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# LASER DAMAGE 2014.

TECHNICAL ABSTRACTS

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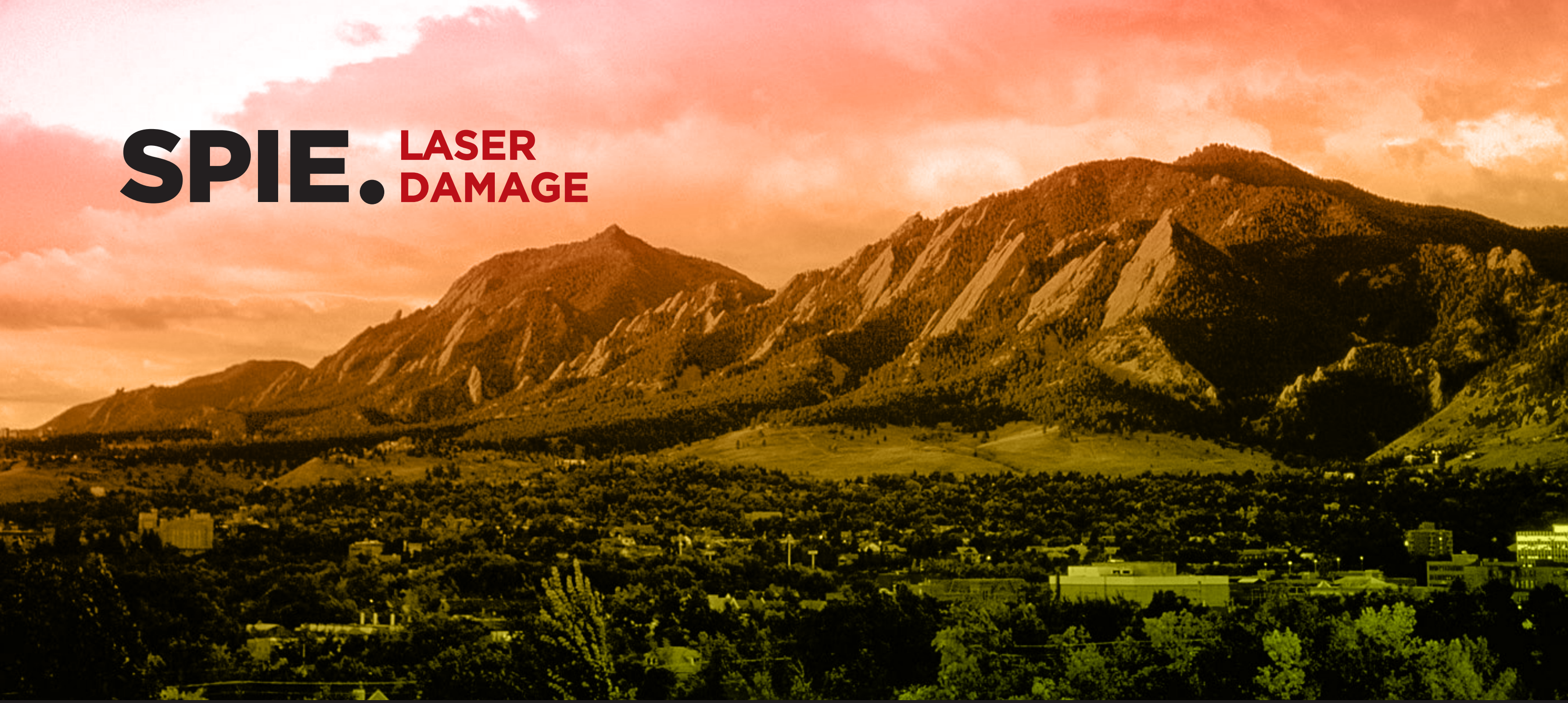
XLVI ANNUAL SYMPOSIUM ON OPTICAL MATERIALS FOR HIGH-POWER LASERS

National Institute of Standards and Technology
Boulder, Colorado, USA

Conferences & Courses:
14–17 September 2014

# SPIE. LASER DAMAGE



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# SPIE. LASER DAMAGE

## XLVI ANNUAL SYMPOSIUM ON OPTICAL MATERIALS FOR HIGH-POWER LASERS

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**Leonid B. Glebov,** CREOL, Univ. of Central Florida (USA)

**Takahisa Jitsuno,** Osaka Univ. (Japan)

**Klaus Mann,** Laser-Lab. Göttingen e.V. (Germany)

**Carmen S. Menoni,** Colorado State Univ. (USA)

**Masataka Murahara,** Tokai Univ. (Japan)

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# SPIE. LASER DAMAGE

## XLVI ANNUAL SYMPOSIUM ON OPTICAL MATERIALS FOR HIGH-POWER LASERS

## SPECIAL EVENTS

### Sunday 14 September

**5:30 to 8:30 pm** — Registration Material Pick-up and Mixer at the Boulder Marriott (2660 Canyon Blvd., Boulder)
**Location: Montrachet Room (1st Floor)**

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

**6:00 to 7:00 pm** — Tutorial: Fundamentals of Growth and Characterization of Amorphous Thin Films for Interference Coatings

Chaired by: **Carmen S. Menoni,** Colorado State Univ. (USA) and **Wolfgang Rudolph**, Univ. of New Mexico (USA)

This tutorial will cover fundamentals of thin film growth of amorphous dielectrics used in the engineering of thin films coatings. Different deposition methodologies and the resulting characteristics of the films will be discussed. Routine and emerging thin film characterization techniques will be described with emphasis on film properties that affect film performance under intense laser illumination.

**7:00 to 8:30 pm** — Welcome and Social Mixer at the Boulder Marriott
**Location: Montrachet Room (1st Floor)**

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

### Monday 15 September

**6:30 to 8:00 pm** — Open House and Reception

### Tuesday 16 September

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

### Wednesday 17 September

**12:10 to 12:55 pm** — NIST Facility Tours

**12:30 to1:30 pm** — Standardization Round-Table Discussion
**Location: NIST, Room 4020**

# Monday AM • 15 September

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

**7:50 to 8:20 am** **Poster Placement at NIST**
*Poster authors for the Monday poster session are to set up their posters at this time.*

**8:20 to 8:50 am** **Opening Remarks, 2013 Awards Presentations, and Tribute**

## Tribute to Dr. Aleksander Manenkov

The Symposium honors the theoretical contributions of the late Dr. Aleksander Manenkov who provided fundamental insight into the dynamics of high-energy laser interactions with optical materials.

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### 8:50 am to 10:10 am • SESSION I

## Surfaces, Mirrors, and Contamination I

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

8:50 am: **Contamination of optical components: protecting optics installed in advanced LIGO from particulate contamination** *(Keynote Presentation)*, Calum I. Torrie, California Institute of Technology (USA) and Scottish Univ. Physics Alliance (United Kingdom) . . . . . . . . . . [9237-1]

9:30 am: **Low-loss and high damage-threshold mirror development for gravitational-wave detectors**, Daisuke Tatsumi, Akitoshi Ueda, National Astronomical Observatory of Japan (Japan); Hitoki Yoneda, The Univ. of Electro-Communications (Japan); Kazunari Sato, Sigma Koki Co., Ltd. (Japan) . . . . . . . . . . [9237-2]

9:50 am: **Control of contamination of optical components in vacuum chambers**, Takahisa Jitsuno, Hidetoshi Murakami, Katsuhiro Mikami, Shinji Motokoshi, Tetsuji Kawasaki, Noriaki Miyanaga, Hiroshi Azechi, Osaka Univ. (Japan) . . . . . . . . . . [9237-3]

### 10:00 am to 10:40 am • Monday Poster Overview

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

### 10:40 to 11:40 am • Poster Viewing and Refreshment Break

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

# Monday AM continued • 15 September

## Mon. 11:40 am to 1:20 pm • SESSION 2

## Surfaces, Mirrors, and Contamination II

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

11:40 am: **The effects of plasma physics target shrapnel and debris plumes arising from early operations of the Orion laser**, James E. Andrew, AWE plc (United Kingdom). . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . [9237-4]

12:00 pm: **Photothermal microscopic studies of surface and subsurface defects on fused silica at 355nm**, Jian Chen, Jingtao Dong, Qi Zhang, Zhouling Wu, ZC Optoelectronic Technologies, Ltd. (China) . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . [9237-5]

12:20 pm: **Influence of organic contamination on laser-induced damage of antireflective coatings and PVD mirrors by nanosecond and femtosecond laser pulses**, Olivier Favrat, Isabelle Tovena-Pecault, Jérôme Néauport, Martin Sozet, Laurent Lamaignère, Commissariat à l'Énergie Atomique (France) . . . . . . . . . . . . . . . [9237-6]

12:40 pm: **Mapping of total scattering as a tool for long-term investigations in the cleaning state of the functional coated samples**, Puja Kadkhoda, Stefan Günster, Lars O. Jensen, Detlev Ristau, Laser Zentrum Hannover e.V. (Germany) . . . . . . . . . . . [9237-7]

1:00 pm: **Surface modification and etching process optimization of fused silica during reaction CHF3-Ar plasma etching**, Sun Laixi, Jin Huang, Xin Ye, Hongjie Liu, Xiaoyan Zhou, Weidong Wu, China Academy of Engineering Physics (China) . . . . . . . [9237-8]

## Mon 1:20 pm to 2:40 pm • Lunch Break

## 9237-1, SESSION 1

# Contamination of optical components: protecting optics installed in advanced LIGO from particulate contamination
*(Keynote Presentation)*

**Calum I. Torrie,** California Institute of Technology (United States) and Scottish Univ. Physics Alliance (United Kingdom)

**ABSTRACT TEXT:** This talk includes a top level overview of these approaches and the status of the current research and development work being carried out by us in this field. This talk will also include an introduction to Gravity Waves, techniques used to detect them and a summary of the status of advanced LIGO. A sister talk titled “Coming Clean: Understanding and Mitigating Optical Contamination in Advanced LIGO” planned talk by my colleague Kate Gushwa will go into detail and present the data collected so far on quantifying contamination sources and the extent of contamination, qualifying the levels of contamination against imposed damage and introducing the practices in order to reduce the sources.

***Keywords:*** *Surfaces, mirrors, contamination, damage*

## 9237-2, SESSION 1

# Low-loss and high damage-threshold mirror development for gravitational-wave detectors

**Daisuke Tatsumi,** Akitoshi Ueda, National Astronomical Observatory of Japan (Japan);
**Hitoki Yoneda,** The Univ. of Electro-Communications (Japan);
**Kazunari Sato,** Sigma Koki Co., Ltd. (Japan)

**SPEAKER BIOGRAPHY:** I am an astronomer in charge of high-quality mirror development for gravitational-wave detector KAGRA in Japan. The gravitational-wave detector of KAGRA is a huge scale laser interferometer to detect faint space-time distrosions caused by gravitational-waves. It has 3km-long optical cavities and 200 Watts laser source of 1064nm. And it is designed to storage 400kW in the optical cavities. Therefore, it requires low-loss and high laser damage threshold mirrors. My main topic is to evaluate performance of such high-quality optics.

**ABSTRACT TEXT:** Low-loss and high damage threshold mirrors are needed for laser interferometer-type gravitational-wave detectors. Collaborative development with Japanese company of SIGMA KOKI CO., LTD and National Astronomical Observatory of Japan was made. As a result, high reflectivity mirror of 99.99% for 1064nm has both low-scattering loss of less than 10ppm and high-damage threshold of over 400 J/cm$^2$.

Such mirrors can be applied for high finesse cavity of more than 10000 with high laser input power of over 100 Watts.

***Keywords:*** *low-loss, high damage threshold, optical cavity, gravitational wave detector, high reflectivity*

## 9237-3, SESSION 1

# Control of contamination of optical components in vacuum chambers

**Takahisa Jitsuno, Hidetoshi Murakami, Katsuhiro Mikami, Shinji Motokoshi, Tetsuji Kawasaki, Noriaki Miyanaga,** Hiroshi Azechi, Osaka Univ. (Japan)

**SPEAKER BIOGRAPHY:** Takahisa JITSUNO was born in 1948. He received Ph.D. degree in Physics from Konan University, Japan. He is currently a specially appointed professor of Osaka University. His present research area is the improvement of damage-threshold in LFEX laser system.

