, coating material, cleaning process, and layer count can be studied within a single year or more broadly across the history of this competition. Although there are instances where participants attempted to isolate a single variable to better understand it's impact on laser resistance, this series of competitions isolates the variable of the damage testing service and protocol for a wide variety of participants. In total 275 samples from 58 different participants have been tested at four different laser damage testing facilities over the last ten years. Hafnia was clearly the best high refractive index material except for UV applications; although a wide range of high refractive index materials performed well. The best deposition process varied significantly between the different competitions, so it was much more strongly dependent on the coating type, wavelength, and pulse duration. For 1064 nm coatings with nanosecond scale pulse lengths, e-beam coatings tended to be the best performers. For short pulse length NIR mirrors and nanosecond pulse length UV mirrors, densified coating processes which all involved sputtering of the target material were the best performers. For UV AR coatings and excimer mirrors, both tested at nanosecond pulse lengths, they tended to favor very low energetic deposition methods yielding soft coatings such as sol gel dip coating for the AR and resistive heating of fluorides for the excimer mirrors. Finally cleaning method and layer count have had a less obvious correlation with laser resistance over the history of this thin film damage competition.

KEYWORDS: laser damage testing; mirror; antireflector; Fabry-Perot filter; thin film; nanosecond laser; femtosecond laser

10805-21, SESSION 5

The History and Presence of High-resolution Laser Spectroscopy and its Applications

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No Abstract Available

10805-72, SESSION PS3

The structure of retired components and irradiated KDP crystals with different fluences

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ABSTRACT TEXT: The electronic structure of phosphorus is essential to the understanding of the laser-induced damage of potassium dihydrogen phosphate (KDP) crystals. The surface electronic structure of retired components and KDP crystals irradiated with different fluences are studied by X-ray absorption near-edge structure. Results indicate that the A/C ratios (the peaks A and C corresponding to the electron transition from 2p→3s and 2p→3p, respectively) in the L2,3-edge spectra are up to 0.9 for the retired samples, and the damage is inhomogeneous on the surface. Furthermore, the electronic structure of phosphorus is associated with laser induced damage.

10805-73, SESSION PS3

Free-carrier heating in wide-band-gap crystals: high-collision-rate Drude model versus low-collision-rate approximation

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A SPEAKER BIOGRAPHY: Vitaly Gruzdev received Ph. D. from the Federal Research Center "S. I. Vavilov State Optical Institute" in St. Petersburg, Russia in November 2000. He works in the field of laser-induced damage of transparent materials since 1993. His major fields of research are theoretical studies of laser-induced electron excitation in non-metal crystals, nonlinear absorption, and ultrafast strong-field laser effects in solids. Since 2005 he is employed by the Department of Mechanical and Aerospace Engineering, University of Missouir, Columbia, MO, USA. Currently, he is a co-chair of SPIE Laser Damage Symposium and an Associate Editor of Optical Engineering.

BSTRACT TEXT: Interaction of ultrashort high-intensity laser pulses with laser-generated free carriers is one of the fundamental processes of energy deposition and transfer during laser-solid interactions. The interaction usually considers single-photon absorption via electron-photon-phonon collisions, heating the laser-generated conduction electrons, linear (with respect to irradiance) optical response of the free carriers, and impact ionization (free-carrier relaxation and trapping are usually neglected for laser pulses shorter than 100fs). The

traditional approaches to simulate those processes include numerical solving some kinetic equations, e. g., Boltzmann equation with proper coefficient. However, the most popular approach to simulate the laser interactions with the free carriers is to numerically solve a rate or multiple-rate equation coupled with the Drude model. The latter model describes heating of the free carriers and their optical response in the way similar to the electronic response of metals, i. e., it is assumed that absorption of single photons is a dominating pathway of energy absorption by the carriers. Attempts to fit experimental data, e. g., scaling of damage threshold, based on the Drude model result in extremely low electron-phonon collision time (about 1 femtosecond and even smaller). That value of electron-phonon collision time is smaller than duration of single optical cycle and violates the approximations underlying the Keldysh formula that is frequently incorporated into the same rate equation(s) together with the Drude model. Also, the low collision time delivered by the fitting with the Drude model is unreasonably smaller than electron-phonon collision time in metals.

To fix that fundamental gap, we explore the low-collision-rate approximation of the Vinogradov equation that evaluates the electron-phonon collision rate (and collision time) from matrix element of electron interaction with polar phonons rather than extracts it from fitting. The conduction-electron states are perturbed by laser action so that the colliding electrons perform laser-driven oscillations in energy-momentum space. Therefore, in contrary to the high-collision-rate Drude model, the Vinogradov approach incorporates ponderomotive energy of the oscillations that scales as squared laser wavelength. The ponderomotive energy can be retained by the oscillating electrons due to electron-field dephasing because of the rare electron-phonon collisions. This assumption opens an extra channel for energy absorption, i. e., absorption of single photons competes with absorption of the oscillation ponderomotive energy. Performing numerical simulations with the Drude and Vinogradov models, we demonstrate that the Drude model predicts very substantial heating of the conduction electrons and produces quasi-equilibrium energy distribution in the conduction band. In contrary, the Vinogradov model predicts lower (approximately by 1-2 orders of magnitude) electron energy and highly non-equilibrium energy distribution. While the two models make similar predictions at shorter wavelengths of visible light, the difference between them substantially increases with increase of laser wavelength towards infreared and mid-infrared parts of the optical spectrum. Obtained results are discussed from the view point of their influence on understanding the fundamental mechanisms of ultrafast laser-pulse absorption and energy transfer during the ultrafast high-intensity laser-solid interactions.

KEYWORDS: laser damage; wide-band-gap solids; nonlinear absorption; Drude model; Vinogradov equation

10805-74, SESSION PS4

Laser damage size analysis (DSA) for efficient lifetime damage threshold measurements

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SPEAKER BIOGRAPHY: Selim Elhadj is the group leader for the Advanced Coatings and Vacuum Process Lab within the Materials Engineering Division (MED) at Lawrence Livermore National Laboratory (LLNL), CA, USA. A chemical engineer by training, Elhadj is matrixed to the National Ignition Facility (NIF) and Photon Science as part of the Optics Materials Science and Technology group. His research centers on programmatic R&D to explore advanced manufacturing

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methods and optics assembly for optoelectronic devices, with a focus on laser–material interactions under reactive gas environments and the development of materials (including semiconductors, optical coatings, and processing methods) for high-power laser applications, or power electronics. Elhadj is also visible daily within and without the gates as an avid cyclist with the Lab's noontime riders, the Cycletrons.

ABSTRACT TEXT: A laser damage test method based on damage size analysis (DSA) is described that simplifies the derivation of the lifetime optical damage threshold of film materials critical in the design of devices used in high-repetition-rate, high-power laser systems. The DSA method presented here is solely based on imaging to measure the damage site size produced from exposure to a known Gaussian-shaped beam with a fixed, systematically selected fluence well above the ablation threshold. The method locates the damage boundary produced from repeated exposures, using images with a high contrast, and maps it to the beam profile to extract a lifetime laser damage fluence threshold value. We validate the DSA approach using a few relevant transparent film material systems and by comparing it to the standard S-1 laser damage test method. The DSA method can be more efficient and accelerate materials development and validation necessary to support the design of high-power repetition-rated lasers and optoelectronic devices.

KEYWORDS: Damage size; lifetime; threshold; film; laser; high power; rapid; efficient

10805-75, SESSION PS4

The nonlinear refractive index of thin films and substrates at various wavelengths and pulse durations

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ABSTRACT TEXT: With the overall trend to higher laser powers, the demands on optical components rise accordingly. A factor of major importance in this context is the consideration of third order nonlinear effects in dielectric optics. On one hand, the suppression of nonlinear processes is necessary to avoid power dependencies in the functionality of high end optics under high intensities. On the other hand, creative applications of these effects would allow new types of optical components, for example power controlled optical switching devices or frequency converting mirrors. To achieve this, a detailed knowledge of the nonlinear parameters of the applied thin film materials is essential. For the substrate materials those values are typically already documented to some extent, but especially for the coating materials, these constants are not generally known. This challenge even increases in complexity, when not only pure dielectric oxides, but also mixtures of those oxides are used in high end optics because of their more flexible properties. In this contribution, an improved interferometric setup for the determination of the nonlinear refractive index of dielectric single layers and substrate materials is presented. The setup utilizes the wave front deformations caused by Kerr-self-focusing in the material to measure the nonlinear refractive index. Improvements in the setup allow for measurements at different wavelengths and pulse durations. Nonlinear refractive indices for various optical substrates and layer materials are presented for different wavelengths as well as pulse durations, and the results are discussed.

KEYWORDS: Kerr-effect; Nonlinear optics; Material properties; Nonlinear refractive index

10805-76, SESSION PS4

Time-resolved analysis of resist removal phenomenon without causing laser damage

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ABSTRACT TEXT: In semiconductor manufacturing, the process of the conventional resist removal needs many environmentally unfriendly chemicals and consumes a great amount of ultra-pure water. Resist removal using laser irradiation is expected to be one of the new removal technologies. Laser damage occurs to the Si wafer surface when a laser beam is irradiated to the resist in the normal atmosphere. Laser irradiation in the water can improve the resist removal effect. However, the mechanism of the removal efficiency improvement is not known regarding laser irradiation in the water.

In this study, resist removal phenomenon with laser irradiation was observed by using a time-resolved analysis. A Si wafer without resist was irradiated with a pump laser beam to easily confirm the intensity change of the probe laser. Within 0.2 s from the pump laser irradiation, the intensity of the probe laser suddenly decreased due to the laser damage on the Si wafer surface. Then, the time change of resist removal phenomenon was also observed from the viewpoint of the intensity change of the probe laser. As for laser irradiation in the water, the probe laser intensity arrived at the maximum after about 40 s. And, during the pump laser irradiation of 8 ns, a large compressive stress of -10 MPa was confirmed inside the resist from the FE analysis results. The generation of this compression stress is important for starting the resist stripping process, and is thought to improve the resist removal efficiency.

KEYWORDS: resist stripping; laser damage; time-resolved analysis; FE method; compressive stress

10805-77, SESSION PS4

Accelerated testing of high fluence protective coated optics

Saptaparna Das, John Melchior, Eric Mason, Cymer LLC (USA)

SPEAKER BIOGRAPHY: Saptaparna Das grew up in India, receiving her MSc. from Indian Institute of Technology Kanpur in 2009 and her Ph.D. from the University of Southern California in 2015. After a year as a postdoctoral researcher at the University of Pennsylvania, she is currently working as a Sr. Optical Engineer at Cymer DUV Optics. Her research involve designing experiments to analysis and increase the optics lifetime for 193 nm light sources. In addition she is also involved in developing optical assemblies for 193 nm light sources.

ABSTRACT TEXT: Excimer lasers are the commonly used light sources for photo-lithography industries; one challenge is to minimize the production interruption by providing a reliable source of DUV (193 nm) photons. This requires CaF2 optics with high transmission and optical uniformity at 193 nm over a long lifetime. However, CaF_2 crystal can possess defects due to mis-orientation and dislocations in the sub-grain boundaries, which can act as an absorption or scattering center leading to transmission loss and thermal stress induced birefringence in the CaF2 crystal. In addition, the CaF_2 surface can suffer from different mechanical stress due to cleaning and finishing processes leading to formation of surface imperfections/fractures known as sub-surface damage. This sub-surface damage layer is prone to damage under high fluence 193 nm exposure and can lead to fluorine escape from the CaF_2 lattice. Protective coatings for CaF_2 optics have been developed to prevent surface fluorine depletion from 193 nm exposure. However, these protective coatings can also develop defects due to imperfections in the coating fabrication process and/or photochemical reaction initiated by 193 nm photons in presence of traces of oxygen, water vapor or carbon dioxide. Therefore to provide uninterrupted 193 nm photons a robust protective coating is required to extend the lifetime of CaF2 optics. Generally, field learnings for high fluence protective coating can require from 6 months to a year of normal operation and thus validation of protective coatings based on field data alone can hinder the adoption of improved technology. To expedite this selection process, an accelerated 193 nm exposure setup was built to test high fluence protective coatings from different suppliers at various elevated fluences for a short period of time (~2-3 weeks). This setup was successful in screening the best high fluence protective coating under highly accelerated 193 nm exposure. Additionally, based on the relative performance of the protective coatings under accelerated conditions and used-case in-chamber fluence conditions, the lifetime for the high fluence protective coatings were estimated for the used-case scenario.

KEYWORDS: excimer; lifetime; DUV; ArF; fluence; transmission

10805-78, SESSION PS4

Photothermal absorption characterization of fused silica laser-induced damage dependence on laser fluence, the number of shots and pulse repetition frequencies

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The laser induced-damage of fused silica under different damage laser parameters is studied by the photothermal spectroscopy technique. The comparison of the damage site size and morphology before and after laser irradiation was devoted in our case. And the correlations existing between the photothermal absorption signals and laser induced damage mechanism are analyzed. Results indicate that the material undergoes two distinct stages of melting and breaking. Compared to optical microscope method, the area and morphology of damage sites can be more precise described by photothermal spectroscopy before the melting stage. Furthermore, the results can provide technique support for repairing materials.