**ABSTRACT TEXT:** We reported the contamination phenomena of optical components in vacuum chambers in previous Laser Damage symposiums. This contamination is commonly observed in several vacuum chambers, and gives a strong degradation of damage threshold in ns region. Several characteristics of this contamination have been studied and reported. We will report a new observation of decrease of contamination due to the improvement of environment. This improvement is based on the understanding of mechanism of contamination in vacuum chambers. We tested the degradation of LIDT of mirror samples in a small vacuum chamber with and without the nitrogen gas purge of outside of the chamber. This process eliminates the penetration of contaminants into the vacuum chamber. We will report the experimental results on the conference.

***Keywords:*** *Dielectric coating, laser induced damage, contamination, vacuum chamber*

## 9237-4, SESSION 2

# The effects of plasma physics target shrapnel and debris plumes arising from early operations of the Orion laser

**James E. Andrew,** AWE plc (United Kingdom)

**SPEAKER BIOGRAPHY:** Dr Andrew is a Team Leader in the Plasma Physics Technical Centre at AWEplc.

**ABSTRACT TEXT:** When lasers are used to produce high temperature, high density plasmas from solid targets it is inevitable that the targets are turned into a variety of products [gas, liquid, solid, sub-atomic particles and electromagnetic radiation] that are distributed around the surfaces of the vacuum chamber used to field such experiments. These by products are produced in plumes of debris and shrapnel that depend on the irradiation conditions, target materials and target geometry. We have monitored the distribution of such plumes by witness plates and used microscopy, photography and spectrophotometry to determine the physical state of material in the plumes and the spatial distribution from various target geometries. The impact of this material on the operations of laser optics and plasma physics diagnostics is discussed.

***Keywords:*** *coating, contamination, glass, debris, metals, polymers, shrapnel, silica*

# 9237-5, SESSION 2

# Photothermal microscopic studies of surface and subsurface defects on fused silica at 355nm

**Jian Chen, Jingtao Dong, Qi Zhang, Zhouling Wu,**
ZC Optoelectronic Technologies, Ltd. (China)

**ABSTRACT TEXT:** It is believed that surface and subsurface defects formed during standard grinding and polishing processes are mainly responsible for laser induced damage in fused silica. The correlation between the laser damage susceptibility and absorption property of these defects has not been totally understood.

In this paper, we present the characterization of surface and subsurface defects of fused silica by measuring their absorption properties based on a photothermal technique at 355 nm. The photothermally measured results are also compared with results obtained by using light scattering mapping and photoluminescence microscopy.

In addition, the feasibility of using the photothermalmethod for large aperture fused silica is also discussed.

***Keywords:*** *surface and subsurface defects, fused silica, absorption defects, photothermal effect, 355 nm*

## 9237-6, SESSION 2

# Influence of organic contamination on laser-induced damage of antireflective coatings and PVD mirrors by nanosecond and femtosecond laser pulses

**Olivier Favrat, Isabelle Tovena-Pecault, Jérôme Néauport, Martin Sozet, Laurent Lamaignère,** Commissariat à l'Énergie Atomique (France)

**SPEAKER BIOGRAPHY:** Olivier Favrat received a master's degree in mechanical engineering at the National Engineering Institute in Mechanics and Microtechnologies (ENSMM), Besançon, France in 2006 and a Ph.D. in Engineering Science from the University of Franche-Comté, France in 2011. He is currently a post doctoral researcher at the "Commissariat à l'énergie atomique et aux énergies alternatives", Le Barp (50km from Bordeaux), France. His research interests include physico-chemical characterisation of solid surfaces.

**ABSTRACT TEXT:** Laser induced damage of optical components is often a limiting factor for the development of high power lasers. Indeed, for many years, organic contamination is identified as a factor decreasing the Laser Induced Damage Threshold of optical surfaces, limiting the use of high fluencies. Also, for the development of its laser facilities, Laser MegaJoule and PETAL, the Commissariat à l'Energie Atomique et aux Energies Alternatives investigates the influence of organic contamination on the optical performances its components. Actually, although great care is provided on the cleanliness of the optics, organic volatile compounds outgassed from surrounding materials can be adsorbed on the sensitive surfaces during its timelife. Thus, for this study, representative samples are intentionally contaminated by qualified protocols to compare their performances with clean components. Qualification and quantification of the organic contamination is realized by automated thermal desorption and gas chromatography coupled with mass spectrometry. Two different coatings are studied: sol-gel antireflective layers and PVD mirrors. According to the specifications of the installations, sol-gel films are then examined with a nanosecond laser pulses at 355 nm whereas mirrors are tested at 1064 nm and 1053 nm with respectively nanosecond and femtosecond laser pulses.

***Keywords:*** *laser-induced damage, organic contamination, sol-gel antireflective coatings, PVD mirrors, nanosecond and femtosecond laser pulses*

## 9237-7, SESSION 2

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

**Puja Kadkhoda, Stefan Günster, Lars O. Jensen, Detlev Ristau,**
Laser Zentrum Hannover e.V. (Germany)

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

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

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

***Keywords:*** *total scattering, ISO 13696, surface inspection, particle density distribution*

## 9237-8, SESSION 2

# Surface modification and etching process optimization of fused silica during reaction CHF3-Ar plasma etching

**Sun Laixi, Jin Huang, Xin Ye, Hongjie Liu, Xiaoyan Zhou, Weidong Wu,**
China Academy of Engineering Physics (China)

**ABSTRACT TEXT:** The ability to predict and control the influence of process parameters on damage precursors of fused silica surface is vital for the development of optics in specialized applications such as inertial confinement fusion (ICF). In the case of reaction ion etch (RIE) of fused silica, experimental results indicate that process parameters, most notably gas/gas mixture, have a strong dependence on surface optical performance of fused silica. In this study, a set of experiments was designed and performed to fully characterize the evolution of surface optical performance of fused silica samples produced under different RIE operating conditions. The designed experiment involved several fused silica samples polished by the same manufacturer which were etched under various gas flow rates and etching depths. Date collected by atomic force microscopy (AFM), time of flight secondary ion mass spectrometry (TOF-SIMS) and fluorescence microscopy was used to determine the response to surface optical performance under different operating conditions. Laser induced damage threshold was measured by 351 nm nanosecond pulse laser. The results showed that the amount of chemical etch was a key factor to surface roughness, which tends to be dominated by surface defects and followed by the surface uniformity. The initial damage is improved significantly and the damage level is more uniform after the etching process. Damage probability is raised by 59.3% when the surface is removed about 10-15μm. The results provide more vivid insight into modification ability of optimal RIE processing, which could be expected to improve the laser damage resistance of critical fused silica optics used in high-peak-power lasers.

***Keywords:*** *fused silica, etch, RIE, surface modification, damage threshold, optics, plasma, CHF3-Ar*

# Monday PM • 15 September

## 2:40 pm to 4:00 pm • SESSION 3

## Mini-Symposium: Applications Related to Laser Damage I

Session Chairs: **Jonathan W. Arenberg,** Northrop Grumman Aerospace Systems (USA); **Stavros G. Demos,** Lawrence Livermore National Lab. (USA)

2:40 pm: **Laser initiated shocks: a successful commercial application in laser peening** *(Plenary)*, Lloyd A. Hackel, Metal Improvement Co. (USA) . . . . . . . . . . . . . . . . . . . . . . [9237-9]

3:10 pm: **Laser-particle interaction: damage and nanopatterning** *(Plenary)*, Philippe Delaporte, Catalin Contantinescu, Aude Vatry, Aude Marchand, Olivier P. Utéza, David Grojo, Lasers, Plasmas et Procédés Photoniques (France) . . [9237-10]

3:40 pm: **High-power fiber laser weapons operational conception**, Ramazan Ekici, Harpak (Turkey) . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . [9237-11]

## 4:00 pm to 4:50 pm • Poster Viewing and Refreshment Break-Monday PM

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

## Mon 4:50 pm to 6:10 pm • SESSION 4

## Mini Symposium: Applications Related to Laser Damage II

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

4:50 pm: **Laser-induced tissue damage and regeneration** *(Plenary)*, Gregory B. Altshuler, Cynosure, Inc. (USA) . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . [9237-12]

5:20 pm: **Laser micro-beam irradiation for cell lysis, molecular delivery, and screening** *(Plenary)*, Vasan Venugopalan, Univ. of California, Irvine (USA) . . . . . . . . . . . . . . . . . [9237-13]

5:50 pm: **Attacking security of quantum key distribution by laser damage**, Vadim Makarov, Univ. of Waterloo (Canada) . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . [9237-14]

## 6:10 pm to 6:20 pm • Closing Remarks

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

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## 9237-10, SESSION 3

# Laser-particle interaction: damage and nanopatterning

**Philippe Delaporte, Catalin Contantinescu, Aude Vatry, Aude Marchand, Olivier P. Utéza, David Grojo,** Lasers, Plasmas et Procédés Photoniques (France)

**ABSTRACT TEXT:** The technique called dry laser cleaning (DLC) is capable of removing efficiently submicron particles and residues. Several descriptions have been proposed to explain these experimentally observed results. They involve damage-free removal mechanisms, like particle ejection by inertia resulting from the rapid thermal expansion of materials or explosive evaporation of the adsorbed humidity in the vicinity of the particles. The electrostatic force, induced by the photo-electrons extracted from a metallic droplet, is also suggested as the main mechanism of metallic particle ejection. Moreover, ablation-based cleaning mechanisms have been reported, like direct ablation of the contamination or local substrate ablation due to near-field enhancement of the laser intensity underneath the particles. All these mechanisms will be discussed as a function of the materials and the irradiation parameters.

Among these mechanisms, local substrate ablation due to near-field enhancement of the laser intensity is very efficient, but it leads to the damage of the surface and represents a strong drawback of the laser process for cleaning applications. However, this effect can be used to break the diffraction limit and to pattern surface at the nanoscale level. Array of nanodots or nanoholes have been realized with a single laser irradiation of a monolayer of self-assembly microspheres. The potential and limitations of this near-field lithography technique will be discussed and some examples will be given.

# 9237-11, SESSION 3

## High-power fiber laser weapons operational conception

**Ramazan Ekici,** Harpak (Turkey)

**SPEAKER BIOGRAPHY:** I am graduated Turkish Air Force Academy in 2006 as a electronic engineering. after school, I took training of fliying. Now I am F-16 pilot, and gets education on master's degree.

**ABSTRACT TEXT:** The idea that have laser weapon on an air platform has been taking by military as a self defense capability since last two decades. Fiber lasers use single or multiple strands of doped lasing fibers that look like common optical fibers. It is possible to combine the outputs of single fiber lasers to achieve higher power outputs. The last achievement in fiber laser makes the output 33 Kw (Laser Weapon System (LaWS)) as a highest level. LaWS are being used for operations such as disabling or reversibly jamming EO sensors, countering UAVs and EO guided missiles, and augmenting radar tracking. The effects of laser show us that the aircraft can survive with the ability of having it. High power fiber laser weapons are seen as a dream of future however they have challenges to solve. One of the problems is achieving precise target acquisition and tracking in operational environment. And also platform mobility is another challenge. In this article I focus on these challenges. How about the current technology applies to aircrafts? Size, weight reduction and platform integrity can be provided by high power fiber laser. The current limitations of Laser weapon cause other defensive assets necessity. The laser weapons in operational arena integrated with the other defensive assets prevent missiles hitting target. For example using with the lots of UAS that have capability of laser weapon in operational, and directed their beam same target simultaneously. Same techniques are applied as fiber laser integrated into one; more platform also gets their energy directed.

***Keywords:*** *high power fiber laser weapons, platform, defensive assets*

## 9237-14, SESSION 4

# Attacking security of quantum key distribution by laser damage

**Vadim Makarov,** Univ. of Waterloo (Canada)

**SPEAKER BIOGRAPHY:** Vadim Makarov is a research assistant professor at the Institute for Quantum Computing, University of Waterloo, Canada, where he leads the Quantum hacking lab http://www.vad1.com/lab/. His laboratory specialises in testing practical security of quantum key distribution systems. Makarov has extensive experience in this field, and is known as a pioneer of it. Prior to his current position in Waterloo, he was a postdoctoral researcher for 4 years at Norwegian University of Science and Technology (Trondheim, Norway), and before that for one year at Department of Physics, Pohang University of Science and Technology (South Korea). He received PhD degree in quantum cryptography from the Norwegian University of Science and Technology (2007) and Master's degree in radiophysics from the St. Petersburg State Polytechnical University (1998).

**ABSTRACT TEXT:** Our society relies on cryptography daily. Currently, mathematical complexity-based methods are used for encryption. Their security is threatened by the development of quantum computer, and by advances in cryptanalysis. The mathematical methods thus need to be replaced. One likely replacement are quantum-physics-based secure communication protocols. For example, quantum key distribution (QKD) allows two remote parties to grow a shared secret key, which can subsequently be used to encrypt and decrypt classical information transmissions. QKD has seen an impressive technological progress over the past 20 years, and is commercially available today.

The security of QKD is based on the laws of physics: it is impossible in principle to measure an unknown quantum state without altering it. The QKD protocol guarantees that any attempt of eavesdropping will be detected. However, as has been demonstrated in the last several years, implementation imperfections are also very important for QKD security. No optical and electrooptical hardware is perfect. Deviations of component characteristics from an idealised protocol model often open exploitable loopholes. Still, imperfections can be pre-characterised and accounted for in the protocol. The amount of information leakage to the eavesdropper because of imperfections can be mathematically upper-bounded, and nullified by applying extra privacy amplification to the shared key data. The privacy amplification compresses the key and removes all potential eavesdropper's information from it. This produces a shorter secure key in the presence of device imperfections.

Have we reached an unbreakable secure communication protocol, and ended the struggle of cryptographers versus hackers? Not so fast! Even if the secure system has been pre-characterised for imperfections, new imperfections can be created on-demand in an installed QKD system by laser damage. We present a proof-of-principle experiment where laser damage is used to permanently change properties of a cryptographic system component (an avalanche photodiode), and create exploitable security loopholes [1]. We illuminated silicon avalanche photodiodes used for single-photon detection in QKD systems with 0.3-3 W continuous-wave 808 nm laser focused on the photodiode. Surprisingly, the photodiodes have first permanently improved their photon detection characteristics, decreasing their dark count rate 2-5 times. At higher levels of damaging illumination, they became permanently blind to single photons yet deterministically controllable by bright light, allowing subsequent application of the bright-light detector-control attack [2]. At still higher damage power, they were of course completely destroyed.

Application of the laser-damage attack to complete QKD systems is an open research question. Countermeasures to the laser-damage attack on quantum communication systems should also be developed and thoroughly tested.

Attacking quantum key distribution systems is a new application for laser damage. Actively engineering imperfections via laser damage represents perhaps the ultimate possibility to breach security of quantum communication. We are excited to present and discuss this new application with the laser damage community, and foster new cross-disciplinary collaboration.

[1] A. N. Bugge, S. Sauge, A. M. M. Ghazali, J. Skaar, L. Lydersen, and V. Makarov, Laser damage helps the eavesdropper in quantum cryptography, Phys. Rev. Lett. 112, 070503 (2014).

[2] L. Lydersen, C. Wiechers, C. Wittmann, D. Elser, J. Skaar, and V. Makarov, Hacking commercial quantum cryptography systems by tailored bright illumination, Nat. Photonics 4, 686 (2010).

***Keywords:*** *laser damage, quantum key distribution, quantum hacking, quantum communications*

# Monday Poster Viewing and Refreshment Break • Rooms 1 & 2

## Thin Films

### 10:40 to 11:40 am and 4:00 to 4:50 pm

**Study on defect in ZnS/YbF3 infrared coating on silicon**, Yinhua Zhang, Wei Huang, Institute of Optics and Electronics (China) . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . [9237-50]

**Repair of a mirror coating on a large optic for high laser-damage applications using ion milling and over-coating methods**, Ella S. Field, John C. Bellum, Damon E. Kletecka, Sandia National Labs. (USA) . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . [9237-51]

**The damage characteristics of laser coatings irradiated from crystal-film interface at oblique incident angles**, Xinbin Cheng, Zhi Song, Hongping Ma, Bin Ma, Zhanshan Wang, Tongji Univ. (China) . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . [9237-52]

**Modification of multilayer mirror top-layer design for increased laser damage resistance**, Drew D. Schiltz, Dinesh Patel, Colorado State Univ. (USA); Luke A. Emmert, The Univ. of New Mexico (USA); Cory Baumgarten, Brendan A. Reagan, Colorado State Univ. (USA); Wolfgang Rudolph, The Univ. of New Mexico (USA); Jorge J. Rocca, Carmen S. Menoni, Colorado State Univ. (USA) . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . [9237-53]

**Post deposition annealing of ion-beam sputtered $Sc_2O_3$, $Ta_2O_5$, $Y_2O_3$ and $SiO_2$ films of varying thicknesses and its impact on laser resistance**, Dinesh Patel, Drew D. Schiltz, Jon A. Peaman, Leandro Acquaroli, Elzbieta Jankowska, Colorado State Univ. (USA); Luke A. Emmert, Wolfgang Rudolph, The Univ. of New Mexico (USA); Carmen S. Menoni, Colorado State Univ. (USA) . . . . [9237-54]

**Comprehensive studies of UV light intensification by nodular defects in $HfO_2$-$SiO_2$ multilayer mirrors**, Linas Smalakys, Gintare Bataviciute, Egidijus Pupka, Andrius Melninkaitis, Vilnius Univ. (Lithuania) . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . [9237-55]

**Study of functional coatings on YAG crystal plate**, Yang Zhao, Hongfei Jiao, Xinbin Cheng, Tongji Univ. (China) . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . [9237-56]

**Electron-beam deposited distributed polarization rotator for high-power laser applications**, James B. Oliver, Terry J. Kessler, Semyon Papernov, Christopher Smith, Brittany N. Taylor, Vern Gruschow, Jeffrey Hettrick, Brian Charles, Univ. of Rochester (USA) . . . . . . . . . . . . . . . . . [9237-57]

**Ring-like damage morphologies produced by continuous-wave laser irradiation**, Lucas N. Taylor, Joseph J. Talghader, Univ. of Minnesota, Twin Cities (USA). . . . . . . . . . . . . . . . [9237-58]

**Influence of polishing and coating techniques on laser-induced damage threshold of AR-coated ceramic Yb:YAG**, Mariastefania De Vido, Paul J. Phillips, Jodie M. Smith, Klaus G. Ertel, Paul D. Mason, Saumyabrata Banerjee, Oleg Cheklov, Thomas J. Butcher, Stephanie Tomlinson, Andrew Lintern, Justin Greenhalgh, Waseem Shaikh, Steve J. Hawkes, Cristina Hernandez-Gomez, John L. Collier, Rutherford Appleton Lab. (United Kingdom); Joachim Hein, Joerg Körner, Friedrich-Schiller-Univ. Jena (Germany) . . . . . . . . . . . . . . . . . . . . . [9237-59]

# Fundamental Mechanisms

### 10:40 to 11:30 am

**Ultrafast UV laser-induced dynamics in fused silica**, Juan Du, Shanghai Institute of Optics and Fine Mechanics (China); Bing Xue, Takayoshi Kobayashi, The Univ. of Electro-Communications (Japan) and Japan Science and Technology Agency (Japan); Zehan Li, Yuanan Zhao, Yuxin Leng, Ruxin Li, Zhizhan Xu, Shanghai Institute of Optics and Fine Mechanics (China) . . . . . . . . . . . . . [9237-60]

**Defects induced laser damage and laser conditioning of DKDP crystals**, Yuanan Zhao, Guohang Hu, Shanghai Institute of Optics and Fine Mechanics (China); Yueliang Wang, Junxiu Chang, Shanghai Institute of Optics and Fine Mechanics (China) and Univ. of Chinese Academy of Sciences (China); Meiping Zhu, Shanghai Institute of Optics and Fine Mechanics (China); Xun Sun, Shandong Univ. (China); Yuangen Yao, Fujian Institute of Research on the Structure of Matter (China); Jianda Shao, Shanghai Institute of Optics and Fine Mechanics (China) . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . [9237-61]

**Bulk breakdown of transparent solids under irradiation with nanosecond laser pulses**, Zia U. Rehman, Yavor V. Grigorov, Khoa A. Tran, Karol A. Janulewicz, Gwangju Institute of Science and Technology (Korea, Republic of). . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . [9237-62]

**Dual-wavelength ultra-short pulse laser damage testing**, Mark Gyamfi, Lars O. Jensen, Peter Jürgens, Laser Zentrum Hannover e.V. (Germany); Mathias Mende, LASEROPTIK GmbH (Germany); Detlev Ristau, Laser Zentrum Hannover e.V. (Germany). . . . . . . . . . . . . . . . . . . . . . . . [9237-63]

**Simulations of $CO_2$ laser interaction with silica and comparison to experiments**, Thomas Doualle, Laurent Gallais, Institut Fresnel (France); Philippe Cormont, David Hébert, Patrick Combis, Jean-Luc Rullier, Commissariat à l'Énergie Atomique (France). . . . . . . . . . . . . [9237-64]

**Laser-induced periodic surface structure (LIPSS) formation in germanium above laser damage fluence by mid-IR femtosecond laser irradiation**, Drake Austin, Kyle Kafka, The Ohio State Univ. (USA); Jian Cheng, Harbin Institute of Technology (China); Simeon Trendafilov, Gennady B. Shvets, The Univ. of Texas at Austin (USA); Hui Li, Allen Yi, Cosmin Blaga, Enam Chowdhury, Louis F. DiMauro, The Ohio State Univ. (USA) . . . . . . . . . . . . . . . . . . . . . . . . [9237-65]

**Multiple wavelengths initiation and growth of laser-induced damage in fused silica in the nanosecond regime**, Maxime Chambonneau, Margaux Chanal, Commissariat à l'Énergie Atomique (France); Guillaume Duchateau, Univ. Bordeaux 1 (France); Pierre Grua, Commissariat à l'Énergie Atomique (France); Jean-Yves Natoli, Institut Fresnel (France); Jean-Luc Rullier, Laurent Lamaignère, Commissariat à l'Énergie Atomique (France) . . . . . . . . . . . . . . . . . . . . . . . . . . . . . [9237-66]

**Dynamics of electron-plasma density induced by ultra-short laser pulses in wide-band-gap solids**, Vitaly E. Gruzdev, Univ. of Missouri-Columbia (USA) . . . . . . . . . . . . . . . . . . . . . . . . . . . [9237-67]

## 9237-50, SESSION PS1

# Study on defect in ZnS/YbF3 infrared coating on silicon

**Yinhua Zhang, Wei Huang,** Institute of Optics and Electronics (China)

**ABSTRACT TEXT:** Studies were made of the influence of deposition parameters and deposition methods on defects of ZnS/YbF3 monolayer and multilayer infrared coatings deposited on silicon, with the aim of reducing the numbers of defects and coating absorption losses. Deposition parameters such as substrate temperature and deposition rates had major influence on the defect densities. Too high or too low substrate temperature and deposition rate could cause the defect densities to increase. The influence of the deposition methods on defect densities was analyzed. The results showed that the defect densities of coatings deposited by thermal evaporation were very lower than by electron beam evaporation. Defect densities were reduced by a factor 20 in the course of the study, resulting in a significant improvement in reducing absorption of the coatings.

***Keywords:*** *defect density, infrared coatings, deposition rate, substrate temperature*

## 9237-51, SESSION PS1

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

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

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

**ABSTRACT TEXT:** When an optical coating is damaged, deposited incorrectly, or is otherwise unsuitable, the conventional method to remove the coating often entails repolishing of the optic surface, which can be costly and incur long lead times. We propose three alternative options to repair or remove unsuitable optical coatings, and evaluate their ability to withstand laser damage. The three options include (i) burying the unsuitable coating under another optical coating, (ii) using ion milling to etch the unsuitable coating completely from the optic surface, and then redepositing the desired coating on the optic, and (iii) using ion milling to etch through a number of unsuitable layers, leaving the rest of the coating intact, and then redepositing the layers that were etched. In this study, we used an incorrectly deposited mirror coating on a 65 cm diameter optic as an example to test the different repair methods. The mirror design was a 42-layer, $HfO_2/SiO_2$ quarter wave stack centered at 1054 nm at 45 degrees in P-polarization, and layer 35 was deposited incorrectly as Hf instead of $HfO_2$. After making repairs according to the above three options on different test optics, the laser damage thresholds of each repaired optical coating were measured to determine which method delivers the best resistance to laser damage.