KEYWORDS: fused silica; laser induced damage

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10805-79, SESSION PS4

Absorption investigations in optical fibers

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ABSTRACT TEXT: We present the results of direct absorption measurements in optical fibers for high power fiber lasers by means of a modified laser induced deflection (LID) setup. Two main applications have been addressed, the locally induced absorption by fiber Bragg grating inscription as well as the induced absorption in the fiber core by long term laser usage (photodarkening). A particular focus has been set on the absolute calibration of a local absorption along the fiber. All measurements were carried out at one of the most prominent high power laser wavelengths of 1070nm.

KEYWORDS: Absorption; Photo-thermal technique; High-power fiber laser; Bragg grating; Instrumentation, measurements, and metrology

10805-80, SESSION PS4

Laser durability evaluations of silica glass at 1064 and 213 nm

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ABSTRACT TEXT: Nd:YAG lasers are easy to operate and used in material processing applications. Because they are high-power lasers, optical materials with high laser durability are required. One of the commonly used materials for high-power lasers is silica glass. The silica glass has not only the high laser durability but also the high transmittance from the UV region to the IR region.

We have studied the laser durability of silica glass samples by Laser-induced BULK damage threshold (LIDT) evaluation. LIDT is one of the key indexes for laser durability, because the surface of silica glass is typically damaged more easily than the inside in general. We reported LIDT of silica glass at 355 nm and 266 nm [1] and presented that the durability of silica glass depended on hydrogen and hydroxyl concentration. However, we have not figured out the durability in infrared (IR) region, the effect of other elements and so on. Therefore, in this study, we measured 1-on-1 and 10000-on-1 LIDT of a variety silica glass samples at 1064 nm and 213 nm. We obtained following results. First, at 1-on-1 LIDT measurements, the LIDTs of samples were almost the same at each wavelength. On the other hand, the LIDT results were different depending on the sample at 213 nm as well as at 355 nm and 266 nm. The more hydroxyl concentration silica glass had, the lower laser durability silica glass had. However the difference of LIDT results at 1064 nm was also small at 10000-on-1 LIDT. Second, the silica glass which includes chlorine had lower durability even if its hydroxyl concentration was very low. Finally, hydrogen concentration dependency of the durability was varied by the hydroxyl content. If the content of hydroxyl was $\leq$10 ppm, LIDT became lower as hydrogen concentration increased. On the other hand, if it was equal to 30 ppm, LIDT became higher as hydrogen concentration increased.

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

REFERENCES

[1] Kashiwagi, R., "Laser-induced bulk damage of silica glass at 355 nm and 266 nm," Proc. SPIE10014, 100141J (2016)

10805-81, SESSION PS4

Laser-induced damage in optical glasses using nanosecond pulses at 1030nm

Mihai Muresan, Pavel Cech, Vojtech Bilek, HiLASE Ctr. (Czech Republic); **Petra Horodyska,** Institute of Plasma Physics of the CAS, v.v.i. (Czech Republic); **Danijela Rostohar, Antonio Lucianetti, Tomáš Mocek,** HiLASE Ctr. (Czech Republic)

SPEAKER BIOGRAPHY: Mihai Muresan received in 2015 his PhD degree in Plasma Physics at the Masaryk University in Brno, working on deposition and characterization of thin films. Since 2013 he started working at the Institute of Physics AVCR, within the HiLASE project. Currently he is focused on laser-induced damage testing.

ABSTRACT TEXT: The "Bivoj" 10 J, 10 ns, 10 Hz, Yb:YAG (1030 nm) diode-pumped solid state laser (DPSSL) at the HiLASE Centre was used to investigate the laser-induced damage of optical glasses with different refractive index (BK7, SF8, FS, LIBA2000). The samples were polished using a combination of methods and cleaned in ultrasonic bath or with ion beams. Sample surface was characterized using white-light interferometry (WLI) and laser confocal microscopy (LCM). For the laser-induced damage threshold (LIDT), an S-on-1 procedure was selected, the testing taking place in accordance with the ISO 21254 standard. Due to the high energy per pulse of the "Bivoj" system we were capable of using beams with more than 500 µm diameter (using a long focusing mirror) and thus, including different surface defect in the LIDT measurement. The damage of the glasses was usually observed on the rear side (ballistic damage), however we manage to see on few samples front damage also. Values above 50 J/ cm^2 were common for all tested samples.

KEYWORDS: LIDT; glasses; High Energy Lasers; high refracting index glass; amorphous materials

10805-82, SESSION PS4

Application of image processing and machine learning for classification of laser-induced damage morphology

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SPEAKER BIOGRAPHY: Linas Smalakys is a PhD student at Vilnius University. His research interests include fundamental mechanisms of laser-induced damage as well as laser-induced damage statistics

ABSTRACT TEXT: The standardized and most commonly used procedure to determine the laser-induced damage threshold (LIDT) is the so-called S-on-1 test [1]. It uses a few hundred to a few thousand test sites on the interrogated optical component to determine its LIDT. Recently we have noticed an increased interest from the community not only in the LIDT value, but in the qualitative analysis of the damaged test sites itself. Such analysis provides valuable information about underlying damage mechanisms and can be used for separation of different damage modes. However, such analysis can be extremely time consuming, since a large number of test sites needs to be visually inspected and classified.

In this work, we present a novel approach to the analysis of damaged test sites based on computational techniques which have become extremely approachable in recent years. Image processing algorithms were applied to digital images of test sites in order to identify damaged test sites and extract features of damage morphology. Further machine learning analysis was performed to automatically classify damaged test sites into clusters of unique damage modes based on these features. We have shown that a large number of test sites can be classified in a relatively short period of time, thus allowing for morphological analysis at a scale which previously seemed infeasible. We have also demonstrated the application of our technique to a few real world cases.

KEYWORDS: damage morphology; image processing; classification; damage mode

REFERENCES:

[1] ISO 21254-2:2011 Lasers and laser-related equipment – Test methods for laser-induced damage threshold – Part 2: Threshold determination, Standard, International Organization for Standardization, Geneva, Switzerland (2011).

10805-83, SESSION PS4

Determination of the laser-induced damage threshold of polymer optical fibers

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ABSTRACT TEXT: Polymer optical fibers are characterized by a low own weight, vibration-insensitivity, flexibility and low stiffness. Therefore, they have advantages compared to glass fibers and are able to replace them in many areas of application i.e. in medicine, automobile industry and aviation. However, the applicability of polymer optical fibers is limited by lower optical radiation resistivity. For these reasons the investigation of the optical losses and laser-induced damage threshold is essential. This work is related to the measurement of the laser-induced damage in polymer optical fibers. The radiation source is a Nd:YAG laser with a wavelength of 532nm and a pulse duration in the nanosecond domain. A specially adapted measurement setup is used to control and detect all vital parameters. Different test protocols are applied to study material properties, like conditioning effects and the defect distribution in dependence on the manufacturing parameters. For this purpose, the laser beam diameter at the interface is varied, and different coupling approaches are investigated. The experiments are repeated numerously to become widely independent of the interface polishing. The transmission of the fiber is continuously measured with an integrating sphere whereby a decrease of the signal and scattered light detected by a CCD-Camera indicates a laser-induced damage. Afterwards the polymer optical fiber is checked with a differential interference contrast microscope to verify the damage. Finally, the obtained results give information about the long-term-behavior and will be used for the optimization of polymer optical fibers.

KEYWORDS: polymer; optical fiber; laser damage; pulsed laser

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10805-84, SESSION PS4

Investigation and characterization of optical signatures in multilayer dielectric gratings to improve cleanliness

Brittany N. Hoffman, Semyon Papernov, Stavros G. Demos, Univ. of Rochester (USA)

ABSTRACT TEXT: Multilayer dielectric (MLD) gratings exposed to different cleaning processes were characterized using luminescence and optical-absorption techniques. The optical signatures collected have distinct features that can be attributed to the materials comprising the MLD grating (hafnia and silica) but also to contaminants left on the surface. Luminescence was used to identify contaminants and defects by comparing signatures to monolayer samples of known contaminants. Characterization of the optical signatures will enable diagnostics to further improve the cleaning process and increase laser-induced–damage thresholds.

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KEYWORDS: grating; absorption; fluorescence

10805-86, SESSION PS4

VIS-to-NIR absorption spectroscopy of magneto-optical materials for high-power laser applications

Tobias Trendle, Jens Kiessling, Jachin Kunz, Frank Kühnemann, Fraunhofer-Institut für Physikalische Messtechnik (Germany)

ABSTRACT TEXT: Photothermal common-path-interferometry (PCI) is considered one of the most sensitive techniques for the measurement of residual absorption in optical materials. This is relevant, in particular, for materials and components to be used with high-power laser applications. At Fraunhofer IPM, PCI is combined with widely tunable optical parametric oscillators (OPOs) as pump sources. This allows one to record the absorption spectra of bulk materials and coatings over a wide spectral range compared to measurements at single wavelengths.

Recently, the measurement portfolio has been extended to include materials containing rare-earth ions which are used, for example, in Faraday rotators. Their high-power performance depends strongly on the low-absorption background at the operational wavelength. Due to the rare-earth atoms in the crystal, these materials feature narrow-band isolated absorption peaks inside the band gap.

The poster will present the new approaches for the absorption calibration and measurement using the absorption peaks. In addition, the materials' absorption spectra offered new possibilities to characterize the overall system behavior of the PCI spectrometer spanning the wavelength range between 450 and 1300 nm.

KEYWORDS: photo-thermal common-path interferometry; absorption spectroscopy; magneto-optical materials; calibration

10805-87, SESSION PS4

Spectrally resolved wavefront measurements on broad-band dielectric coatings

Klaus Mann, Jennifer Ahrens, Bernd Schäfer, Laser-Lab. Göttingen e.V. (Germany); **Michael Vergöhl, Chris Britze, Stefan Bruns,** Fraunhofer-Institut für Schicht- und Oberflächentechnik (Germany); **Volker Kirschner,** European Space Research and Technology Ctr. (Netherlands)

SPEAKER BIOGRAPHY: Klaus R. Mann received his diploma in physics in 1981 and the PhD in 1984 from Univ. of Göttingen. 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.

ABSTRACT TEXT: The paper addresses the influence of non-uniformity effects on the spectral transmission properties of broad-band dielectric optical coatings. Recently, it was observed that in modern complex dielectric coatings significant spectral errors of the reflected wavefront can occur at specific wavelengths, which are induced by lateral coating non-uniformities [1]. For a detailed investigation of this effect, a setup was developed for monitoring the spectrally dependent wavefront error, utilizing a monochromatized plasma lamp as light source and a high sensitivity Hartmann-Shack wavefront sensor for detection. Reflected and transmitted wavefronts can be acquired over a spectral range from 400 – 900nm at a spectral resolution of 2nm on samples up to 140mm in diameter. A method for absolute calibration of the measured wavefront data is presented. As a first example, a broad-band beamsplitter coating deposited by magnetron sputtering with a high reflectance between 400 and 900nm and a high transmittance between 920 and 2300nm was investigated. Different coating designs were analyzed with regard to both spectral performance and spectral wavefront error. It is shown that by an optimized coating the spectral wavefront error can be significantly reduced compared to a standard beam splitter design.

KEYWORDS: wavefront; coating non-uniformity; Hartmann-Shack; spectral transmission properties; spectral wavefront error

10805-88, SESSION PS4

Online detection of hot image in the large aperture near field of the final optics assembly

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SPEAKER BIOGRAPHY: Zhaoyang Jiao (1988~), male, Shanghai, China. He is an associate researcher in Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Sciences. He received his doctor's degree in optical engineering from Shanghai Institute of Optics and Fine Mechanics in 2014. His current research interests include the laser propagation simulation, beam quality control and laser induced damage in high power laser system.

ABSTRACT TEXT: The beam quality information of 3ω laser is very important to analyze the damage problem in the final optics assembly in the high power laser system. Sometimes there is a hot image whose intensity is several times of the average intensity in the near field. It can easily damage the optical components. However, it is very hard to detect the hot image online due to its small spatial size in a large aperture near field, which is usually about 100μm or smaller. Here we propose a method to detect and evaluate the possibility of the hot image in the online experiment. It is based on the near field information of multiple resolutions. The hot image intensity can be deduced from the near filed modulation variations if there is any hot image in the near field. The method could give some references to the online near filed beam quality measurement and system damage diagnosis in the final optics assembly.

KEYWORDS: hot image; beam quality; final optics assembly

10805-89, SESSION PS4

Study of the role of interface on the defect density in HfO_2 films using STEREO-LID (Spatio-TEmporally REsolved Optical Laser-Induced Damage)

Luke A. Emmert, Sebastian Töpfer, The Univ. of New Mexico (USA); **Thomas Willemsen, Marco Jupé, Detlev Ristau,** Laser Zentrum Hannover e.V. (Germany); **Wolfgang Rudolph,** The Univ. of New Mexico (USA)

ABSTRACT TEXT: Spatio-TEmporally REsolved Optical Laser-Induced Damage, or STEREO-LID, is a laser damage technique, which measures the actual fluence (and intensity) at which damage occurs in a single pulse [1]. This is accomplished by measuring the initiation time during the pulse and the initiation position within the beam profile. It has been shown that the results of this measurement can be used to extract the LIDT-relevant defect distribution of the film or surface tested [2,3].