***Keywords:*** *laser damage, repair optical coatings, large optics, ion milling, etching, overcoating, $Hf0_2$, high reflection*

## 9237-52, SESSION PS1

# The damage characteristics of laser coatings irradiated from crystal-film interface at oblique incident angles

**Xinbin Cheng, Zhi Song, Hongping Ma, Bin Ma, Zhanshan Wang,** Tongji Univ. (China)

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

**ABSTRACT TEXT:** The nano-precursors and electric field distributions in the subsurface of Nd: glass slab are two contributing factors that affect the laser-induced damage threshold (LIDT) of high reflection (HR) coatings irradiated from crystal-film interface. Here we first investigate how the electric field distribution varies with oblique incident angle and polarization. Then we discuss how different electric field distributions lead to different damage behaviors of HR coatings. It was found that the discontinuity of P-polarized electric field at the crystal-film interface was the reason that HR coatings had lower LIDT for P-polarization than S-polarization when the proper coating design was used.

***Keywords:*** *high-reflection coatings, crystal film interface irradiation, oblique incidence, electric-field distributions, nano precursors*

## 9237-53, SESSION PS1

# Modification of multilayer mirror top-layer design for increased laser damage resistance

**Drew D. Schiltz, Dinesh Patel,** Colorado State Univ. (United States); **Luke A. Emmert,** The Univ. of New Mexico (United States); **Cory Baumgarten, Brendan A. Reagan,** Colorado State Univ. (United States); **Wolfgang Rudolph,** The Univ. of New Mexico (United States); **Jorge J. Rocca, Carmen S. Menoni,** Colorado State Univ. (United States)

There is significant interest in the use of the low stress $Ta_2O_5$ in multilayers for high energy infrared lasers. However, $Ta_2O_5/SiO_2$ stacks typically show lower laser damage resistance compared to similar designs based on $HfO_2/SiO_2$. We report a 50% enhancement of the laser induced damage threshold (LIDT) of ion beam sputtered $Ta_2O_5/SiO_2$ quarter-wave stacks when the $Ta_2O_5$ in the top few layers of the stack is replaced by either $HfO_2$ or $Y_2O_3$. LIDT testing was performed with a Yb:YAG chirped pulse amplification system (100 on 1, $\lambda = 1$ µm, $\tau = 350$ ps). The results are consistent with previous work that show laser damage occurs on the top few layers of the mirror structure where the amplitude of the electric field standing wave is highest. Spectrophotometer traces suggest that substitution of these top layers does not significantly affect the performance at the designated center wavelength of 1.06 um. Laser damage was also performed using a continuous wave laser operating at 1 µm, demonstrating that the coating does not damage at the maximum irradiance of 7 MW/cm$^2$.

This work was supported by the DOD Office of Naval Research and High Energy Laser Joint Technology Office.

***Keywords:*** *ion beam sputtering, high reflector, laser damage, $Ta_2 05$, $SI0_2$, tantala, silica, infrared*

## 9237-54, SESSION PS1

# Post deposition annealing of ion-beam sputtered $Sc_2O_3$, $Ta_2O_5$, $Y_2O_3$ and $SiO_2$ films of varying thicknesses and its impact on laser resistance

**Dinesh Patel, Drew D. Schiltz, Jon A. Peaman, Leandro Acquaroli, Elzbieta Jankowska,** Colorado State Univ. (United States); **Luke A. Emmert, Wolfgang Rudolph,** The Univ. of New Mexico (United States); **Carmen S. Menoni,** Colorado State Univ. (United States)

**ABSTRACT TEXT:** Recent report [Anghinolfi et al] showed an increase in the pore volume fraction in $Ta_2O_5$ with annealing. Annealing  is employed to lower absorption loss in optical coating however, increase in pore volume may influence the laser damage of these type of coatings.

We have investigated the role of post deposition annealing on ion-beam sputtered (IBS) $Sc_2O_3$, $Ta_2O_5$, $Y_2O_3$ and $SiO_2$. X-ray diffraction measurements show an increase in nano-crystallinity of IBS deposited of $Sc_2O_3$ and $Y_2O_3$ however, both $Ta_2O_5$ and $SiO_2$ show  minimum nano-crystallinity up to 400ºC annealing temperatures. Corroborative evidence of optical parameters including absorption losses, refractive index, atomic force microscopy will be presented. Laser induced damage on these annealed single layers will be presented.

L Anghinolfi et al 2013 J. Phys. D: Appl. Phys. 46 455301

***Keywords:*** *Sc203, Ta205, Si02, ion beam sputtering, optical properties, laser induced damage*

## 9237-55, SESSION PS1

# Comprehensive studies of UV light intensification by nodular defects in $HfO_2$-$SiO_2$ multilayer mirrors

**Linas Smalakys, Gintare Bataviciute, Egidijus Pupka, Andrius Melninkaitis,**
Vilnius Univ. (Lithuania)

**ABSTRACT TEXT:** Nodular defects embedded within multilayer dielectric coatings have been proved to be the reason of low damage threshold of laser optics. Initiation of localized laser damage sites is associated with laser light intensification due to interference effects caused by defect geometry initiated by seed particles – nodular defects of deposition process. Modelling of the electric-field enhancement within coating defects is an effective tool that helps to understand consequences of laser light intensification. The phenomenon was shown to be sensitive to multiple nodular characteristics (size, geometry, depth, etc.) as well as laser irradiation conditions (wavelength, polarization, angle of incidence, etc.). However, most of the parametric studies were carried out for infrared spectral range assuming that nodule is made out of low refractive index material. Thus, existing results are non-sufficient to explain the behavior of coatings dedicated to UV applications. Herewith comprehensive theoretical analysis has been made on laser intensification by nodular defects in HfO2-SiO2 multilayer mirrors operating at UV range (355 nm). Electromagnetic wave propagation simulations were carried out using software package MEEP – open-source implementation of the finite-difference time-domain (FDTD) method. Extended parametric studies of electric-field characterization were performed for the various cases of nodular parameters, including diameter, shape and material as well as irradiation features such as wavelength, angle of incidence and polarization. The preliminary results show that maximal laser field intensification can be reached within layers of distinct materials (either low or high) depending on nodule parameters and irradiation conditions. New insights were made about UV optics that complements knowledge already existing for nodular defects.

***Keywords:*** *laser induced damage, nodular defects, coatings defects, Hf02/Si02 multilayer mirrors, laser intensification, electric-field modeling, FDTD simulation*

## 9237-56, SESSION PS1

# Study of functional coatings on YAG crystal plate

**Yang Zhao, Hongfei Jiao, Xinbin Cheng,** Tongji Univ. (China)

**ABSTRACT TEXT:** The YAG crystal plate played an important role in the solid middle infrared lasers, this paper focuses on the primary purpose and series of characteristics of the functional coatings on YAG crystal plate, and on the theoretical design of wide-band bump beam antireflection coating (808nm HT) as evanescent film and dichroic coating (808nm HR and 1064 HT). The optical and physical characteristics had been analyzed and the laser damage performance and mechanism had been studied as well.

***Keywords:*** *laser damage, YAG crystal plate, solid infrared laser*

## 9237-57, SESSION PS1

# Electron-beam deposited distributed polarization rotator for high-power laser applications

**James B. Oliver, Terry J. Kessler, Semyon Papernov, Christopher Smith, Brittany N. Taylor, Vern Gruschow, Jeffrey Hettrick, Brian Charles,** Univ. of Rochester (United States)

**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. His current work is focused on coatings for ultrafast applications and polarization control. 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:** Glancing-angle deposition (GLAD) is used to fabricate anisotropic alumina and silica films with significant birefringence. A primary limitation of most GLAD processes has been the area over which the film structure and associated performance has been maintained since the film properties are dependent on the angle at which the evaporant vapor strikes the surface of the substrate. By depositing the coating through a stationary aperture onto a moving substrate, selective patterning of the surface can be obtained, enabling a distributed-polarization rotator to be fabricated that is suitable for use in high-peak-power laser systems such as the National Ignition Facility (NIF) or OMEGA. Quarter-wave and half-wave retardance films have been demonstrated at 351 nm, with 1-on-1 laser-damage thresholds of 10.42±0.46 J/cm$^2$ for silica films and 11.31±–0.31 J/cm$^2$ for alumina films achieved with a 0.7-ns pulse. A system has been developed to pattern a 100-mm-diam substrate using an alumina film, with a sol-gel antireflection coating applied to limit Fresnel reflectances on both the GLAD-coated and clear-substrate regions using a process suitable for meter-scale optics.

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

***Keywords:*** *thin film, laser damage, polarization, GLAD, DPR, NIF*

## 9237-58, SESSION PS1

# Ring-like damage morphologies produced by continuous-wave laser irradiation

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

**SPEAKER BIOGRAPHY:** Luke is a graduate student studying high-power laser materials in Joey Talghader's research group at the University of Minnesota. Luke enjoys working in the laser lab. Luke is interested in metamaterials, especially ones that work well in the high-power regime.

**ABSTRACT TEXT:** The surface damage morphologies produced by continuous-wave laser irradiation of coated optics were measured and analyzed. The laser damage threshold of crystalline and amorphous films under continuous-wave (CW) irradiation appears to be different than in the nanosecond and shorter pulse regimes. This is attributed to the differing thermal properties of the films. Some of the laser damage morphologies we observed were bullseye patterns. These bullseye patterns correspond very nearly to Bessel distributions of the form found in basic heat transfer solutions. If these morphologies are truly thermal phenomenon, then Bessel ring diameter is a function of thermal diffusivity. This is exciting because it may be a physical metric for measuring a film's resistance to laser damage.

CW damage tests were performed on two types of coatings: first, a uniform atomic layer deposited (ALD) film of hafnia ($HfO_2$) or titania ($TiO_2$); second, an ALD film containing periodic spacer layers of alumina. In this second type, every 100 ALD cycles of the main film was followed by 5 cycles of alumina. This type of film structure is called a nanolaminate. We had four sample groups: uniform hafnia, nanolaminate hafnia, uniform titania and nanolaminate titania. The total film thickness was approximately 100 nm for all samples.

In previous work, it was observed that nanolaminate films have reduced crystallinity compared to uniform films. Previous laser damage studies on nanolaminate films found that they have improved laser damage resistance in the nanosecond regime. Preliminary tests found that the opposite is true in the CW regime. Tests comprised a set of stepped laser power levels with otherwise constant experimental conditions. The power level where half the irradiation sites produced damage was determined as the laser damage threshold.

During these tests, a variety of laser damage morphologies were created. Craters, delamination, rings and complex surface patterns were observed. Damage was not observed within the bulk of the sample when viewed through an optical microscope (the samples were optically transparent). Some crater-like features were observed at the back of the samples. Ring-like and complex features were only observed at the surface, however. Ring-like features consisted of a central crater – of substrate damage as well as film delamination – surrounded by a ring of unmolested film, followed by another ring of delaminated film, before reaching the final extent of the visibly damaged region. Complex features were observed in all the samples tested at irradiances above the damage threshold. However, ring-like features were only observed in the uniform and nanolaminate hafnia samples.

Preliminary analysis was informed by standard heat transfer solutions. It was assumed that the film delamination was caused by a temperature profile that reached melting point or delamination-temperature in a radial distribution. Bessel-like modes are solutions of cylindrical heat transfer problems with a boundary at a fixed radius. Additionally, Bessel-like modes are solutions of various surface wave phenomena. The exact solution of the ring-like delamination remains an open question.