We use the technique to study the role of interface preparation on the measured defect density. Three 30 nm HfO2 films with distinct interfaces were prepared by ion-beam sputtering (IBS) on fused silica substrates. First, a film was prepared directly on a polished fused silica substrate. In the other two cases, a 500 nm buffer layer was included to separate the film from the polished substrate. In one case, a discrete SiO_2/HfO_2 interface was prepared by stopping the deposition of SiO_2 and then starting deposition of HfO_2. In the other case, the switch from the SiO_2 buffer layer to HfO_2 film was performed gradually using a zone target [4] without interrupting the deposition. Rugate filters with gradual interfaces have been shown to exhibit superior laser damage resistance when compared to conventional coatings with discrete interfaces [5]. The three films were tested at 1064 nm using single 10-ns pulses. The differences in the defect density distribution and absorption of these films will be presented.

KEYWORDS: dielectric films and interfaces; defect density; nanosecond pulse; 1064 nm

REFERENCES:

1. Y. Xu et al, "Spatio-TEmporally REsolved Optical Laser Induced Damage (STEREO LID) technique for material characterization," Opt. Express 23, pp. 21607-21614 (2015).
2. Y. Xu et al., "Comparative STEREO-LID (Spatio-TEmporally REsolved Optical Laser-Induced Damage) studies of critical defect distributions in IBS, ALD, and electron-beam coated dielectric films," Proc. of SPIE 9632, 963215 (2015).

NOTES

3. Y. Xu et al., "Comparison of defects responsible for nanosecond laser-induced damage and ablation in common high index optical coatings," Opt. Eng. 56, 011019 (2017).
4. M. Lappschies et al., "Optical monitoring of rugate filters," Proc. SPIE 5963, pp. 1Z1-1Z9 (2005).
5. M. Jupé et al., "Laser induced damage in gradual index layers in rugate filters," Proc. SPIE 6403, 640311 (2006).

10805-90, SESSION PS4

Distribution of the laser damage threshold: extreme value statistical analysis

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ABSTRACT TEXT: This report expands the results previously presented on the problem of the distribution of minimal fluence that can cause damage on an optic of finite size, the threshold[1],[2] In these reports it was shown that this minimal strength is not a single value, but a distribution of values, depending on the defect distributions functional shape and the area under consideration. In this report, these results are generalized through the use of extreme value (EV) statistics. EV statistics are well suited to this problem and hold promise to allow for a generalization of earlier results. This paper will present relevant elements of EV analysis and apply them to the problem of the distribution of laser damage threshold. The results will be analyzed for their impact on underlying and implicit assumptions in current methods of threshold measurement.

KEYWORDS: Threshold; extreme value statistics

REFERENCES

[1] "Accurate measurement of the onset laser damage threshold", Jonathan W. Arenberg, Presented at SPIE Laser Damage, Boulder CO, 2016
[2] "Laser damage threshold: useful idea or dangerous misconception?", Jonathan W. Arenberg ,Proc. SPIE 9632, Laser-Induced Damage in Optical Materials: 2015, 96320P (November 23, 2015)

10805-22, SESSION 6, KEYNOTE PRESENTATION

Shaping nonlinear ultrafast laser interactions: gateway to novel bulk glass and intra-film devices

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SPEAKER BIOGRAPHY: Peter R. Herman earned MASc (1982) and PhD (1986) degrees studying lasers and diatomic spectroscopy in the Physics Department at the University of Toronto and followed with a post-doctoral position at the Institute of Laser Engineering in Osaka University, Japan (1987) to the study of laser-plasma physics and x-ray lasers. He joined the Department of Electrical and Computer Engineering at the University of Toronto in 1988 where he holds a full professor position. He directs a large and collaborative research group that develops and applies laser technology and advanced beam delivery systems to control and harvest laser interactions in new frontiers of 3-D nanofabrication. Our mantra is: "We begin with light and we end with light devices." Professor Herman is OSA, SPIE and IAPLE fellow, holds several patents, spun out one company (FiLaser), and has published over 300 papers in journals and conference proceedings. http://photonics.light.utoronto.ca/laserphotonics/

ABSTRACT TEXT: Confined ultrafast laser interactions driven with controlled beam shapes are a major opportunity today for internal 3D nano-structuring of transparent materials and film with tailored optical and mesoscopic properties. This presentation examines the fundamental beam propagation and interaction physics for generating long narrow filament tracks through to creating thin intra-film cleaving planes. A spatial light modulator (SLM) has been applied toward enhancing and inhibiting of femtosecond nonlinear interactions for elongating filaments, lowering optical waveguide loss, and accelerating etching rate of nanograting tracks over a range of shallow to deep processing depths in fused silica. Alternatively, thin-film interference has been applied to selectively open film into nano-thin glass bubbles, vertical skirts, or inter-nested layers of nano-cavity structure. The potential for developing lab-in-film concepts, compatible with CMOS technologies in SiOx-coated silicon, are discussed towards applications in sub-cellular and DNA studies.

10805-23, SESSION 6

Laser-induced periodic structures on optical materials

M.J. Soileau, Yingjie Chai, CREOL, The College of Optics and Photonics, Univ. of Central Florida (USA)

SPEAKER BIOGRAPHY: M.J. Soileau received his PhD in Quantum Electronics from the University of Southern California, is currently Professor of Optics, Electrical and Computer Engineering and Physics and is the Vice President for Research. His research interests include the nonlinear optical properties of materials and laser-induced damage. He is a Fellow of IEEE, the SPIE--The International Optical Engineering Society, and the Optical Society of America.

ABSTRACT TEXT: High power laser-induced periodic surface structures (LIPSS, also referred as ripples) could be generated and deliberately modulated by controlling the incident laser pulse. LIPSS has been observed on metals, dielectrics and semiconductors surface. The periodicity, orientation and structure are the typical parameters in the study of LIPSS. The formation mechanism of LIPSS is still under investigation, both on nanosecond laser and femtosecond laser. The current formation mechanisms on LIPSS include self-organization, second/third harmonic generation, excitation of surface plasma polaritons, split, coulomb explosion, cavitation instability and so on. In our work, the laser-induced damage experiment was conducted on both dielectrics (e.g. fused silica) and semiconductors (e.g. ZnSe) by using 10.6μm CO_2 nanosecond laser and few-cycle femtosecond laser for generate the LIPSS. Artificial structure were introduced for verifying the structure dependence with polarization, periodicity, and laser induced damage threshold. The mechanism was investigated by comparisons of damage morphologies.

KEYWORDS: Laser-induced periodic structures; Laser-induced damage; Ripples; CO_2 laser damage; few-cycle laser damage

10805-24, SESSION 6

Revisiting of the laser-induced filamentation damage conditions in fused silica for energetic laser systems

Eyal Feigenbaum, Wade H. Williams, Raluca A. Negres, Mary A. Norton, Christopher F. Miller, Gabriel Mennerat, Clay Widmayer, Christopher W. Carr, Jean-Michel G. Di Nicola, Jeffrey D. Bude, Lawrence Livermore National Lab. (USA)

ABSTRACT TEXT: The need for optics that can sustain higher laser fluences and intensities grows as new technological advancements allow laser systems to operate at increased in peak power. This has motivated a substantial effort in the last decades with the study of laser induced damage mechanisms and their mitigation. One well known laser induced damage mechanism is filamentation in fused silica glass, due to Kerr self-focusing of the light [1]. The study of filamentation has been an on-going effort for the last few decades [2] as it turned out to be a major limitation to laser systems at high peak intensities. The past studies had led to a set of simplified rules that allows for the operation of laser system below the onset point for this mechanism to take place, namely what is known as the IL rule (intensity times the length before filamenting equals some empirical constant) and the Bespalov-Talanov perturbation growth theory [3-6]. The need to increase the laser beam intensities and optimize the throughput, closer to the point where the optical propagation length in the material is comparable to the predicted filamentation distance, requires revisiting and improving our understanding of the current rule set. In this talk we will present the observed modifications to the former models in a parameter space that is relevant to currently operating high energy laser systems, based on experimental and modeling investigations.

This study is a combined effort of different synergetic campaigns: ultraviolet large beam nano-second pulse measurements, infrared beam pico-second pulse measurements, whole beam-chain detailed beam propagation code, and small aperture beam propagator equipped with more filamentation relevant physics. The experiments at the ultra-violet was conducted in the Optical Science Laser (OSL), a master oscillator power amplifier system, with a front-end pulse shaping capability that was configured to deliver a 1.3 ns Gaussian shape at 351 nm. A 38-mm thick fused silica test piece was illuminated with 1 cm diameter beam in different locations with fluences varied from 2 J/cm2 to 11 J/cm2. The filamentation location and length where observed using varying focal length microscopy and using the registered incident beam fluence map, their initiation fluence was extracted for further analysis. The infrared experiment was conducted in the Advanced Concepts Lab (ACL) using a 1053 nm, 80-micron diameter spot, with 30-50 ps pulse lengths, and fluence range of 10-30 J/cm2, within a 1-cm thick fused silica glass sample. The OSL experiments were compared to a paraxial approximation laser propagation code (LLNL's Virtual Beamline [7]), along with the measured spatial shape of the beam entering the sample. To further study the initiation conditions of filamentations in the different wavelengths, local fluences and spatial contours, and with a more complete physics beyond self-focusing and diffraction, a dedicated beam propagation code was used. This in-house code was initially developed and validated with experiments in the infra-red [8] and was further modified through this campaign. The experimental and modeling results and their comparison will be presented, as well as the revised understanding towards filamentation threshold rules and mitigations.

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Livermore National Laboratory under Contract DE-AC52-07NA27344.

KEYWORDS: filamentation; fused silica

REFERENCES

[1] K.R. Manes, et al., Fusion Science and Technology 69, 146-249 (2016)

[2] Y. R. Shen “The Principles of Nonlinear Optics”, Wiley (2002)

[3] E.S. Bliss, et al., Appl. Phys. Lett. 25, 448-450 (1974).

[4] W.H. Williams, et al. , ICF quarterly report, UCRL-LR-105821-96-1 (1995)

[5] E.L. Dawes, J.H. Marburger, Phys. Rev. 179 (1969)

[6] H. Bercegol, et al., SPIE 4932, 0277-786X/03 (2003)

[7] R.A. Sacks, et al, J. Phys. 112, 032024 (2008).

[8] E. Feigenbaum, T. A. Laurence, Appl. Opt. 56, 3666-3672 (2017)

10805-25, SESSION 6

Laser-induced-damage mechanisms under nanosecond laser irradiation in absorbing glasses

Stavros G. Demos, Brittany N. Hoffman, Univ. of Rochester (USA); **Christopher W. Carr, Jeffrey D. Bude, David A. Cross,** Lawrence Livermore National Lab. (USA)

ABSTRACT TEXT: It is well established that laser induced damage in optical (dielectric with large band gap) materials under nanosecond laser excitation arise from the coupling of laser energy to defects located near the surface or even in the bulk of the materials. Sufficient absorption of photons by the defects initiate a cascade process that can lead to exposure of the material to localized temperatures in the 1-eV range and initial pressures up to ~10 GPa, which results in an explosive boiling process. Significant progress has been made over the past 15 years in understanding these processes via experimentally studying the dynamics involved, characterizing the resulting material modifications and modeling the initial steps of the energy-deposition process.

Understanding the damage mechanism in ion-doped dielectric materials, which can inherently attenuate the propagation of laser light, has received very little attention. The focus of this work is to investigate the mechanism associated with laser-induced damage in absorbing glasses. The experiments were performed under 355-nm, 8-ns laser excitation and involved an array of diagnostics that monitored the dynamic material behavior during laser irradiation. Our results indicate that there are two leading mechanisms. The first is the change of the refractive index of the material caused by the build up of an excited-state population. The second is the heating of the material that can reach its melting temperature. The damage morphology depends on the relative “potency” of each mechanism. This, in turn, depends on the electronic properties of the doping ion, the doping concentration, the thermal properties of the host material, and the size of the laser beam.

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10805-26, SESSION 6

Damage morphology at pulse-lengths near the transition from intrinsic to defect-driven initiation in hafnia-silica high reflectors

Alexei A. Kozlov, Brittany N. Hoffman, James B. Oliver, Stavros G. Demos, Univ. of Rochester (USA)

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

ABSTRACT TEXT: We report the results on studies of the morphology of damage sites generated in vacuum on hafnia/silica-based high reflectors by 1053-nm-wavelength picosecond pulses in a range from 0.6 ps to 10 ps. We have previously reported that the damage-initiation mechanism changes from intrinsic (Type I) at 600 fs pulse length to defect-driven (Types II and III) damage for 10-ps and longer pulses.1 The focus of this work is to determine the exact pulse length where the damage initiation mechanism changes from intrinsic to defect driven. Furthermore, we vary the laser pulse energy through the damage threshold to observe intermediate states of the damage morphology, where the energy is just sufficient to initiate damage but not in excess to generate the typically observed damage morphologies.

Damage-initiation experiments were performed using single pulses (1-on-1) for s- and p polarized beams with pulse lengths of 0.6 ps, 1.3 ps, 2.3 ps, 2.9 ps, 4.7 ps, 6.7 ps, and 10 ps, selected to best capture the transition. The damage crater’s morphology was investigated under optical differential contrast (Nomarski), scanning electron, and atomic force microscopies. The damage morphologies and spatial characteristics of damage sites revealed that the damage-initiation mechanism changes from intrinsic to localized-defect–driven damage in the pulse-length range from 2.5 ps to 3 ps at both s- and p-polarizations. The plurality of multimodal images obtained from characteristics damage sited provide intriguing insight into the material modification pathway.

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

1. Kozlov, A. A., Papernov, S., Oliver, J. B., Rigatti, A., Taylor, B., Charles, B. and Smith, C., “Study of the picosecond laser damage in HfO2/SiO2-based thin-film coatings in vacuum,” Proc. SPIE 10014, 100141Y (2017).

KEY WORDS: picosecond pulses, thin-film coatings, laser damage in vacuum, atomic force microscopy.

10805-27, SESSION 7

Towards quantification of laser-induced damage phenomena: experimental assessment of absorbed pulse energy via time-resolved digital holography

Balys Momgaudis, Robertas Grigutis, Viaceslav Kudriašov, Mikas Vengris, Andrius Melninkaitis, Vilnius Univ. (Lithuania)

SPEAKER BIOGRAPHY: A first-year graduate student in laser physics, from Vilnius University.

ABSTRACT TEXT: In order to correlate laser damaging fluence with the pertinent theoretical considerations, there were many attempts in the past to establish reliable - damage predicting criterion Such criterion then could be used to estimate laser fluence that triggers the damage process in various optical materials. For example, reaching of materials critical property such as - temperature (melting point), - thermoelastic stress, - electron density are good examples. On the other hand, however, it is already clear that damage mechanism is irradiation condition (wavelengths, pulse duration) and material property dependent. There are no physical restrictions of causing damage by reaching critical stress without critical electron density and vice versa. Accordingly, total absorbed energy or absorbed energy density is likely more suited candidate of universal damage criteria as a common denominator for all critical processes. To our best knowledge, it was never estimated experimentally in the vicinity of the damaging fluence of optical materials. In this study, we present a novel approach based on pump-probe digital holographic microscopy that enables quantitative assessment of absorbed energy during the damage process in transparent dielectric media. By using this method, a case study is conducted in fused silica glass with sharply focused infrared laser pulses at 1030 nm central wavelength and 450 fs pulse duration. By doing so we were able to estimate energy fraction of the incident pulse that is needed to trigger optical damage.

KEYWORDS: digital holography microscopy; pump probe; optical damage; damage criterion; absorbed energy

10805-28, SESSION 7

Few-cycle pulse single shot laser ablation of single layer TiO_2 thin films

Noah Talisa, Kevin Werner, Enam A. Chowdhury, The Ohio State Univ. (USA)

SPEAKER BIOGRAPHY: Noah Talisa is a graduate student working with Dr. Enam Chowdhury at The Ohio State University, studying ultrashort, high-intensity laser-solid interactions. A large part of the work toward his dissertation involves irradiating high bandgap dielectrics and optical thin film coatings with broadband, high intensity few-cycle pulses.

ABSTRACT TEXT: Introduction: The high intensity, ultrafast laser-solid interaction has been a topic of intense research for the past several decades, and as advances towards achieving higher peak intensities are being made at facilities such as the Petawatt Field Synthesizer and the MTW-OPAL beamline at the Laboratory for Laser Energetics, the need for high efficiency thin film optics that have high laser-

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induced damage thresholds is increasing. Laser-induced damage of multilayer thin film optics is not as well-understood as damage of bulk materials, owing to the complicated field distribution that forms within the layers of the optics when a femtosecond pulse is incident, as well as the mechanical compressive stresses of the layers inherent from the deposition process. To gain a better understanding of the laser-induced damage of multilayer thin film stacks, a fundamentally simpler system comprising a single TiO_2 thin film layer on an SiO_2 substrate is studied in this work. Previously, the single shot ablation crater morphology was observed to depend on the layer thickness. For the “anti-reflective” thickness (λ/2, ~183.3 nm), the step-like depth profile exhibits a shallow ~10 nm depth change on the perimeter of the crater and a deep depth change close to the film thickness in the center of the crater. The craters on the “reflective” thickness (λ/4, ~91.65 nm) comprise only a single “step” down with a depth close to the film thickness. The observed dependence on layer thickness could be due to the difference in field distribution within the films, leading to differences in the spatial distribution of excitation. The dependence of the crater morphology on pulse duration is presented, as well as the ablation dynamics measured using a time-resolved microscopy setup.

Experimental setup: Few-cycle pulses with nominal central wavelength ~760 nm are generated with a hollow-core fiber and chirped mirror compressor setup (Kaleidoscope, Spectra Physics), pumped by 0.5 mJ pulses from a home-built 3 mJ/pulse, 35 fs Ti:Sapphire laser operating at 500 Hz. The pulse duration was varied by evacuating the hollow-core fiber and adjusting the grating compressor before the fiber. Pulse durations of 10, 50, 100, and 150 fs were used in the experiment. The dispersion is carefully managed using wedge pairs and ultra-low dispersion mirrors to ensure the correct pulse duration at the target sample. The laser focus was characterized in situ by image relaying onto a camera for fluence calibration. Test sites were irradiated with single pulses at 45° angle of incidence with p-polarization in air. Damage morphologies were studied with optical- and atomic force-microscopy (AFM). In the time-resolved microscopy experiment, a pickoff of the damaging pump pulse is frequency-doubled in a BBO crystal and is used to back-illuminate the sample surface in the in situ imaging system. The blue probe pulse is delayed in time with respect to the pump between 0 and ~9.6 ns.

Results: The crater morphology of the λ/4 thickness is independent of pulse duration, whereas the areal size of the shallow step of the craters on the λ/2 thickness relative to the central deep hole decreases as pulse duration increases. A possible mechanism for this dependence involving how the interaction between the field and excited free-carriers during the pulse affects the final spatial distribution of excitation is discussed. The time-resolved microscopy images show several stages of the ablation process. During the time between 0 and ~10 ps, the pump-irradiated spot appears very dark in transmission; presumably the excited electrons and lattice are thermalizing during this interval. At around 10 ps, concentric interference fringes begin to form, similar to those observed in Ref 1, marking the onset of material removal. The fringe spacing decreases in time until ~1.5 ns, at which point they are no longer resolved and the transmission image begins to resemble the final morphology of the crater.

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

KEYWORDS: few-cycle pulse; ablation; thin film; time-resolved; ultrashort; morphology; transmission microscopy; laser damage

REFERENCES:

[1] D. von der Linde, K. Sokolowski-Tinten, The physical mechanisms of short-pulse laser ablation, Applied Surface Science 154-155 (2000).

10805-29, SESSION 7

Changes of the nonlinear absorption in crystals under irradiation with trains of high-repetition rate femtosecond pulses

Valdas Sirutkaitis, Karolis Bagocius, Mantas Sirutavicius, Simas Butkus, Julius Vengelis, Ieva Pipinyte, Vygandas Jarutis, Vilnius Univ. (Lithuania)

SPEAKER BIOGRAPHY: Valdas Sirutkaitis received his Diploma in physics, Ph.D. and Habilited Dr. Nat. Sci. Degrees from Vilnius University in 1975, 1982 and 1997, respectively. Since 1975 he has been with Physics Faculty of Vilnius University. In 1997 he became a full time professor and in 2012-2017 he was a head of Quantum Electronics Department. Main current research interests is nonlinear optics, laser-induced damage, and micromachining with femtosecond laser pulses.

ABSTRACT TEXT: The nonlinear absorption which occurs in the transparency region of the solid under irradiation with ultrashort laser pulses of high-intensity is important mechanism in laser-induced damage formation. Mainly nonlinear absorption is estimated by simple transmission measurements with single or low repetition rate pulses increasing their intensity up to LIDT. However at high repetition rates accumulation effects must be included and it could change nonlinear absorption behavior drastically. We report results on the observation of the nonlinear absorption changes in KDP and LiNbO3 crystals under irradiation with trains of high repetition rate femtosecond pulses.

The setup of the experiment included 220 fs pulses at 1030 nm wavelength with up to 1 MHz repetition rate from Carbide laser, produced by Light Conversion Ltd. The focused laser beam passed through the crystal sample (length ~4 mm) and was collected with the integrating sphere and was registered by a fast photodiode. The analog signal from the photodiode was processed with a multifunctional data acquisition device and transferred to the computer for the further analysis. The transmission of every femtosecond pulse in train which consists of 100 pulses was measured. The experiments were performed at few pulse repetition rates in range from 50 kHz to 700 kHz. Energy fluences used in experiments could be rised up to 1.5 J/cm^2.

For both crystals at the pulse intensities which were by ~85-40 % lower than crystal‘s LIDT drop of the laser beam transmission (reflections losses were subtracted) from ~98 % in the initial pulses of the train to ~ 80 % in next 20-40 pulses was observed. The energy fluency at which drop in transmission was observed for LiNbO3 crystal was ~5 times smaller than for KDP crystal at 400 kHz repetition rate. Increasing pulse energy and respectively the pulse intensity the transmission droped faster and was only 30-40 % at intensities close to LIDT. At intensities higher than LIDT the laser-induced damage on the crystal surfaces was observed. At intensities lower than LIDT the transmission curves were reproducible in subsequent by 5 s one after other trains of pulses. The dependence on the decreased LIDT value from the pulse repetition frequency was observed as well. Additionally, the LIDT values were estimated for o-polarized and e-polarized beams in KDP crystal. The LIDT for e-polarized beam in KDP crystal was larger by 35% - 40% depending on the tested pulse repetition rate.

KEYWORDS: femtosecond pulses; nonlinear absorption; LIDT; KDP; $LiNbO_3$

10805-30, SESSION 7

First principles simulation of near- and mid-infrared ultrashort pulse laser damage using the particle-in-cell method

Alex Russell, Douglass Schumacher, The Ohio State Univ. (USA)

ABSTRACT TEXT: First Principles Simulation of Near- and Mid-Infrared Ultrashort Pulse Laser Damage using the Particle-in-Cell Method Ultrashort pulse lasers in the near- and mid-infrared have been used for both materials processing and medical treatment due to the availability of lasers in this regime and the responsivity of organic materials. However, the effects of longer wavelength dynamics at damaging fluences have yet to be fully understood. At these higher intensities and longer wavelengths, the laser target interaction is more strongly affected by ponderomotive forces, ballistic particles, impact ionization and overall collisional behavior of the electrons, little of which can be extrapolated from thermal, low fluence behavior. We have developed a simulation approach utilizing the particle-in-cell (PIC) framework which is capable of modeling the laser damage process over six orders of magnitude in time and on the same spatial scale as the laser. With it we can not only kinetically model the interaction of infrared ultrashort laser pulses with metals and dielectrics, but also model the subsequent diffusive and ablative processes. The latter is done through the use of a molecular dynamics based PIC pair potential model (PPPM)[1] coupled with a variation of the Two Temperature Model capable of handling material movement. Implementing our algorithm within the PIC code LSP [2], we investigate ultrashort pulse laser damage on copper and zinc selenide for a range of near- and mid-infrared wavelengths and compare to experiment.

The comparison between simulation and experiment involves determining the threshold fluence through simulation and comparing to experimental values. For copper, this is done through modeling both the laser induced energy deposition and subsequent ablation at a range of fluence values and analyzing the depths and widths of the resultant craters. Both electron-ion and electron-electron collisionality is explicitly modeled during the laser target interaction using temperature dependent rates appropriate for copper, while the ionic motion during the ablation process is determined through the use of an embedded atom potential. For zinc selenide, only the laser target interaction is calculated, and the threshold fluence is determined via the critical density. Here we model photoionization, impact ionization, and the energy dynamics of ionized electrons.

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

KEYWORDS: particle in cell; infrared; ultrashort pulse; modeling;

REFERENCES

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

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

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10805-31, SESSION 8, KEYNOTE PRESENTATION

Recent advances on light-matter interaction in layered media

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ABSTRACT TEXT: In this paper, we show how the design of a multilayer stack can be optimized to achieve some active functionalities such as all-optical switching, control by light of the spectral properties of filtering devices or high efficiency frequency conversion.