***Keywords:*** *thin films, continuous wave, laser damage, morphology, rings, bullseye, bessel*

## 9237-59, SESSION PS1

# Influence of polishing and coating techniques on laser-induced damage threshold of AR-coated ceramic Yb:YAG

**Mariastefania De Vido, Paul J. Phillips, Jodie M. Smith, Klaus G. Ertel, Paul D. Mason, Saumyabrata Banerjee, Oleg Cheklov, Thomas J. Butcher, Stephanie Tomlinson, Andrew Lintern, Justin Greenhalgh, Waseem Shaikh, Steve J. Hawkes, Cristina Hernandez-Gomez, John L. Collier,** Rutherford Appleton Lab. (United Kingdom); **Joachim Hein, Joerg Körner,** Friedrich-Schiller-Univ. Jena (Germany)

**ABSTRACT TEXT:** $Yb^{3+}$ doped YAG is one of the most promising materials for high energy, high repetition rate laser systems producing nanosecond pulses. YAG as the host medium offers good thermo-mechanical and thermo-optical properties and, if it is used in ceramic form, it can be produced in large sizes with laser-grade optical properties. Large sized, laser-grade gain media is pivotal for the development of high energy kJ-class laser systems. Much effort has been devoted to the development of advanced polishing and coating techniques in order to produce optical materials able to withstand high fluence levels at different environmental conditions. In this paper, we present experimental results for 1 on 1 laser induced damage threshold (LIDT) tests in the nanosecond regime following ISO11254-4 standard on anti-reflective coated ceramic Yb:YAG samples. The aim of this experimental campaign was to assess what impact both fabrication techniques and environmental parameters have on LIDT value and damage morphology. Different polishing techniques, namely standard, super-polishing, ion beam sputtering and magneto-rheological finishing, were applied to Yb:YAG ceramic samples. Different RMS roughness values of the resulting substrate surface were obtained, depending on the particular technique applied. Substrates were subsequently AR-coated by means of ion assisted deposition (IAD) and ion beam sputtering (IBS). LIDT tests were performed under different combinations of temperature and pressures. Experimental results showed that, generally, IBS coating performed better than IAD coatings on low roughness substrates, while the situation is reversed in the case of higher roughness substrates. No clear correlation was instead observed between LIDT values and temperature or pressure for both IAD and IBS coated samples and for all polishing techniques. Damage sites were analysed using both optical microscopy and white light interferometry in order to thoroughly characterise damage morphology. As a result of this analysis, we were able to conclude that coating technique, temperature and pressure have relevant impact on damage morphology. However, polishing technique does not influence damage morphology.

***Keywords:*** *ceramic Yb:YAG, laser induced damage threshold, polishing techniques, coating techniques, damage morphology*

## 9237-60, SESSION PS2

# Ultrafast UV laser-induced dynamics in fused silica

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

**SPEAKER BIOGRAPHY:** He was born in Xi`an, China, in 1983. He got his bachelor degree from Xi`an Jiaotong University in 2005, and master degree from University of Chinese Academy of Sciences (CAS) in 2009. Since 2011, he joined Kobayashi group in Advanced Ultrafast Laser Research Center in University of Electro-Communications (UEC) for his Ph.D. degree. During and after his master degree research in the CAS, his research was focus on THz pulse generation and THz imaging. And in UEC, his research is the development of ultrafast deep ultraviolet laser system and the ultrafast dynamics research on biochemical samples by using UV and DUV light.

**ABSTRACT TEXT:** Although many research studies have been carried out on carrier dynamics inside fused silica, the basic ionization mechanisms of fused silica under direct excitation of ultrafast UV laser is not well understood, which points out the need to specify induced dynamics in dielectric coating materials before laser damage. To better understand the multiphoton and avalanche ionization mechanisms, broadband ultrafast UV femtosecond laser pulses centered at 400nm with the pulse duration of 9fs was used to excite the ultrafast carrier dynamics inside the fused silica, for the first time to the best of our knowledge.

Since the high photon energy of the UV light, the multiphoton ionization is very easy to realize even using the pump energy of 130 nJ in the present study. Both the pump and probe laser pulse has broad laser spectrum range from 360nm to 440nm, so two dimensional time dependence of the absorbance changes ($\Delta$A) could be achieved. We found the observed. A signal were positive at nearly all the probe wavelength, except those the long-wavelength edge, which suggestion that what we observed is due to the laser-induced absorption, not bleaching or stimulated emission. For each real-time $\Delta$A traces, ultrafast decay of free electrons is observed within about 166±7 fs, which indicates that the free carrier in the conductive band is trapped into self-trapped excitons after an ultrafast decay within about 166±7 fs. We also notice that the real-time trace does not go to zero after the trapping, but it decays slowly which beyond our measure time. Reasonable explanation is that these trapped excitons are excited and ionized after trapping, which contributes to the long-time term in the real-time traces.

***Keywords:*** *ultrafast, UV, dynamics, fused silica, multiphoton ionization, excitons, real-time trace, absorbance changes*

## 9237-61, SESSION PS2

# Defects induced laser damage and laser conditioning of DKDP crystals

**Yuanan Zhao, Guohang Hu,** Shanghai Institute of Optics and Fine Mechanics (China); **Yueliang Wang, Junxiu Chang,** Shanghai Institute of Optics and Fine Mechanics (China) and Univ. of Chinese Academy of Sciences (China); **Meiping Zhu,** Shanghai Institute of Optics and Fine Mechanics (China); **Xun Sun,** Shandong Univ. (China); **Yuangen Yao,** Fujian Institute of Research on the Structure of Matter (China); **Jianda Shao,** Shanghai Institute of Optics and Fine Mechanics (China)

**ABSTRACT TEXT:** Laser damage of TYPE-II DKDP plate was investigated. DKDP crystals used for third harmonic frequency generation were prepared by traditional growth. Dark field microscopy was employed to analyze the pre-existing laser scattering defects, and the correlations between scattering and laser damage initiations were identified. It's found that there were three kinds of bulk defects: micron, sub-micron and nano-scale defects. The damage behaviors were dominated by the defect scale and density. The sparse distributed micron-size defects had lowest damage initiation fluence (~2J/cm$^2$), and LIDTs of the DKDP samples decreased as the density of submicron size defects increased. SEM and XRD were employed to analyze the defects, and the possible formation processes of different kinds of defects were discussed. Laser conditioning was employed to improve the laser damage resistance of the DKDP samples, and high precision transmission detection setup was established to evaluate the obscuration due to pinpoints. It was found that the obscuration of the pinpoint scattering is mainly originated from the sub-micron and nano-scale defects. Moreover, moderate laser fluence and conditioning steps can eliminate or weaken scattering induced by the sub-micron and nano-scale defects. The laser conditioning mechanism was discussed.

***Keywords:*** *laser induced damage, DKDP crystals, defects, laser conditioning*

# 9237-62, SESSION PS2

# Bulk breakdown of transparent solids under irradiation with nanosecond laser pulses

**Zia U. Rehman, Yavor V. Grigorov, Khoa A. Tran, Karol A. Janulewicz,**
Gwangju Institute of Science and Technology (Korea, Republic of)

**SPEAKER BIOGRAPHY:** Graduated from university of Peshawar,Pakistan in 2006.Currently working as a PhD student in X-Ray Laser and Intense Laser-Matter Interaction Laboratory, Kwangju Institute of Science and Technology, Korea Republic .

**ABSTRACT TEXT:** Localized energy deposition via pulsed laser is responsible for a broad range of nonlinear effects. They lead to generation of excessive ionization and as a consequence, to high temperature and pressure in the deposition area. Abrupt changes in the physical parameters of the material induce shock waves emanating from locus and change optical properties of the surrounding material. Thus, localized deposition of energy by the optical pulses enables investigation of the materials in the regime comparable to the high energy density ($p \geq 1$ Mbar).

In our investigation, a single pulse of a nanosecond laser was tightly focused to a beam spot of ~ 3.7 μm in the bulk of transparent materials (soda lime glass, borosilicate glass, fused silica and PMMA). This measured value assured high level of the energy density in the laser focus even if the energy deposition is extended in time. Morphology of the breakdown, observed under high resolution microscopes, showed existence of the shock waves and connected with them high temperature in the focus. These effects were analyzed using classical moving breakdown model but extended by existence of shocks creating cavity in the broken material. Energy absorbed in transparent materials was measured and discussed. Surprisingly, results for some materials suggest significantly higher breakdown threshold fluence than reported earlier for looser focused laser pulses. Energy absorption level was verified by estimates from the changes in the temporal profile of the laser pulse. An integrating sphere was used to identify part of energy scattered the long-lived breakdown process. It was found that 5-10% of the incident radiation was scattered and the total absorption achieved 75 %. Using absorption characteristics optical damage threshold (ODT) and breakdown threshold were estimated for all materials under investigation. Multiple-breakdown effect, observed for some materials was also analyzed within the frame of the existing models. Analysis revealed dependence of the channels length and position on the incident energy. Spectroscopic study of the light emission accompanying breakdown showed typical quasi-continuum emission.

***Keywords:*** *absorption, bulk damage, transparent material, shockwave, cavity*

## 9237-63, SESSION PS2

# Dual-wavelength ultra-short pulse laser damage testing

**Mark Gyamfi, Lars O. Jensen, Peter Jürgens,** Laser Zentrum Hannover e.V. (Germany);
**Mathias Mende,** LASEROPTIK GmbH (Germany);
**Detlev Ristau,** Laser Zentrum Hannover e.V. (Germany)

**ABSTRACT TEXT:** In the femtosecond regime the laser damage threshold is determined by the electric field distribution within the optical component. Commercially available ultra-short pulse laser systems provide ever increasing output powers in fundamental and harmonic wavelengths. Dichroic optics for combining and splitting fundamental and second harmonic radiation are under increased strain due to one wavelength passing through the whole layer stack. Also, the electric field distribution is of higher complexity and favors multi-photon excitation of higher efficiencies.

We investigate the LIDT of single layers and dichroic beam splitters under dual (1ω and 2ω) and single wavelength exposure. As a laser source we use a Ti:Sapphire System delivering sub 220fs pulses at 780nm/390nm. Different designs for the dichroic optics have been developed and deposited with an IBS process using $SiO_2$, $Nb_2O_5$, $HfO_2$ and $Ta_2O_5$. The LIDT as a function of the material band gap is investigated. Further, for the single layer designs damage thresholds are calculated using the Keldysh theory and are compared with the experimental results.

***Keywords:*** *laser damage threshold, femtosecond, NIR-VIS, dichroic optics*

# Simulations of $CO_2$ laser interaction with silica and comparison to experiments

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

**ABSTRACT TEXT:** Localized $CO_2$ laser heating of silica glass has demonstrated its capacity to mitigate surface damage on optics used in high power laser application. The parameters for this process such as the power, the beam size, the exposition time are however critical and some fundamental studies on the silica behavior under $CO_2$ irradiation are required to develop the processes. It is necessary for instance to understand the silica transformation, the material ejection and the thermo-mechanical stresses induced by the laser heating and subsequent cooling.

In this context and based on previous work on the subject we have used a 3 dimensional finite element model to calculate the temperature of silica heated by a $CO_2$ laser and the residual stresses after cooling of the heated area. The case of multiple irradiations as well as the case of a moving beam on the sample can be simulated. The input thermal parameters are derived either from bibliographic studies or from previous works based on comparison of simulations to infrared thermometry measurements. A viscous-elastic model is used for the evaluation of the residual stresses. Moreover an analytical model based on thermodynamics and the kinetic theory of gases allows us to evaluate depth of the crater created by the laser irradiation.

The theoretical calculations are compared to experiments involving different kind of silica (silica of type II and II, sol-gel treated silica, annealed silica) irradiated with various laser parameters (power, beam size, irradiation time). The crater depth and shape, the measured residual birefringence are particularly the subject of investigation.