10805-32, SESSION 8

Effects of film stress in laser-induced damage

Lars O. Jensen, Tammo Boentgen, Laser Zentrum Hannover e.V. (Germany); **Helmut Kessler,** Manx Precision Optics Ltd. (Isle of Man); Detlev Ristau, Laser Zentrum Hannover e.V. (Germany)

ABSTRACT TEXT: Investigations of reduced laser-induced damage thresholds in dielectric coatings when tested under vacuum show that film stress is one of the contributors to this effect.

Also, there are a number of different approaches to ensure wavefront integrity of surfaces that high stress films have been applied to. To not only identify optimum wavefront integrity but also optimum laser-induced damage threshold, a specific set of samples has been designed, coated and tested. This paper reports on these results, based on films produced in an ion beam sputtering process.

KEYWORDS: Thin Film Stress; Laser-induced damage; stress compensation

10805-33, SESSION 9

1064-nm Mirror Thin Film Damage Competition

Raluca A. Negres, Christopher J. Stolz, Lawrence Livermore National Lab. (USA); **Andrew J. Griffin, Michael D. Thomas,** Spica Technologies, Inc. (USA)

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

ABSTRACT TEXT: A double-blind laser damage competition was introduced at the 2008 Boulder Damage Symposium to determine the status of thin film laser resistance within the private, academic and government sectors. The competition continued every year since then and focused on different coating types and/or use conditions, primarily high reflectors at different wavelengths from 193-nm up to 1064-nm, but also polarizers, Fabry-Perot interference filters and broadband, dispersion-controlled high reflectors for use with near-IR, femtosecond laser pulses.

With the 50th anniversary of this conference upon us, we propose to determine the progress in nanosecond laser damage resistance of 1064-nm, 0-degree multilayer high reflector coatings over the last ten years since the 2008 initial launch of this thin film damage competition with mirrors of the same specifications. The participants in this effort will select the coating materials, coating design, and deposition method. The samples will be damage tested using the raster scan method with a 5-ns pulse length laser system operating at 10 Hz in a single longitudinal mode. Experiments will be performed at a single testing facility to enable direct comparison among the participants. Details of the deposition processes, cleaning method, coating materials, and layer count will be shared.

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

KEYWORDS: thin films; multilayer dielectric mirrors; laser damage

10805-34, SESSION 9

Extensive time-resolved investigation of laser-induced damage fatigue of single layer dielectric coatings

Linas Smalakys, Balys Momgaudis, Mikas Vengris, Robertas Grigutis, Andrius Melninkaitis, Vilnius Univ. (Lithuania)

SPEAKER BIOGRAPHY: Linas Smalakys is a PhD student at Vilnius University. His research interests include fundamental mechanisms of laser-induced damage as well as laser-induced damage statistics.

ABSTRACT TEXT: The decrease of laser-induced damage threshold (LIDT) when exposed with high number of laser pulses is a well-known phenomenon in most dielectrics. In the femtosecond regime this fatigue is usually attributed to the accumulation of laser-induced lattice defects. Generation of such defects in SiO2 was thoroughly investigated during the past few decades: intense laser pulse ionizes the material, the resulting electrons are converted into self-trapped excitons at a time scale of 150 fs, which, at room temperature, are then converted to permanent color centers [1]. Subsequent laser pulses can re-ionize laser-induced color centers, thus the total number of generated electrons increases with each pulse [2]. However, little is known about the accumulation mechanisms in oxides with a much lower band gap which are commonly used for thin film production. Previous experiments suggest the existence of laser-induced states [3], however the information about their origin and characteristic features is extremely scarce.

In this work, a unique approach combining digital holography and time-resolved spectroscopy was employed in order to investigate laser-induced lattice defects in single layer dielectric coatings deposited by IBS process. Two dimensional numerical model based on finite-difference time-domain (FDTD) method was developed in order to numerically simulate the pump-probe geometry of digital holography experiments and decouple ultra-fast processes overlapping in both space and time. Spectral information about laser-induced lattice defects from time-resolved spectroscopy experiments was employed to determine the system of rate equations required to simulate the dynamics of the electronic subsystem. The results of this work provided valuable insights into the probable cause of LIDT fatigue in thin film coatings.

KEYWORDS: digital holography; time-resolved spectroscopy; thin film; finite-difference time domain; fatigue

REFERENCES:

[1] Guizard, S., Martin, P., Petite, G., D'Oliveira, P. & Meynadieri, P. Time-resolved study of laser-induced colour centres in SiO2. J. Phys. Condens. Matter 8, 1281–1290 (1996).

[2] Emmert, L. A., Mero, M. & Rudolph, W. Modeling the effect of native and laser-induced states on the dielectric breakdown of wide band gap optical materials by multiple subpicosecond laser pulses. J. Appl. Phys. 108, 1–7 (2010).

[3] Mero, M., Sabbah, A. J., Zeller, J. & Rudolph, W. Femtosecond dynamics of dielectric films in the pre-ablation regime. Appl. Phys. A Mater. Sci. Process. 81, 317–324 (2005).

10805-35, SESSION 9

Predictions of electric-field–limited laser damage for multilayer coatings

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SPEAKER BIOGRAPHY: Dr. James Oliver is a scientist at the University of Rochester's Laboratory for Laser Energetics working primarily on design, process development, and production of hafnia/silica thin film coatings for high fluence applications including OMEGA, NIF, and other fusion-class lasers. He specializes in thin-film uniformity modeling, stresses, and system design for large-aperture coating deposition. He also teaches optical coating design at the Institute of Optics as well as at the Institute's annual thin film summer school program.

ABSTRACT TEXT: Prediction of the laser-damage threshold of an optical coating design is typically quite difficult, with best practices pursued to improve the manufactured coating performance as much as possible. These practices can include material selection for maximum electronic band gap, choice of the deposition method to limit film defects, and modification of the optical coating design to shift the peak standing-wave electric-field intensity into the material with the higher laser-damage threshold.[1] The effort by Hervy et al. to quantify the laser-damage performance of an electric-field–limited optical coating provides significant insight into the limitations based on the layer materials and the thin-film design.[2]

This study includes an effort to replicate the results demonstrated by Hervy et al., qualify the electric-field–limited damage model, and then use this quantitative approach to refine the coating design for higher laser-damage performance. While the calculated laser-damage thresholds could be fit quite well with measured results for hafnia/silica mirror coatings, the intrinsic damage thresholds for both hafnia and silica layers were found to be much lower than those reported by Hervy. In addition, the laser-damage threshold of one of the mirror designs deviated significantly from the prediction, suggesting an additional term is needed in the formula to accurately calculate the fluence for damage initiation. This was further investigated with coating designs modified with enhanced electric fields at a fixed point in the multilayer design to evaluate the impact of depth within the coating structure on the damage-initiation fluence. These results are evaluated, and modifications to the electric-field–limited model are proposed.

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KEYWORDS: Thin film; Optical coating; Laser damage; Electric-field intensity; Hafnia

REFERENCES

1. Apfel, J. H., "Optical coating design with reduced electric field intensity," Appl. Opt. 16(7), 1880–1885 (1977).
2. Hervy, A., Gallais, L., Chériaux, G. and Mouricaud, D., "Femtosecond laser-induced damage threshold of electron beam deposited dielectrics for 1-m class optics," Opt. Eng. 56(1), 011001 (2016).

10805-36, SESSION 9

Production of high laser-induced damage threshold (LIDT) mirror coatings using plasma assisted evaporation (PAD), plasma assisted reactive magnetron sputtering (PARMS) and ion beam sputtering (IBS)

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ABSTRACT TEXT: Completing its suite of deposition equipment, Bühler has developed a new Ion Beam Sputtering (IBS) System with different substrate configurations: the High Throughput version (HT) and the High Precision version (HP). The HT version enables the coating of 4 planets of up to 350mm diameter substrates, whereas the HP version allows coating of substrates up to 600mm diameter in a single planet configuration. The IBS system is configured with a Bühler proprietary Optical Monitoring System for layer termination, a large 22cm RF sputtering source, and a LION plasma source for assist. In this presentation the optical performance of this IBS coatings, including LIDT, absorption, total loss and residual coating stress, will be discussed and compared to the other available deposition techniques, such as Plasma Assisted Reactive Magnetron Sputtering, and Plasma Assisted Evaporation. Preliminary results of a 1064nm mirror show less than 5ppm absorption, reflectivity's of 99.994%, and no visible damage in CW LIDT testing up to 10MW/cm^2. Pulsed laser damage testing is in process and will be reported. These results will be compared to the coatings being done using PARMS and Evaporation.

KEYWORDS: Ion Beam Sputtering; Thin Films; LIDT; Absorption; Optical Coatings

10805-37, SESSION 9

Laser-induced pits in optical coatings

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ABSTRACT TEXT: A kind of HfO_2/SiO_2 355nm and 1064nm high-reflective (HR) coatings were deposited by electron beam evaporation. Laser-induced damage of the coatings were tested by 355nm-7ns pulses and 1064nm-30ps pulses in 1-on-1 mode. Both tests were carried out with S-polarized and P-polarized pulses in two angles of incidences (AOIs) of 30° and 50°. Damage morphologies and cross-sectional profiles were characterized using scanning electron microscope (SEM) and focused ion beam (FIB), respectively. It is shown that the typical morphologies in both two tests were μm-sized pits. In the 1064nm-30ps tests, the damage pits appeared mostly as 3-5μm ripple-like pits with a density of 15000-25000 mm-2, accompanied by a few tiny pits around. The ripple-like pits were all conical pits with a cylindrical cavity at the bottom, the depth of which was around 1μm. The tiny pits were all cylindrical shaped with a depth of about 400nm. Some much smaller pits were also observed under which located a cavity with two cracks alongside. In the 355nm-7ns tests, most of the pits were flat-pits scaled from 4 to18μm with a density of 500-900 mm-2, few with a bulge in the bottom. The depth of the pits increased with their size, which can be 2.5μm for the largest ones. The damage pits were preliminary inferred to be formed because of the material removal induced by the thermal stress.

KEYWORDS: high-reflective coatings; laser induced damage; picosecond pulse; ultraviolet-pulsed-laser

10805-38, SESSION 9

Development of adaptively mixed thin film (AMTF) deposited by a dielectric material and a plastic

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SPEAKER BIOGRAPHY: **Kunio Yoshida** is a former Professor of Osaka University and Osaka Institute of Technology. He is currently working for Okamoto Optics Works Inc. and for Osaka University.

ABSTRACT TEXT: We had developed a unique porous thin films by a special coating method1. In this technique, two dielectric materials A and B having different refractive indices nA and nB ,where nA>nB are simultaneously deposited in vacuum on a substrate such as fused silica or optical glasses. Then the coated surface is processed in ultra-pure water which preferentially dissolves the material B. These processes result in a porous thin film which has gradient refractive index and has the antireflection (AR) property over broad andwidth.

The porous coating obtained by this method cannot apply depositing a multilayered dielectric thin film. We have developed a novel method. The present technique, a dielectric material D and a plastic P are simultaneously deposited in vacuum on a heated-substrate such as fused silica, ceramic or optical glasses. Then the coated surface forms an adaptively mixed thin film (AMTF) with dielectric material and plastic. In this coating process, plastics partially evaporate due to the heated-substrate. The refractive index of the coated AMTF mainly decided by the mixing ratio of the dielectric material and plastic. In our samples the damage threshold was confirmed to be 115 J/cm^2 at 10 ns and λ=1064 nm. The band width of AMTF with MgF_2 and Teflon (AMTF: MgF_2) was confirmed to cover from 200 to 8000 nm. This AMTF: MgF_2 can be applicable not only to AR thin film, but to a high reflectance mirror and polarizer in various high intensity laser syetems.

KEYWORDS: porous coatings; low stress coatings; low index coatings

1. K.Yoshida, H.Yoshida, Y.Kato, and C.Yamanaka, Appl.Phy.Lett.47,911(1985)

10805-39, SESSION 9

Laser damage of Yb:YAG active mirrors under atmospheric, vacuum, and cryogenic conditions

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2008-2012: Bachelor of Science, Department of Physics, Nanjing University, Nanjing, China
Refereed publications:
Liang Yin, Hanchen Wang, et al, Study of Gd/Tb LPP emission near = 6.7nm for beyond EUV lithography, Proceedings of the SPIE, Volume 9776, id. 97761M 7 pp. (2016)
Brendan A. Reagan, Hanchen Wang, et al. Development of a kilowatt-class, joule-level ultrafast laser for driving compact high average power coherent EUV/soft x-ray sources, Proc. SPIE 9740, Frontiers in Ultrafast Optics: Biomedical, Scientific, and Industrial Applications XVI, 97400R (March 9, 2016)
T.Day, H.Wang, et al, Impacts of SiO2 planarization on optical thin film properties and laser damage resistance, Laser-Induced Damage in Optical Materials 2016, 1001422 (December 6, 2016)

ABSTRACT TEXT: The demonstration of a Yb:YAG chirped pulse amplification laser producing 1 J, 5 ps pulses at 500 Hz repetition rate [1] and recently 1 J pulses at 1 kHz repetition rate [2] relied on efficient thermal management and high performance multilayer dielectric coatings on the laser amplifier active mirrors. In the active mirror configuration, the Yb:YAG amplifier crystals use HfO2/SiO2 multilayer dielectric anti-reflection (AR) and high reflection (HR) coatings. The Joule-level amplifier is operated in vacuum and at liquid nitrogen boiling temperature (77 K) with 1030 nm, 220 ps duration laser pulses making four reflections from each HR coating and 8 passes through each AR coating. The LIDT performance of these coatings is crucial to the future scaling of these amplifiers.

In this work we describe results of an investigation of the laser induced damage threshold (LIDT) of Yb:YAG active mirror laser amplifier disks at atmospheric, vacuum and cryogenic temperature conditions. The measurements were conducted for 220 ps pulses, the typical pulse duration of stretched pulses we are using to implement kW-class average power CPA laser amplifiers [1,2]. We measured the 1-on-1

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(single-shot) and 3000-on-1 LIDT on Yb:YAG crystals with and without the coatings. The results show that the LIDT for single shot damage occurs near 20 J/cm2, and 100% damage probability occurs near 29 J/cm2 for either the uncoated or coated Yb:YAG crystal at atmospheric conditions. Similar results were obtained in the vacuum and cryogenic temperatures tests. This leads to the conclusion that the Yb:YAG material itself, and not the coatings, is the limiting factor in the LIDT.

This work was performed under the auspices of the U.S. Department of Energy, Office of High Energy Physics, Accelerator Stewardship Program under Award DE-SC0016136.

KEYWORDS: Yb:YAG; laser induced damage; multilayer coatings; anti-reflection coatings; high-reflection coatings

REFERENCES

[1] C. Baumgarten, M. Pedicone, H. Bravo, H. Wang, L. Yin, C. S. Menoni, J. J. Rocca, and B. A. Reagan, Optics Letters 41, 3339 (2016).

[2] Brendan A Reagan, Cory Baumgarten, Elzbieta Jankowska, Han Chi, Herman Bravo, Kristian Dehne, Michael Pedicone, Liang Yin, Hanchen Wang, Carmen S Menoni, Jorge J Rocca, High Power Laser Science and Engineering 6, e11 (2018).

10805-40, SESSION 10

Effect of water vapor on the properties of coatings deposited by electron-beam evaporation

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SPEAKER BIOGRAPHY: Meiping Zhu received her Bachelor's degree in Optical Engineering at Zhejiang University, and received her PhD in Optical Engineering at Shanghai Institute of Optics and Fine Mechanics (SIOM), CAS. She has been in the coating research group at Key Laboratory of Material for High Power Laser, SIOM since 2006, researching high power laser coatings.

ABSTRACT TEXT: The properties of the porous coatings by electronic beam (e-beam) deposition are sensitive to moisture because of water absorption. A capping layer employed by plasma ion assisted deposition (PIAD) is an attractive method for impeding water diffusion. In our experiment, SiO_2 mono-layer, HfO_2 mono-layer and SiO_2/HfO_2 multi-layer coatings with/without dense PIAD SiO_2 capping layer are fabricated. The mechanical stress evolution and optical spectrum shift in VIS-NIR of the prepared samples are recorded and investigated in a temperature/humidity controlled clean room. An atomic force microscope (AFM) is exploited to characterize surface morphologies. To determine the reaction product of water vapor and coating materials, Infrared (IR) measurement has been carried out. The existence of lateral water vapor diffuse is confirmed and a theoretical equation concerning water vapor transmission rate (WVTR) is extracted based on Bruggeman effective medium approximation method. Based on experiment results, the effect of water vapor on HfO_2/SiO_2 e-beam coatings are discussed.

KEYWORDS: E-beam coatings; capping layer; stress evolution; optical spectrum shift; IR measurement; water vapor transmission rate; interaction mechanism

10805-41, SESSION 10

The role of entrapped Argon on laser performance of hafnia coatings under nanosecond UV laser exposure

Colin Harthcock, S. Roger Qiu, Raluca A. Negres, Alexander M. Rubenchik, Gabe Guss, Marlon G. Menor, Tommaso Pardini, Luis A. Zepeda-Ruiz, Christopher J. Stolz, Paul B. Mirkarimi, Lawrence Livermore National Lab. (USA); **Gourav Bhowmik, Mengbing Huang,** Univ. at Albany (USA)

SPEAKER BIOGRAPHY: Colin Harthcook earned his Ph.D. at Oregon State University under Dr. Wei Kong, where his work focused on the far-infrared spectroscopy of ionized polycyclic aromatic hydrocarbons (PAHs) and nitrogen substituted PAHs. Following graduation, Colin worked at Washington State University investigating ultra-high vacuum scanning tunneling microscopy and spectroscopy investigating Au-porphyrin and graphene surface interactions with atomic radical species. He joined LLNL in 2017 as a postdoctoral fellow investigating ion beam sputtered optics to understand optical damage precursors in optical coatings materials relevant to high performance laser systems.

ABSTRACT TEXT: As the scientific community pushes the state-of-the-art of high power and high energy laser systems, optical multilayer dielectric (MLD) coatings are often the impeding factor. To develop an effective strategy for producing high performance optical coatings, a fundamental understanding of damage-prone precursors is needed. In this study, we investigate the response of a model system, single layer hafnia coatings under exposure of pulsed UV laser light. Both 1-on-1 and 5-on-1 standard laser damage testing protocols were performed with 355-nm, 8-ns laser pulses formatted to a 600 µm 1/e2 diameter beam print at 45° angle of incidence. The half-wave hafnia single layers were prepared by ion beam sputtering (IBS) deposition under different conditions yielding two hafnia films which are nearly identical in stoichiometry (i.e., in terms of the Hf to O ratios) and structure, however with different detected Ar contents. It is observed from the 1-on-1 and 5-on-1 damage test results that the optical damage behavior is inversely proportional to the Ar content of the coating. Furthermore, the hafnia films with high embedded argon also exhibit unique 1-on-1 morphology compared to that of the films with less embedded argon, while the 5-on-1 morphology of both hafnia coatings are remarkably similar. Our results suggest that the entrapped Ar from the IBS process plays a significant role in degrading the hafnia laser performance under UV exposure. The work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

KEYWORDS: Hafnia; Ion beam sputtering; Argon; 3w; ultra-violet; nanosecond

10805-42, SESSION 10

Damage thresholds in hafnia and silica monolayers and correlation to optical signatures

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ABSTRACT TEXT: Improvement of the laser-induced damage threshold (LIDT) of multilayer dielectric (MLD) coatings is of fundamental importance, particularly for coatings for high power lasers operating in the short pulse regime (i.e. picosecond and sub-picosecond). The LIDT in the short-pulse regime is governed by nonlinear absorption processes, requiring selection of low-absorption materials. The localized electric field within each layer, in combination with the layer's intrinsic damage threshold, determines the overall damage fluence of the MLD and the location (depth) of damage initiation. Therefore, efforts to improve the damage performance in such optics focus on two areas: a) design coatings that minimize the internal standing-wave electric field intensity and b) develop coating materials that have higher intrinsic damage thresholds. This work is part of an ongoing effort to improve the design of the coating and the intrinsic damage threshold of the constituent coating materials. Since hafnia and silica are the two dielectric materials most commonly used for high power laser applications, we damage tested monolayers of each deposited by various methods and vendors with 1053 nm, 800 fs pulses. Theoretically, the intrinsic LIDT for a given material is expected to be approximately the same, assuming full material stoichiometry. However, we observed considerable differences in the inherent LIDT in each set of samples (hafnia and silica single layers). To understand the underlying origin of these differences, all samples were characterized with photo-thermal absorption and spectrophotometric measurements. The results suggest there is a strong correlation between the material absorption and the LIDT, with high absorption at 351 nm resulting in low LIDT. This correlation may allow development of nondestructive damage characterization methods of a material by estimating the LIDT from the photo-thermal absorption measurement and/or developing in situ material characterization approaches during the coating deposition. Furthermore, since unknown parameters during the manufacturing process impact the LIDT, noninvasive material characterization methods can be employed to improve the manufacturing process without the need to employ the time-consuming process of damage testing.

KEYWORDS:laser damage; thin films; optical properties; ultrafast optics; deposition and fabrication; hafnia; silica

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10805-43, SESSION 10

The role of interfacial roughness on laser performance of silica/ hafnia multilayer coatings under nanosecond UV laser exposure

S. Roger Qiu, Eyal Feigenbaum, Colin Harthcock, Raluca A. Negres, Ted A. Laurence, Gabe Guss, Marlon G. Menor, Tommaso Pardini, Sonny Ly, Christopher J. Stolz, Hoang T. Nguyen, Paul B. Mirkarimi, Lawrence Livermore National Lab. (USA); **Gourav Bhowmik, Mengbing Huang,** SUNY CNSE/ SUNYIT (USA)

SPEAKER BIOGRAPHY: S. Roger Qiu holds a PhD in physics and is a physicist at Lawrence Livermore National Laboratory. His research involves the development of optical materials for high energy and power laser systems and the understanding of interfacial phenomena. His areas of interest include optical interference coatings, optical filters, biominerals, and laser crystals. He has numerous publications including one book chapter and two invited reviews. He is an associate editor of the Journal of Crystal Growth.

ABSTRACT TEXT: Interfaces are a common feature in optical multilayer dielectric (MLD) coatings and their role on the MLD laser performance in high power and high energy laser systems is of great interest to the community. In the present study, single layer, layer pairs, and multilayer dielectric coatings of silica and hafnia deposited by ion beam sputtering (IBS) process are used to investigate the impact of interfaces and interfacial roughness on the response of the coating films upon exposure to pulsed UV lasers at ns regime. Standard laser damage testing protocols including both 1-on-1 and 5-on-1 are performed with 355 nm, 8 ns laser pulses formatted to a 600 µm 1/e2 beam shape at 45 degrees of angle of incidence. We find that the fluence-limiting laser damage predominantly originates from the high index material of hafnia and that the resulting morphology is related to the sequence of the high-low index materials at the interface as well as the terminating environment. The observed laser-induced damage in these model systems also display a polarization dependence. Theoretical calculations utilizing a commercially available finite-difference time-domain (FDTD) code demonstrate that the interfacial roughness can result in local E field intensification at the interfacial region and the extent to which the field intensifies is strongly correlated to the laser polarization. It is postulated that the highly localized and intensified region can amplify the laser absorption by pre-existing absorbing defects leading to laser induced coating modification. Our preliminary results suggest that the laser performance of the MLD films can be greatly improved when the interfacial roughness is properly managed. This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

KEYWORDS: Dielectric Coatings; Hafnia; Interfaces; Interfacial Roughness; E-field intensification; Ion Beam Sputtering ; High index material

10805-44, SESSION 10

Laser damage property of the ultra-steep edge filter

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ABSTRACT TEXT: Ultra-steep edge filter is key element for the laser beam combining technology, it has strong resonant electric- field forms in the thin film coatings, which makes its damage behavior quite different with that of the widely studied high-reflectance coating or antireflection coating during the radiation of the high power laser. However, the damage property of edge filter is rarely studied, in this paper, a Ta_2O_5/SiO_2 ultra-steep edge filter was design and precisely fabricated with high transmission at 1064 nm and rejection at 1053 nm at the incident angle of around 20degree. Firstly, it was irradiated by the high power continuous-wave laser, the temperature rise, laser-induce spectral shift and laser damage property was investigated in different laser power with the wavelength tuned between 1050 and1070nm. The correlation between the temperature rise and the absorption of the filter is analyzed. Then, the laser damage property under the irradiation with 1064-nm, 10-ns laser pulses is also studied, the damage threshold and damage morphology for the filter operating on the high-reflection and high-transmittance regime is given. Finally, the laser damage mechanism of the edge filter during the laser irradiation is discussed.

KEYWORDS: optical coating; edge filter; laser damage

10805-45, SESSION 10

LIDT measurements and contamination mitigation techniques of optical coatings at ELI beamlines facility

Praveen Kumar Velpula, Michal Durák, Daniel Kramer, Bedrich Rus, ELI Beamlines (Czech Republic)

SPEAKER BIOGRAPHY: Praveen Kumar Velpula is now a Senior Researcher at ELI-Beamlines. He received his Ph.D. in Optics and Photonics from CNRS- Laboratory of Hubert Curien, France, in 2015. He received his master degree in physics from Banaras Hindu University, India, in 2008. From 2008 to 2011, he was a junior research fellow at University of Hyderabad. During his Ph.D., he explored the various fundamental mechanisms of laser damage using time-resolved imaging. His current research interests include LIDT measurements for Peta-Watt class optics, contamination mitigation techniques of optical coatings and optical and structural surface cleanliness.

ABSTRACT TEXT: The Extreme Light Infrastructure (ELI)-Beamlines facility is host to high energy, ultrashort high repetition rate lasers with state-of-the-art parameters. The design peak powers range from 10's of TW/1kHz to 1PW/10Hz or even a 10PW class shot every minute. Those chains contain broadband systems as well as many ns or ps high power pump lasers.