***Keywords:*** *laser damage, mitigation process, $CO_2$ laser, stress, silica*

## 9237-65, SESSION PS2

# Laser-induced periodic surface structure (LIPSS) formation in germanium above laser damage fluence by mid-IR femtosecond laser irradiation

**Drake Austin, Kyle Kafka,** The Ohio State Univ. (United States); **Jian Cheng,** Harbin Institute of Technology (China); **Simeon Trendafilov, Gennady B. Shvets,** The Univ. of Texas at Austin (United States); **Hui Li, Allen Yi, Cosmin Blaga, Enam Chowdhury, Louis F. DiMauro,** The Ohio State Univ. (United States)

**SPEAKER BIOGRAPHY:** A leading expert in the field of short pulse lasers, ultra-intense and high energy density laser matter interaction, Prof. Chowdhury led the design and construction of the 500 TW SCARLET laser system at the Ohio State University. He also heads an AFOSR funded Femtosecond Solid Dynamics Laboratory (FSD Lab) in OSU Physics with short pulses of lasers operating with wavelengths from 200 – 10,000 nm and pulsewidth from 5 – 500,000 femtoseconds. This lab is dedicated to studying the fundamental mechanisms of damage caused to materials exposed to intense laser pulses.

**ABSTRACT TEXT:** Introduction: Femtosecond laser induced periodic surface structures (LIPSS) have been actively investigated over two decades and are now gaining attraction due to the broad industrial applications in surface modifications such as solar cells, colorization, waveguides, and surface enhanced Raman scattering [1]. The LIPSSs present quite different characteristics (e.g. ripple periodicity and orientation) depending on the laser parameters, experimental environments, and material properties. LIPSSs may form on metals, semiconductors, and insulators, and are typically classified by two distinct categories according to the scale of ripple period: low spatial frequency LIPSS (LSFL, period > $\lambda$ /2) and high spatial frequency LIPSS (HSFL, period < $\lambda$ /2). Because of the wide transmission window and high third-harmonic optical nonlinearity [2], germanium gained recent interest as a promising nonlinear material in the mid-IR region (3-10 µm). In this region, Ge is transparent and behaves like a 'high bandgap' semiconductor. Also, since critical density in a plasma is proportional to the square of frequency of incident light, surface plasmon coupling in the presence of mid IR light may become important at much lower free electron densities. Here we report for the first time study of femtosecond LIPSS generation at mid-IR frequencies in Ge.

Experimental Setup: The details of experimental setup are described in a previous paper by Poole et. al. [3]. LIPSS formation was studied using 800, 1900 and 3600 nm femtosecond laser pulses at 45 degree angle of incidence with p-polarized light. The mid IR wavelengths were generated by two separate OPA's which are BBO (1900 nm) and KTA (3600 nm) based, and are pumped by Ti:Sapphire based regenerative amplifiers producing 3 mJ TEM00 pulses @ 800 nm with pulsewidth of 60 fs. The laser modes and focal spots were characterized with mid IR cameras, and damage spots were studied with optical microscopes and scanning electron microscopes.

Results and discussion: After irradiation with mid-IR femtosecond laser pulses, both LSFLs and HSFLs were formed on germanium when the laser fluence was above the damage threshold at various pulse numbers (3 – 10,000 shots). This was determined by imaging the damage spots using atomic force microscopy, scanning electron microscopy, and white light interferometry (Wyco Profiler). The LSFLs were observed in the center of the laser spot area with periodicity $\Lambda/\lambda$ = 0.47–0.61, groove depth from 50 – 70 nm and the orientation perpendicular to the laser beam polarization. The HSFLs were observed at the periphery of the laser spot with periodicity $\Lambda/\lambda$ = 0.11–0.17 and the orientation parallel to the laser beam polarization. At slightly higher fluence than damage threshold (1,000 pulses), HSFL tend to form parallel to laser polarization direction; whereas, at ~4 J/cm$^2$, LSFL's form at the central region with orientation perpendicular to laser polarization. This type of LSFL formation is widely accepted to be due to phase matching between the k-vector of surface-bound electromagnetic wave (surface plasmon polaritons or SPPs) and that of the incident laser light [4]. Numerical simulations based on COMSOL multiphysics package showed 'resonant' enhancement of magnetic field for p-polarized incident light at $\lambda$=3600 nm, 45 degree AOI when simulated Ge surface LSFL period matched the LSFL period observed during experiments. Electron plasma densities are estimated during LIPSS formation assuming a Drude like dielectric function. Effects of forward/backward propagating SPPs, reduction of critical plasma density due to longer wavelength, groove profile, and surface structuring by previous pulses will also be presented.

*Acknowledgement: This work was supported by the Air Force Office of Scientific Research, USA under grant no. # AFPSR-FA9550-12-1-0454.*

References:

[1] W. Han et. al. Optics Express, Vol 21, Issue 13, pp. 15505-15513 (2013).

[2] R. Malik, et. al. Appl. Phys., A Mater. Sci. Process. 113, 127–133 (2013).

[3] Poole et. al. Optics Express, Vol. 21, Issue 22, pp. 26341-26351 (2013).

[4] M. Huang, et. al. Acs Nano 3, 4062–4070 (2009).

***Keywords:** fundamental mechanism, LIPSS, femtosecond laser machining, LFSL, HFSL, Mid-ir laser damage, femtosecond laser matter interaction, surface plasmon*

# Multiple wavelengths initiation and growth of laser-induced damage in fused silica in the nanosecond regime

**Maxime Chambonneau, Margaux Chanal,** Commissariat à l'Énergie Atomique (France); **Guillaume Duchateau,** Univ. Bordeaux 1 (France); **Pierre Grua,** Commissariat à l'Énergie Atomique (France); **Jean-Yves Natoli,** Institut Fresnel (France); **Jean-Luc Rullier, Laurent Lamaignère,** Commissariat à l'Énergie Atomique (France)

**ABSTRACT TEXT:** Laser-induced damage (LID) phenomenon is one of the key parameters for the success of high-power laser facilities such as the Laser MégaJoule (France). On this facility, the nanosecond laser beams at 1053 nm (1ω) are converted in frequency at 351 nm (3ω) by means of non-linear crystals. The downstream focusing gratings are then simultaneously irradiated at several wavelengths. In this particular multiple wavelengths configuration, both LID initiation and growth in fused silica components could be different compared with the single wavelength cases. In our study, a significant increase in damage densities is experimentally measured and expressed as a function of the 1ω and 3ω fluences. These results suggest a coupling between the ultraviolet and the infrared wavelengths. We propose a theoretical approach based on defect-assisted absorption that is in good agreement with the experimental one. Previous studies show that LID growth phenomenon is amplified in such a multiple wavelengths configuration. Here we express both the probability of growth and also the growth coefficient as two functions of the 1ω and 3ω fluences.

***Keywords:*** *laser induced damage, silica, multiple wavelengths, 355NM 1064nm, nanosecond, initiation, growth*

## 9237-67, SESSION PS2

# Dynamics of electron-plasma density induced by ultra-short laser pulses in wide-band-gap solids

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

**SPEAKER BIOGRAPHY:** Dr. Vitaly Gruzdev received his Ph. D. in optics from S. I. Vavilov State Optical Institute in St. Petersburg, Russia in 2000. He has been working in the fields of laser-induced damage, high-power laser-solid interactions, and nonlinear propagation since 1992. In 1994 he presented the first talk at Boulder Damage Symposium (now Laser Damage Symposium). In 2001 – 2003 he conducted research at the group of Professor Dr. D. von der Linde (University of Duisburg-Essen, Germany). Now he is with the Center for Ultra-fast Ultra-intense Lasers of Department of Mechanical and Aerospace Engineering, University of Missouri, USA.

**ABSTRACT TEXT:** The commonly accepted concept of laser-induced ionization by ultrashort laser pulses [1] considers significant contribution from impact ionization seeded by conduction-band electrons. The seed electrons are assumed to be generated by multiphoton ionization via simultaneous absorption of N photons. This concept implies that time profile of the photo-ionization follows profile of N-th order of laser intensity while electron density increases monotonously throughout laser pulse [1]. By simulating dependence of density of conduction-band electrons on peak laser irradiance in time domain, we demonstrate that dynamics of electron-plasma generation can be more complicated and can exhibit certain specific features. Our model employs single rate equation with contributions from the photo-ionization (described by the Keldysh formula in one case and by a cosine-band formula in the other case) and from the avalanche ionization (described by the Drude model [2]). Electron relaxation is neglected. Material parameters correspond to alkali halides and are taken from published data [3]. Obtained results clearly demonstrate that conduction-band electron density exhibits three different regimes of time variations depending on peak laser intensity and pulse duration. The regimes and their special features are associated with competition between the avalanche ionization and the photo-ionization. They are clearly identified from density scaling with peak laser irradiance. Weak-avalanche regime is driven by the photo-ionization that provides monotonous increase of conduction-band electron density with laser irradiance followed by plateaus. Each plateau corresponds to Keldysh-type singularity of the photo-ionization rate due to laser-driven modifications of band gap. Moderate-avalanche regime exhibits very complicated dynamics. It results from competition between avalanche ionization and photo-ionization which rates are similar. In this case, the avalanche ionization rate can form strong peaks delayed by few hundreds of femtoseconds from peak laser irradiance. Finally, strong-avalanche regime is associated with total domination of the impact ionization over the photo-ionization and reproduces the traditional dynamics of laser-induced ionization. We compare obtained results with available experimental data on laser-induced electron dynamics in transparent solids to figure out useful approaches for experimental identification of dominating ionization mechanism.

REFERENCES

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

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

[3] Sirdeshmukh D. B., Sirdeshmukh L., Subhadra K. G.Alkali Halides: A Handbook of Physical Properties. Berlin: Springer-Verlag (2001).

***Keywords:*** *laser damage, laser induced ionization, photo-ionization, avalanche ionization, wide-band-gap materials, femtosecond laser material interations*

## NOTES

# NOTES

# Tuesday AM • 16 September

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

**7:50 am to 8:20 am** **Poster Placement at NIST**
Poster authors for the Tuesday poster session are to set up their posters at this time.

## 8:20 am to 9:50 am • SESSION 5

## Thin Films I

Session Chairs: **James E. Andrew,** AWE plc (United Kingdom);
**Joseph A. Menapace,** Lawrence Livermore National Lab. (USA)

8:20 am: **Large-aperture plasma-ion-assisted coatings for femtosecond-pulsed laser systems** *(Keynote Presentation)*, James B. Oliver, Jake Bromage, Christopher Smith, Daniel Sadowski, Univ. of Rochester (USA) . . . . . . . . . . . . . . . . . [9237-15]

8:50 am: **Ultrafast optical breakdown of multilayer thin-films at kHz and MHz repetition rates: a direct comparison**, Ivan B. Angelov, Max-Planck-Institut für Quantenoptik (Germany); Michael K. Trubetskov, Max-Planck-Institut für Quantenoptik (Germany) and Moscow State Univ. (Russian Federation); Vladislav S. Yakovlev, Max-Planck-Institut für Quantenoptik (Germany) and Ludwig-Maximilians-Univ. München (Germany); Olga Razskazovskaya, Max-Planck-Institut für Quantenoptik (Germany); Martin Gorjan, Max-Planck-Institut für Quantenoptik (Germany) and Ludwig-Maximilians-Univ. München (Germany); Helena G. Barros, Ludwig-Maximilians-Univ. München (Germany); Ferenc Krausz, Max-Planck-Institut für Quantenoptik (Germany) and Ludwig-Maximilians-Univ. München (Germany); Vladimir Prevak, Ludwig-Maximilians-Univ. München (Germany) and UltraFast Innovations GmbH (Germany) . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . [9237-16]

9:10 am: **UV to IR laser damage of magnetron sputtering films submitted to multiple sub-picosecond pulses**, Dam-Be L. Douti, Laurent Gallais, Christophe Hecquet, Thomas Begou, Mireille Commandré, Institut Fresnel (France) . . . . . . . . . . . . . . . . . [9237-17]

9:30 am: **Thin films characterizations to design high-reflective coatings for ultrafast high-power laser systems**, Adrien Hervy, Sagem SA (France) and Aix-Marseille Univ. (France) and Ecole Polytechnique (France); Laurent Gallais, Aix-Marseille Univ. (France); Daniel Mouricaud, REOSC (France); Gilles Chériaux, Ecole Polytechnique (France); Olivier P. Utéza, Raphael G. C. R. Clady, Marc L. Sentis, Aix-Marseille Univ. (France); Antoine Freneaux, Ecole Polytechnique (France) . . . . . [9237-18]