The Laser-Induced Damage Threshold (LIDT) of optical components is one of the greatest concerns for developing the high power ultrafast lasers, particularly, for the high repetition laser systems. For an optimal optical performance, it is important to evaluate the resistance of test optical components to the used laser fluence level. In this respect, we developed a LIDT test station to characterize the damage threshold of various critical optical components of ELI Beamlines lasers and

to their beam transport. The developed LIDT test station can offer the measurements at various laser parameters and environmental conditions that are similar to operational conditions of the ELI beamlines lasers.

The damage resistance of various multilayer dielectric coatings and beam dump materials were tested using LIDT test station at ELI Beamlines. The LIDT tests were performed using 800nm, ultrafast laser beams with pulse durations of 50fs and 120fs mostly at 1kHz repetition rate. Various samples of low GDD high reflectivity mirrors, chirped mirrors and beam dump materials were tested. The LIDT test methods such as S-on-1, R-on-1 and Rasterscan were used for determining the damage threshold. From the presented results, we discuss the damage growth and behavior in multi-layer dielectric coatings and potential LIDT test methods for determining the appropriate threshold.

Given the use of high repetition rate lasers, mirror and grating samples modified by the ultrashort pulses due to contamination are becoming available. We, therefore, present our recent results on contamination mitigation techniques of coated optical elements using ultrafast laser pulses or UV exposure in air and oxygen-rich atmospheres.

KEYWORDS: Ultrashort Laser Pulses; Peta-Watt Class Optics; Laser-Induced Damage; Threshold; Optical Contamination

10805-46, SESSION 11, KEYNOTE PRESENTATION

Getting a high-power UV laser into space: the story of the Aladin laser development for the European Space Agency's Aeolus Satellite

Denny Wernham, European Space Research and Technology Ctr. (Netherlands); **Wolfgang Riede,** Deutsches Zentrum für Luft- und Raumfahrt e.V. (Germany)

SPEAKER BIOGRAPHY: Denny Wernham has worked in the European Space Agency for 15 years and is the manager of the Aladin instrument which is the only payload on ESA's Aeolus satellite. As such, he has been responsible for overseeing the technology developments that have been conducted by a large number of establishments throughout Europe which were necessary to guarantee the Aladin instrument performance in-orbit.

ABSTRACT TEXT: The Aladin instrument will be the only payload of the European Space Agency's Aeolus satellite. The instrument is a Doppler wind LIDAR which is designed to measure wind speeds throughout the atmosphere which are then used as inputs to numerical weather prediction models in order to improve the short to medium term forecasts. One of the main elements of the Aladin instrument is the power laser head which is a Q-switched, diode-pumped, Nd:YAG which is frequency tripled to 355nm, emitting 20ns pulses of 80mJ or more. The Aeolus satellite is due to launch from French Guiana on a VEGA rocket on August 21st. The development of the technologies to enable this exciting mission has proven to be a long and sometimes painful process, mainly due to issues with laser-induced damage and laser-induced contamination. An exhaustive number of verification tests at sample, subsystem, and satellite level has provided excellent evidence that Aladin will survive it's 3 year lifetime in-orbit and meet the mission requirements. This talk will describe the main challenges that we faced on the laser development and how we overcame them.

KEYWORDS: laser damage; laser-induced contamination; Aladin instrument; Aeolus satellite; space

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10805-47, SESSION 11

A system to identify small damage sites (<50 µm) to increase the lifetime of recycled fused silica optics

Christopher F. Miller, Laura Kegelmeyer, Mike C. Nostrand, Rajesh N. Raman, David A. Cross, Zhi M. Liao, Raminder Garcha, Christopher W. Carr, Lawrence Livermore National Lab. (USA)

SPEAKER BIOGRAPHY: Chris Miller graduated with a B.S. in Chemical Engineering in 2017 from the University of California, Davis. He currently works in the optical and materials science group for the National
Ignition Facility.

ABSTRACT TEXT: The National Ignition Facility (NIF) uses an in-situ system called Final Optics Damage Inspection (FODI) to identify damage as it occurs and alert operators when a site necessitates repairs (~300 microns) and triggers the removal of the damaged optic. FODI, which can reliably detect damage sites larger than 50 microns, also passes the size and location of all sub-critical damage observed on the optic, so all damage can be repaired at once. However, by identifying, and hence mitigating only sites as small as 50 microns, optics are left with numerous smaller sites, some fraction of which resume growing when the host optic is reinstalled. Here we present a method of identifying damage sites down to 20 microns, where sites are much less likely to grow. High resolution images are collected of all objects on each optic, and a machine learning algorithm is used to determine if each object is a damage site or some other type of object (particle, scratch, coating defect, etc....). Any damage site greater than 20 microns is flagged for subsequent mitigation. By additionally repairing these smaller sites, recycled optics had a 40% increased lifetime on NIF.

10805-48, SESSION 11

Pulsed LiDT of transversely resonant nano-structure array high reflectors at 1064nm

Douglas S. Hobbs, Bruce D. MacLeod, Anthony D. Manni, Stephen M. Consoles, TelAztec LLC (USA)

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

ABSTRACT TEXT: Surface relief structures can be configured to produce high efficiency wavelength selective high reflectors (HR) and polarizers. Nano-structure resonant (NSR) HR arrays are typically built in a low index substrate material that is conformally coated with just one or two higher index dielectric materials. Minimizing the number of materials and overall structure thickness reduces the deposition related defect count, as well as the effect of intrinsic film absorption. Recently, a significant increase in laser damage resistance has been demonstrated for conventional longitudinally resonant multi-layer HR film stacks fabricated from non-conventional porous silica layers. The jump in damage resistance was attributed in part to the reduction in the refractive index of the variable porosity, high-low index silica layer pairs. A limitation of this all porous silica design appears to be the large increase in the thickness of the 50- to 100-layer film stack required for sufficient HR performance. Transversely resonant nano-structure arrays with just a few layers do not have this limitation, and therefore by superimposing periodic sub-wavelength-scale features with non-periodic nanometer-scale features, uniquely functional optics can be created with low surface absorption and the reduced refractive index that may potentially increase laser damage resistance. For this study, NSR HR optics for 1064nm wavelength lasers were designed to include non-periodic, ultra-low refractive index features fabricated within conventional high- and low- index dielectric films such as hafnia, tantala, alumina, silica, and magnesium fluoride. The surface absorption, spectral performance and damage resistance of these nano-textured HR optics was then compared to commercial thin-film stack HR optics through standardized, 10ns pulse, LiDT testing at Quantel.

KEYWORDS: Nano-Texture; Micro-Structured High Reflector; Guided Mode Resonant Mirror; Pulsed LiDT; High Energy Laser; Random AR; Surface Structure Resonance; Polarizer Optic

10805-49, SESSION 11

Cleaning process to improve the laser-induced damage threshold of anti-reflection subwavelength structures in near-infrared region

Fei Liu, Jinlong Zhang, Hongfei Jiao, Bin Ma, Zhanshan Wang, Chun Xie, Xinbin Cheng, Tongji Univ. (China)

ABSTRACT TEXT: The photoresist residues were limiting factor that decreased the laser-induced damage threshold (LIDT) of anti-reflection subwavelength structures (ARSS). To improve the laser damage characteristics of ARSS, oxygen plasma and ultrasonic cleaning process were applied to remove residues. The LIDT of the as-deposited ARSS was very low due to the large number of residues. Although most of the photoresist residues could be removed with oxygen-plasma cleaning, the LIDT improved slightly. X-ray photo-election spectroscopy (XPS) detected that there was still a small amount of fluoride that could decreased LIDT. After an optimal ultrasonic cleaning, the residues could be completely removed and the subsurface quality of the structural quartz substrate could also be improved. The LIDT of the ARSS was significantly improved to be comparable to LIDT of the bare quartz substrate.

KEYWORDS: Laser damage; subwavelength structures; nanostructures

10805-50, SESSION 11

Novel etching fluids for water-sensitive optical crystals

Salmaan H. Baxamusa, Paul Ehrmann, Jemi Ong, Ted A. Laurence, Steven A. Hawks, John J. Adams, Kathleen Schaffers, Lawrence Livermore National Lab. (USA)

SPEAKER BIOGRAPHY: Salmaan Baxamusa received his PhD from MIT in 2009 and is the author or co-author of more than 40 peer-reviewed publications. His laser damage interests include material processing technology for mitigating or reducing laser damage precursors.

ABSTRACT TEXT: Optically absorbing electronic defects at fractures is a leading cause of damage in high-fluence laser environments. In fused silica, etching in hydrofluoric acid is used to remove the electronic defects associated with surface fractures such as scratches and digs. We have recently extended this concept to crystalline optics by developing novel etching fluids for water-sensitive optics such as potassium dihydrogen phosphate (KDP).

These fluids are water-in-oil emulsions that consist of nanoscale (5-10 nm) water domains dispersed in a continuous and inert hydrocarbon phase. Similar emulsions have been reported for abrasive-free polishing and we have adapted them for remote-controlled whole-optic etching based on global material removal. In a quiescent emulsion, the etch rate of KDP is very slow (<10 nm/min) and is determined by the rate at which KDP moves from the solid phase to the dispersed water domains. This interphase transport rate can be increased by a factor of 100× by activating the fluid in an acoustic field, allowing the etch to be turned "on" and "off." Based on an analysis of water domain size and number density, we show that the emulsion microstructure is the key determinant of the etch rate.

KDP surface fractures etched in an emulsion evolve similarly to fused silica surface fractures etched in hydrofluoric acid. KDP etched in a microemulsion shows a global reduction in surface photoluminescence of approximately 10×, similar to magnetorheologically polished KDP surfaces. These results suggest that whole-optic etching is a pathway for enhanced surface laser damage resistance of KDP.

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

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KEYWORDS: Etching; Laser Damage; Material removal; Microemulsion

10805-69, SESSION 11

Novel AMP surface treatment for improving optical fiber strength and laser gain

Diana VanBlarcom, Derrek R. Drachenberg, Marcus V. Monticelli, Gabriel E. Davalos, Steve R. Davis, Nick Schenkel, Matthew J. Cook, Robert P. Crist, Michael J. Messerly, Jay W. Dawson, Lawrence Livermore National Lab. (USA)

ABSTRACT TEXT: Contaminants can severely limit the efficiency, laser damage threshold, and strength of photonic crystal fiber-based

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lasers. Such contamination can occur due to environmental exposure during the pulling or stacking of rods and tubes or improper handling and storage of these glass components. A preform made by the "stack and draw" process is susceptible to incorporating surface contaminants into the bulk laser glass.

We have adapted cleaning and handling protocols originally developed for processing large fused silica optics for the National Ignition Facility. The etch cleaning process reported here mimics the "AMP" or "Advanced Mitigation Process" developed for NIF optics that see high fluence 351nm light. In addition, all cleaning, fixturing and assembly processes used to prep a stack for pulling into a fiber are done in a Class 100 cleanroom. Glass rods (1-3mm in diameter and 10" long) are assembled into a Teflon fixture that only contacts the rods at each end. The loaded fixture receives 120kHz ultrasonic cleaning in 10% sodium hydroxide at 45C and 3% Brulin 1696 detergent at 55C. Parts are thoroughly rinsed using ultrasonicated ultrapure water and spray rinses. A 200nm etch in buffered hydrofluoric acid (6:1 BOE diluted 2:1 in DI water) is followed by additional ultasonicated (120kHz-270kHz) ultrapure water and spray rinse. Finally, the components are allowed to fully dry inside the Teflon frame. The rods are cleaned, stacked, and assembled into a fused silica tube.

The preform stack is then returned to a non-cleanroom area to be pulled into fiber using standard telecom fiber-based draw tower equipment and without clean air filters around the draw area. Four fibers were made to test independently the damage threshold and the background loss, two Yb core active fibers and two silica core (F clad) fibers. One of each was cleaned with the AMP process, and one of each with a methanol wipe cleaning process. The active fiber was coated with a dual acrylate coating, first with a low-index inner coating to provide a pump cladding, and then with a relatively hard coating to protect the relatively soft primary coating. The active fibers were pumped at 980nm in a double Fresnel cavity configuration and the power increased until the fiber was damaged up to 1kW. The passive fiber background loss was measured using a standard cut-back technique. Replacing the former methanol wipe clean process with this aqueous cleaning process improved the 1060nm damage threshold of a fiber laser by >30x to above the kW level in the laboratory and reduced the background attenuation by >18x. Early indications are that the acid etching also makes the tensile strength of the fiber consistently high.

This work was performed under the auspices of the U.S. Department of Energy by Lawrence

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10805-51, SESSION 12

Damage performance and developments of final optics system for UV nanosecond high-power laser systems

Mingying Sun, Zhaoyang Jiao, Yajing Guo, Chong Liu, Rong Wu, Lei Ren, Ping Shao, Jianqiang Zhu, Zunqi Lin, Shanghai Institute of Optics and Fine Mechanics (China)

ABSTRACT TEXT: UV laser damage is still the key issue of high power nanosecond laser systems. The operation performance of the final optics in SGII-UP facility is first reviewed. Based on a high power laser prototype, laser-induced damage of large aperture final optics at 351nm was experimentally studied, including damage initiation, growth and morphologies. The near filed of 351nm laser beam was precisely measured with a high resolution by using the precision diagnostics system (PDS) to study the effects of laser modulation and propagation on laser damage. The damage behaviors were comprehensively analyzed and the main contributors to laser damage were discussed. The development perspective of final optics system for high power laser system is briefly introduced.

KEYWORDS: Beam propagation; Near-field modulation; UV laser damage; Contamination; High power laser; Final optics

10805-52, SESSION 12

Mitigation of a novel phase-defect-induced laser damage mechanism on NIF final optics

Michael C. Nostrand, Phil Miller, Pamela K. Whitman, Christopher W. Carr, David A. Cross, Aaron Peer, Rajesh N. Raman, Tayyab Suratwala, Lawrence Livermore National Lab. (USA)

A SPEAKER BIOGRAPHY: Since receiving his Ph.D. in Applied Science in 2000 from UC Davis, **Mike Nostrand** has worked as a research scientist and process engineer in the Optical Materials & Science and Technology group at the Lawrence Livermore National Laboratory. Mike has led the Optical Sciences Laser laboratory which conducts laser-material interaction studies, and has helped develop the Optical Mitigation Facility for repairing damaged optics for the National Ignition Facility.

ABSTRACT TEXT: Operating the National Ignition Facility (NIF) near its power and energy performance limits has revealed a new damage initiation mechanism in the final UV optics. The typical damage event involves the last three optics in the NIF beamline: the final focusing lens, the grating debris shield, and the target debris shield. It occurs on high power shots from intensifications from small phase defects (pits) on the exit surface of the focusing lens that travel through the grating debris shield before reflecting off the AR-coated target debris shield about 75 cm downstream, then propagate back upstream and damage the input surface of the grating debris shield optic which is 15 cm downstream of the focusing lens. Ray tracing has firmly established the direct relationship between the phase defects on the final focusing lens and the damage on grating debris via the reflection from the target debris shield. In some cases, bulk filamentary damage is also observed in the 1-cm thick fused silica grating debris shield. It is not fully understood at this point how there can be enough energy from the reflected beam to cause damage where the forward-going beam did not. It does not appear that interaction between the forward-going beam and the backward-going reflected beam is necessary for damage to occur. It does appear necessary that the target debris shield be previously exposed to laser shots and/or target debris. Furthermore,

there is no evidence of damage imparted to the target debris shield or the final focusing lens. We will describe all the conditions under which we have (and have not) observed these relatively rare events, and the steps we have taken to mitigate their occurrence, including identification and elimination of the source phase defects.

KEYWORDS: damage; mechanism; laser; silica; NIF

10805-53, SESSION 12

Fragment plume evaluations from high-energy density laser target interactions

James E. Andrew, AWE plc (United Kingdom)

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

ABSTRACT TEXT: The Orion laser facility at AWE is used mainly for the study of high energy density physics. It consists of ten "long" pulse [ns] Ultra-Violet laser beams, two "short" pulse [~500fs] Infra-Red Petawatt class beams and ancillary laser beams for X-ray backlighting and ultra violet probing of experimental conditions. Experiments are performed within a 4-meter diameter vacuum target chamber equipped with laser beam, target and instrumentation positioning capabilities. During the evaluation of experiments for the Orion laser facility a variety of laser beam, laser pulse shape and target combinations are proposed. Some of these combinations may pose a damage risk to the unprotected short pulse off axis focussing mirrors, long pulse debris shields and lenses, delicate plasma diagnostic instruments or mechanical components.

Typically, plasma physics targets are of millimetre or sub millimetre dimensions and use an irradiance of ~1016 W/cm_2 in nanosecond pulses or ~1021 W/cm_2 for "short" pulse lengths. These conditions lead to target and target mount materials being raised in temperatures that cause changes from the solid state into liquid, gaseous and plasma conditions. Matter from the altered states are then subsequently ejected from the originally solid target location and are spread around in space with a variety of masses and velocities and form layers or regions of contamination or damage some of which may be deposited on sensitive and/or expensive laser or X ray optical surfaces.

Occasionally experimental teams are requested to perform dedicated shots of a given configuration to obtain information on laser target fragments and their effects on surfaces within the target chamber. Here we discuss two examples of such evaluations. Typically target material was collected on witness plates fielded in specific locations determined by the target chamber configuration. After these test shots the plate surfaces were inspected by optical microscopy so that palliative measures could be taken or modifications to the experiment undertaken to minimise any deleterious effects on laser optics or diagnostic instrumentation.

KEYWORDS: contamination; debris; fused silica; glass; metal; Orion; polymer; shrapnel

10805-54, SESSION 12

Study of the first stages of laser-induced contamination

Georges Gebrayel El Reaidy, Frank R. Wagner, Jean-Yves Natoli, Institut Fresnel (France); **Delphine Faye,** Ctr. National d'Études Spatiales (France)

ABSTRACT TEXT: A novel vacuum chamber was designed and assembled to study the risk of Laser Induced Contamination (LIC) on optical payloads integrated on spaceflight missions in order to qualify optical components and organic materials designed for space applications. In this context, tests were performed with a nanosecond pulsed laser operating at a repetition rate of 10 Hz at 355 nm on fused

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silica substrates under toluene exposure with multiple laser irradiation. Specific experimental procedures are described in order to obtain repeatable and reproducible results. Several series of tests were performed to investigate the onset and further development phases of the induced deposit and the finally appearing contamination-induced laser-damage. In-situ (transmission and fluorescence) and ex-situ (profilometer, fluorescence, DIC microscopy) measurements were used for the characterizations. A slight anti-reflective effect is reproducibly observed at the onset of the deposition process at fluences between 0.25 and 1J/cm^2. We suggest that this is an indication that the LIC deposition process in our experimental conditions starts with a nucleation layer consisting of small dense islands of deposit. Contrarily, for fluences above 1.0 J/cm^2 a rapid decrease in the transmission signal was observed. Besides toluene, different materials and adhesives used in spacecraft were tested at different temperatures which are representative of typical flight operating temperatures with different wavelengths with the aim to provide helpful insight for designers of space instruments in order to achieve mission success.

KEYWORDS: Laser damage; Laser-induced contamination; Toluene; Fused Silica; Fluorescence

10805-55, SESSION 12

Stochastic nature of interaction between nanosecond-pulsed 351nm laser and glass contaminants on fused silica exit surface

Rajesh N. Raman, Christopher F. Miller, Raminder Garcha, Mary Norton, Christopher W. Carr, Lawrence Livermore National Lab. (USA)

SPEAKER BIOGRAPHY: Rajesh N. Raman is a research scientist designing and conducting experiments that probe the fundamental processes governing laser-induced damage in optical materials since 2009, with the mission to extend the lifetime and capabilities of NIF optics. His research interests include determining the role of properties of intrinsic precursors and extrinsic contaminants in reducing the laser-damage threshold of optics and developing diagnostics for the detection and characterization of defective optical materials and dysfunctional tissue. He earned his Ph.D. in Engineering, Applied Science from U.C. Davis in 2009.

ABSTRACT TEXT: An improvement in the damage resistance of large-aperture optics on fusion class lasers of several orders of magnitude has been realized but not the absence of damage, as suggested by laboratory measurements. The sharp reduction in intrinsic damage has revealed additional environmental damage sources such as the interaction of the laser with surface-bound glass micro-particle contaminants generated during laser operation. These particles were identified as ejecta from 1) laser damage on armor glass protecting the installation hardware from known stray focusing reflections in the optical path and 2) input surface bulk eruption (ISBE) on the borosilicate disposal debris shield (DDS). The dependence of the initiation rate of this newly recognized damage source on laser shot parameters is not yet known, making it difficult to predict how this source would affect optic lifetime under changing facility shot conditions.

In this work, a detailed investigation into the 351-nm fluence dependence of glass particle production (distributions), probabilities of damage initiation, damage growth, and cleaning of particles ejected from armor and borosilicate shield glass is performed in the laboratory in a configuration mimicking the facility environment. DDS ISBE sites (100-1000 µm in diameter) were isolated from DDS that had been removed from service and were placed downstream of a fused silica window in a vacuum chamber. Following 351-nm, 5-ns flat-in-time exposure to a 3-cm diameter laser pulse of >11 J/cm^2, DDS particles (typically on the order of thousands) were ejected and deposited onto the exit surface of the fused silica window. Fates of these particles were tracked over subsequent laser exposures. Particle generation and propensity for damage from such particles and how they can be cleaned by laser light is studied.

We compare the behavior observed in laboratory experiments to that of particles and damage on large aperture optics participating on the facility and relate particle morphology and texture to its likelihood of damaging using image analysis algorithms.

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

KEYWORDS: particles; laser cleaning; morphology; laser-particle interaction; damage initiation; damage growth; nanosecond laser

10805-56, SESSION 12

Removal of particle contaminations on dielectric pulse-compressor gratings by laser cleaning and the effect on laser-damage threshold

Jingxuan Wang, China Academy of Engineering Physics (China)

ABSTRACT TEXT: In this study, a laser cleaning method was proposed for removing the surface contaminations of the dielectric pulse-compressor gratings. A Nd:YAG Q-switched laser at 1064 nm wavelength was used in the removal of SiO2 and Al_2O_3 particle contaminations on the gratings. SEM has been used to characterize the irradiated spots after cleaning at the different laser fluences. The time-resolved imaging method was performed to capture the dynamic process of the contamination detachment. The laser-induced-damage threshold (LIDT) variation was also investigated before and after the laser cleaning process.

The results showed that, using the appropriate laser fluences, the particle contaminations on the grating was effectively removed without damaging the grating's fragile 3D profile. The results indicated that the laser cleaning process can be characterized by two well-defined threshold fluences: for the SiO_2 particle contaminations, the cleaning threshold was 1.47 J/cm^2 and the damage threshold was 3.51 J/cm^2, for the Al_2O_3 particle contaminations, the cleaning threshold was 1.32 J/cm^2 and the damage threshold was 3.19 J/cm^2. And the LIDT showed an increase after the laser cleaning technique, comparing with the LIDT under contaminated condition.

KEYWORDS: Laser cleaning; Contamination; Dielectric grating; Laser-induced-damage threshold (LIDT)

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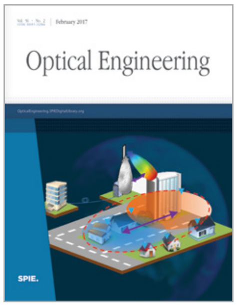

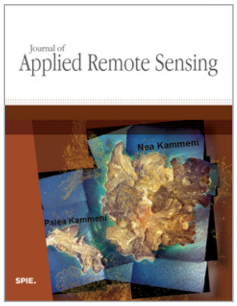

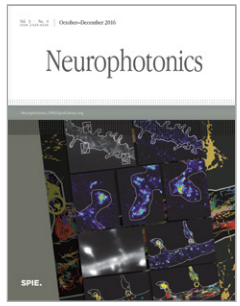

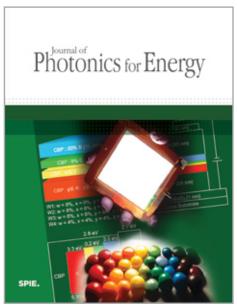

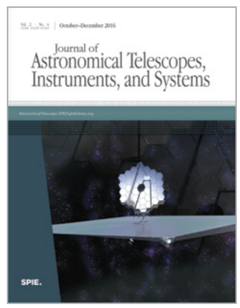

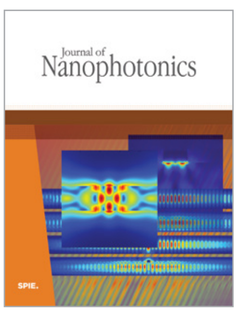

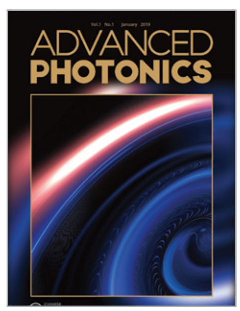

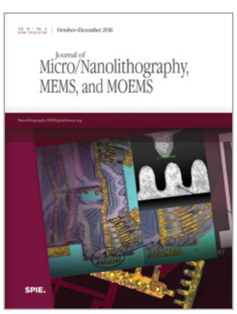

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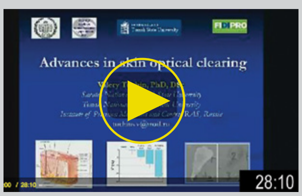

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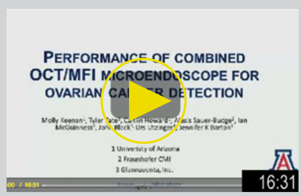
Materials Innovation: It's no longer only about resolution

Nobu Koshiba



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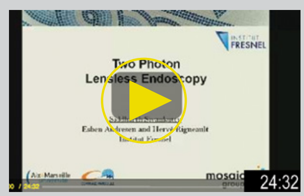
Performance of combined OCT/MFI microendoscope for ovarian cancer detection

Jennifer Barton, et al.



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