## 10:00 am to 10:40 am • Tuesday Poster Overview

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

## 10:40 am to 11:40 am • Poster Viewing and Refreshment Break

## 11:40 am to 1:00 pm • SESSION 6

# Thin Films II

Session Chairs: **Jérôme Néauport,** Commissariat à l'Énergie Atomique (France); **Detlev Ristau,** Laser Zentrum Hannover e.V. (Germany)

11:40 am: **Research on thin films with high laser-induced damage threshold deposited by atomic layer deposition**, Yaowei Wei, Chengdu Fine Optical Engineering Research Ctr. (China). . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . [9237-19]

12:00 pm: **Nonlinear behavior and damage of dispersive multilayer optical coatings induced by two-photon absorption**, Olga Razskazovskaya, Tran Trung Luu, Michael K. Trubetskov, Eleftherios Goulielmakis, Max-Planck-Institut für Quantenoptik (Germany); Ferenc Krausz, Max-Planck-Institut für Quantenoptik (Germany) and Ludwig-Maximilians-Univ. München (Germany); Vladimir Pervak, Ludwig-Maximilians-Univ. München (Germany). . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . [9237-20]

12:20 pm: **Design concepts for stable AR coatings on UV frequency conversion crystals**, Lars O. Jensen, Marius A. Mrohs, Stefan Günster, Detlev Ristau, Laser Zentrum Hannover e.V. (Germany). . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . [9237-21]

12:40 pm: **1064nm Fabry Perot Transmission Filter Laser Damage Competition**, Christopher J. Stolz, Lawrence Livermore National Lab. (USA); Mark Caputo, Andrew J. Griffin, Michael D. Thomas, Spica Technologies, Inc. (USA) . . . . . . . . . . . [9237-22]

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

## 1:00 pm to 2:20 pm • Lunch Break

## 9237-15, SESSION 5

# Large-aperture plasma-ion-assisted coatings for femtosecond-pulsed laser systems *(Keynote Presentation)*

**James B. Oliver, Jake Bromage, Christopher Smith, Daniel Sadowski,**
Univ. of Rochester (United States)

**ABSTRACT TEXT:** Large-aperture coatings for femtosecond-pulsed laser systems are currently needed for projects such as the Multi-Terawatt optical parametric amplifier line (MTW OPAL) project at the University of Rochester's Laboratory for Laser Energetics, the Extreme Light Infrastructure, and the Apollon Laser System. A plasma-assisted electron-beam evaporation process that is scalable to larger apertures has been demonstrated on 300-mm substrates for deposition of high-laser-damage-threshold coatings. These coatings are for a 15-fs optical parametric chirped-pulse–amplification (OPCPA) laser system having a spectral bandwidth of 810 to 1010 nm. Coating materials and designs must be selected to yield high laser-damage thresholds, and spectral phase is spatially controlled to ensure the preservation of the temporal pulse shape. Deposition nonuniformity of <0.10% has been demonstrated without high spatial frequencies in the reflected phase of the coating. Performance of an all-dielectric solution for a 45? incidence s-polarized reflector includes R > 99.5%, a laser-damage threshold of >0.7 $J/cm^2$ (coating design centered at 800 nm and tested with a 59-fs pulse), and a low-order group-delay dispersion <50 $fs^2$.

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 paper.

## 9237-16, SESSION 5

# Ultrafast optical breakdown of multilayer thin-films at kHz and MHz repetition rates: a direct comparison

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

**ABSTRACT TEXT:** We report on the experimental and theoretical study of optical breakdown induced in multilayer thin-films by ultrashort pulses at kHz and MHz repetition rates, while keeping all other parameters similar. Two distinct band gap dependencies are obtained and compared.

The MHz-rate measurements were performed using a mode-locked Yb:YAG thin-disk oscillator operating at 1030 nm and generating 1 ps, 5 µJ pulses at 11.5 MHz repetition rate. The resulting maximal average power was equal to 56 W. The kHz-rate measurements were carried out with pulses coming out of an Yb:YAG regenerative amplifier operating at 1030nm and at 5kHz repetition rate. It delivered 1.4ps, multi mJ pulses, hence only a small fraction of the available pulse energy was sufficient to perform the damage threshold measurements. In both cases, the laser beam was focused on the sample down to a spot with diameter of 25 µm measured at level 1/e2 of the peak intensity.

The investigated samples were coatings composed of $TiO_2$, $Ta_2O_5$, $HfO_2$, or $Al_2O_3$ as high-index material and $SiO_2$ as low-index material. Each measurement spot was illuminated with a particular fluence for a certain amount of time, during which the scattered light from the sample was recorded. The fluence was then increased and the same spot was illuminated for the same period of time. That procedure was repeated until scattered light increased rapidly, indicating damage.

To the best of our knowledge, we show the first direct comparison of ultrafast optical breakdown in multilayer thin-films at kHz and at MHz repetition rates. We obtained linear band gap dependencies in both regimes. However, the slope of the band gap dependence obtained at kHz rate was steeper and crossed the abcissa at a higher value than its MHz counterpart.

***Keywords:*** *laser induced damage threshold, ultrashort pulses, multilayer thin films, MHz repetition rate*

# 9237-17, SESSION 5

# UV to IR laser damage of magnetron sputtering films submitted to multiple sub-picosecond pulses

**Dam-Be L. Douti, Laurent Gallais, Christophe Hecquet, Thomas Begou,**
Mireille Commandré, Institut Fresnel (France)

**ABSTRACT TEXT:** Sputtering techniques are known to produce extremely dense, smooth, stoichiometric, and amorphous layers that are very suitable for laser applications. In the last 10 years, the laser damage resistance of films made by Ion Beam Sputtering has been particularly investigated in the femtosecond range and NIR wavelength. Under such irradiation conditions, the damage process is a result of electronic excitation and in the case of single pulse irradiation it was shown that the laser damage resistance was directly related to the bandgap of the material and similar LIDT compared to bulk materials could be achieved. In the case of multiple irradiation however a decrease of threshold with the number of applied pulses is observed, which is related to the implications of native and photo-induced electronic defects in the films.

In this work we have studied single layers made by Plasma Assisted Magnetron Sputtering at the Fresnel Institute. Single layers of $Nb_2O_5$, $SiO_2$ and $HfO_2$ (including a low $SiO_2$ content) have been deposited on fused silica substrates. The coatings have been characterized by spectrophotometry in order to determine their optical properties and then the laser-induced damage threshold have been measured. These last measurements have been made at 1030nm, 515nm and 343nm with 500fs pulses. S-on1 test procedures were applied with S in the range 1 to 100000, with low repetition rates (10 to 1000Hz).

The results are discussed in view of existing empirical or theoretical models that describe LIDT dependence with the number of applied pulses, and compared to other high quality coatings made by different deposition techniques.

***Keywords:*** *femtosecond laser damage, thin films, magnetron sputtering*

## 9237-18, SESSION 5

# Thin films characterizations to design high-reflective coatings for ultrafast high-power laser systems

**Adrien Hervy,** Sagem SA (France) and Aix-Marseille Univ. (France) and Ecole Polytechnique (France); **Laurent Gallais,** Aix-Marseille Univ. (France); **Daniel Mouricaud,** REOSC (France); **Gilles Chériaux,** Ecole Polytechnique (France); **Olivier P. Utéza, Raphael G. C. R. Clady, Marc L. Sentis,** Aix-Marseille Univ. (France); **Antoine Freneaux,** Ecole Polytechnique (France)

**SPEAKER BIOGRAPHY:** Material Engineer since 2011, studying now his 3rd year-PhD on the development of multi dielectrics coatings for femtosecond lasers.

**ABSTRACT TEXT:** The peak power handling capability of ultra-short pulse lasers is main concern for new facilities, like those for the European ELI project. Indeed, these last generation lasers require large (Ø 1m) and resistant optical components with optimized thin-films coatings. In this context and in the framework of a joint project, LOA, Fresnel Institute and Reosc are working together to develop high performance coatings for ultra-short pulse laser applications.

The damage of dielectric materials in the femtosecond regime can be understood as a result of electronic processes. The electronic structure of materials is then particularly significant. As a consequence of these processes it is possible to increase the Laser-Induced Damage Threshold (LIDT) by adjusting the Electric Field Intensity (EFI) distribution in the stack of High-Reflective (HR) coatings. LIDT of many currently used oxides, often deposited by Ion-Beam Sputtering (IBS), are well known and a correlation with the band gap energy was shown.

With these results we decided to study the LIDT of oxides-made stacks with Electron Beam Deposition (EBD) processes compatible with 1-meter class optics. Samples were coated at Reosc. The quality of the coating is determined by adhesion tests, spectral controls (reflectance and transmittance), absorption measurements (by photothermal deflection at 511nm) and stress calculations from Wave-Front Error (WFE) measurements. Single layers sample of various oxide materials and high-reflective coatings made with these materials have been investigated.

Samples were irradiated at Fresnel Institute by a 500fs KYW:Yb pulsed laser (AMPLITUDES SYSTEMES S-Pulse HP) delivering 1mJ at 1030nm, at the LOA by a 40fs (resp. 150ps) Ti:Sa pulsed laser delivering 1.5mJ (resp. 3mJ) in a gaussian spectrum 20nm FHWM centered at 790nm and at the LP3 by a 11fs Ti:Sa pulsed laser (ASUR laser infrastructure) delivering 50µJ in a gaussian spectrum 130nm FHWM centered at 790nm. Irradiated areas are optically inspected under a Nomarski microscope and any visible modification of the surface is considered as damage. A statically distribution of the damages gives the LIDT as the mean of the highest fluency class undamaged and the lowest fluency class damaged. Single pulse and multi pulses tests in air and in vacuum were performed.

We present the tests results of the intrinsic materials, the evolution of the LIDT with the increase of pulse number and the conditioning effect we observed by multi-pulses irradiation compared to the single pulse LIDT. We also study the electric field intensity distribution inside the layers and discuss about the relationship between the LIDT of a multilayer dielectric and the LIDT intrinsic materials composing the stack.

***Keywords:*** *Laser-induced damage threshold, multilayers, femtosecond, electric field enhancement, single layer, dielectrics, oxides, electron-beam deposition*

# Research on thin films with high laser-induced damage threshold deposited by atomic layer deposition

**Yaowei Wei,** Chengdu Fine Optical Engineering Research Ctr. (China)

**ABSTRACT TEXT:** Process parameters affected atomic layer deposition (ALD) film properties. In this paper, different process parameters such as deposition temperature, precursor type and pulse duration were adopted in ALD process to deposit laser thin film. Laser induced damage threshold (LIDT) as a key property for laser thin film was analyzed. Reasons for film damage were also investigated. Finally, the LIDTs for laser thin films deposited by improved process parameters reached a higher level. Especially, for the $Al_2O_3$ thin film, the LIDT reached 40 J/cm$^2$. The $HfO_2/Al_2O_3$ anti-reflector reached 18 J/cm$^2$. Which were the highest for ALD single and anti-reflect film as reported. In addition, the LIDT can be improved by further changing the process parameters. All results show ALD was an effective film deposition method for high power laser system.

***Keywords:*** *atomic layer deposition, laser induced damage threshold, optical properties*

## 9237-20, SESSION 6

# Nonlinear behavior and damage of dispersive multilayer optical coatings induced by two-photon absorption

**Olga Razskazovskaya, Tran Trung Luu, Michael K. Trubetskov, Eleftherios Goulielmakis,** Max-Planck-Institut für Quantenoptik (Germany); **Ferenc Krausz,** Max-Planck-Institut für Quantenoptik (Germany) and Ludwig-Maximilians-Univ. München (Germany); **Vladimir Pervak,** Ludwig-Maximilians-Univ. München (Germany)

Laser damage in the femtosecond domain is governed by multiphoton absorption (MPA) and subsequent impact ionization that causes ablation of coating materials [1]. Nowadays it is acknowledged, that the order of the triggered MPA process is of high importance. The MPA orders higher than 2nd have relatively low ionization rates, what is a prerequisite for high damage thresholds. The ionization rate increases by several orders of magnitude upon transition from 3rd to 2nd order of MPA, consequently damage threshold noticeably drops [2]. Therefore, appearance of two-photon absorption (2PA) puts significant limitation on coating performance and is preferably avoided. Here we report on observation of non-linear behavior and subsequent damage of $Ta_2O_5/SiO_2$ and $HfO_2/SiO_2$ dispersive dielectric mirrors (DMs), caused by the appearance of 2PA. We describe the model, which simulates observed behavior and is applicable to the determination of the coefficient of 2PA, ß. With the knowledge of ß it is feasible to design coatings where 2PA is taken into account.

We studied series of DMs produced from $Ta_2O_5/SiO_2$ or $HfO_2/SiO_2$ material pairs. The mirrors were tested at 400 nm wavelength with ~40 fs and ~28 fs pulses. DMs of the series were designed to introduce different amounts of negative group delay dispersion (GDD) ranging from -50 fs2 to -150 fs2 through the exploitation of so-called “penetration effect” [3]. It was recorded that in the range of peak intensities from ~ 2*109 W/cm$^2$ to ~ 5*1011 W/cm$^2$ the mirrors demonstrate intensity dependent reflectivity. Particularly, at high intensities the reflectivity of the mirrors is lower in comparison to the reflectivity at low intensities. The severity of the effect is correlated with implemented material pair and absolute value of introduced GDD. Despite the drop, the mirrors stay undamaged and effect is “reversible”, i.e., if the intensity is decreased, the reflectivity rolls back to the previously recorded higher values. It is worth noticing, that quarter-wave high reflectors (QWHR), produced from the same material pairs for the purposes of comparison, did not show any noticeable intensity dependent behavior of the reflectivity within our range of intensities.

On the intensities in the range from 7*1011 W/cm$^2$ to 2*1012 W/cm$^2$ (fluence from 0.02 J/cm$^2$ to 0.05 J/cm$^2$) the damage occurs. Both mirror types, DMs and QWHRs, are damaged at the same levels of intensity. Therefore, it suggests that despite the observed behavior, the damage is still determined by the intrinsic properties of coating materials themselves. The morphology of the damage is similar to those typically observed for the femtosecond MPA induced damages [1].

Our thermal tests revealed, that the surface of DMs warms up significantly more than the surface of QWHRs. This observation, supported by additional data has driven us to conclusion that 2PA is the main cause of observed behavior. Based on our data, we have developed a model allowing us to estimate the coefficient of 2PA, ß. We simulated 2PA in multilayer mirrors as an induced extinction coefficient proportional to the intensity of the electric field component. Due to the fact that the band gap of $SiO_2$ is significantly wider than the band gap of $Ta_2O_5$, we considered the induced extinction coefficient of the latter only. Solving the system of Maxwell equations describing interaction of light with the multilayer mirror, that has been reduced to a boundary-value problem for a system of two non-linear ordinary differential equations, we were able to fit the measured data and extract the value of [m$^2$/V$^2$]. Taking into account 2PA effect in the DM synthesis procedures, we developed a new series of DM designs. These new designs demonstrated significant improvement of averaged reflectivity being much less dependent on the incident light intensity. With respect to the thermal performance, new DMs demonstrated much lower increase of surface temperatures. In general, experimental data confirm validity of the developed model and indicate significant improvement of DM performance at high intensities.

REFERENCES

[1]. B. C. Stuart, M. Feit, S. Herman, A. M. Rubenchik, B. W. Shore, and M. D. Perry, “Nanosecond-to-femtosecond laser-induced breakdown in dielectrics”, Phys. Rev. B, 53, 1759-1761 (1996).

[2]. M. Jupé, L. Jensen, A. Melninkaitis, V. Sirutkaitis, and D. Ristau, “Calculation and experimental demonstration of multi-photon absorption governing fs laser-induced damage in titania”, Opt. Express 17, 12269 (2009).[3]. R. Szipocs and K. Ferencz, C. Spielmann and F. Krausz, “Chirped multilayer coatings for broadband dispersion control in femtosecond lasers”, Opt.Lett. 19, 201-203 (1994).

***Keywords:*** *dispersive mirrors, two photon absorption, Ta205 thin films, Hf02 thin films*

## 9237-21, SESSION 6

# Design concepts for stable AR coatings on UV frequency conversion crystals

**Lars O. Jensen, Marius A. Mrohs, Stefan Günster, Detlev Ristau,**
Laser Zentrum Hannover e.V. (Germany)

**SPEAKER BIOGRAPHY:** Lars Jensen received a Diploma and a PhD in physics from the Leibniz University of Hannover. Since 2005 he has worked as part of the scientific staff of the characterization group of the department with a main focus on laser damage mechanisms in dielectric coatings and optical losses in optical materials and coatings. His work covers the spectral ranges from the near IR to the deep UV. In 2011 he was appointed group leader of this research group and has since been responsible for a number of national and international research projects and scientific collaborations. One main focus of the group is the development of highly sensitive characterization tools of optical thin films for laser applications.

**ABSTRACT TEXT:** In an effort to develop next generation UV frequency conversion systems, several steps have to be considered. One aspect crucial for the final conversion stage is a durable coating which shows high resistance for all incident wavelengths. In the regular case, two wavelengths are involved in the generation of the fourth harmonic of the Nd:YAG laser. For a conversion process involving the wavelengths 532nm and 266nm, model AR-coating designs have been developed and tested including $SiO_2$, $Al_2O_3$, and $HfO_2$ deposited in an IBS process. Refractive indices, layer count and interfaces have been varied in order to find an optimized configuration for stable laser operation.

During the testing, test procedures have been applied that involve both wavelengths at the same time. As in the application, the exit surface is exposed to visible and UV laser radiation, a qualifying test should account for these conditions as well.

***Keywords:*** *dual wavelength damage testing, AR coating, crystal coatings*

## 9237-22, SESSION 6

# 1064nm Fabry Perot Transmission Filter Laser Damage Competition

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

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

**ABSTRACT TEXT:** Narrow bandwidth Fabry Perot transmission filters are used in the telecommunications industry and because of their interference properties, extremely high electric fields occur at peak transmission. For this study the filters met a minimum transmission of 75% and were spectrally centered within an angle tuning range of 10-30 degrees. The participants selected the coating materials, design, and deposition method. Laser damage testing was performed using a raster scan method with a 5 ns pulse length on a single testing facility to facilitate a direct comparison among the participants. Details of the deposition processes, cleaning method, coating materials, layer count, and spectral results are shared. (LLNL-ABS-652732)

# Tuesday PM • 16 September

## 2:20 pm to 3:40 pm • SESSION 7

## Thin Films III

Session Chairs: **Vitaly E. Gruzdev,** Univ. of Missouri-Columbia (USA);
**Takahisa Jitsuno,** Osaka Univ. (Japan)

2:20 pm: **Characterization of $HfO_2$-$SiO_2$ rugate multilayers deposited by ion beam sputtering**, Roman Rauhut, Kristina Nehls, Lars Mechold, Laser Components GmbH (Germany). . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . [9237-23]

2:40 pm: **Coupling effect of subsurface defect and coating layer on the laser-induced damage threshold of dielectric coating**, Meiping Zhu, Kui Yi, Hongji Qi, Hu Wang, Wei Sun, Zhenkun Yu, Yuanan Zhao, Jianda Shao, Shanghai Institute of Optics and Fine Mechanics (China) . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . [9237-24]

3:00 pm: **Interface absorption versus film absorption in HfO2/SiO2 thin-film pairs in the near-ultraviolet and relation to pulsed-laser damage**, Semyon Papernov, Alexei A. Kozlov, James B. Oliver, Univ. of Rochester (USA) . . . . . . . . . . . . . . . . . . . [9237-25]

3:20 pm: **Defect-initiated dielectric breakdown by nanosecond laser pulses in optical thin films studied by a single-shot laser damage test**, Yejia Xu, Luke A. Emmert, The Univ. of New Mexico (USA); Dinesh Patel, Carmen S. Menoni, Colorado State Univ. (USA); Wolfgang Rudolph, The Univ. of New Mexico (USA) . . . . . . . . . . . [9237-26]

## 3:40 pm to 4:30 pm • Poster Viewing and Refreshment Break

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

## 4:30 pm to 5:50 pm • SESSION 8

## Fundamental Mechanisms I

Session Chairs: **Jonathan W. Arenberg,** Northrop Grumman Aerospace Systems (USA);
**Carmen S. Menoni,** Colorado State Univ. (USA)

4:30 pm: **Silica laser damage mechanisms, precursors, and their mitigation** *(Keynote Presentation)*, Jeffrey D. Bude, Lawrence Livermore National Lab. (USA). . [9237-27]

5:10 pm: **Microstructure variation of intrinsic defects and voids in fused silica after exposure to low-fluence laser pulse at 355nm**, Chunhong Li, Xin Ju, Univ. of Science and Technology Beijing (China) . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . [9237-28]

5:30 pm: **The effects of subsurface defects on laser damage performance for fused silica optics**, Hongjie Liu, Jin Huang, Fengrui Wang, Xinda Zhou, Xiaodong Jiang, China Academy of Engineering Physics (China) . . . . . . . . . . . . . . . . . . . . . . . . . . . . [9237-29]

## 5:50 pm to 6:00 pm • Closing Remarks

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

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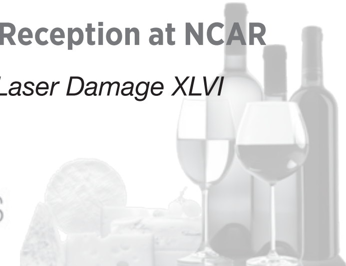

# Characterization of $HfO_2$-$SiO_2$ rugate multilayers deposited by ion beam sputtering

**Roman Rauhut, Kristina Nehls, Lars Mechold,** Laser Components GmbH (Germany)

Ion beam sputtering is a deposition technique well known for its very dense and damage-resistant coatings, due to high kinetic energies of the sputtered atoms. While different layers are deposited homogeneously, abrupt interfaces between the materials are the most susceptible part of the stack.

Therefore, we aim for an improvement of the laser damage threshold by sputtering material mixtures. Using a target with high and low-index material next to each other, arbitrary refractive indices can be implemented by adjusting the target axis. Our material system of choice is $HfO_2$/$SiO_2$, already yielding good LIDT results with non-rugate coatings.

A comparison in terms of laser damage threshold between these designs and varying refractive index coatings will be shown.

## 9237-24, SESSION 7

# Coupling effect of subsurface defect and coating layer on the laser-induced damage threshold of dielectric coating

**Meiping Zhu, Kui Yi, Hongji Qi, Hu Wang, Wei Sun, Zhenkun Yu, Yuanan Zhao, Jianda Shao,** Shanghai Institute of Optics and Fine Mechanics (China)

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

**ABSTRACT TEXT:** Many reported works have demonstrated that the subsurface defects will decrease the laser induced damage threshold (LIDT) of dielectric coating. However, the mechanism by which the subsurface defect affect the laser induced damage performance of coating is still not well elucidated. To illustrate the coupling effects at film-substrate interface, the LIDT and damage morphology of coatings prepared by both E-beam evaporation and Sol-Gel process have been characterized and compared. Detailed results will be shown in the report.

***Keywords:*** *Laser induced damage threshold, damage morphology, subsurface defect, coupling effects*

## 9237-25, SESSION 7

# Interface absorption versus film absorption in $HfO_2/SiO_2$ thin-film pairs in the near-ultraviolet and relation to pulsed-laser damage

Se**myon Papernov, Alexei A. Kozlov, James B. Oliver,** Univ. of Rochester (United States)

**ABSTRACT TEXT:** Near-ultraviolet absorption in hafnium oxide and silica oxide thin-film-material pairs in a configuration strongly departing from the regular quarter-wave-thickness approach was studied with the goal to separate film and interfacial contributions to absorption. For this purpose, narrow layers of high-index material ($HfO_2$) were incorporated inside a thick layer of low-index material ($SiO_2$), and vice versa. Absorption in the electron-beam–deposited films was measured using photothermal heterodyne imaging. Comparison of absorption, normalized to internal E-field distribution, for different film-pair designs makes it possible to estimate the partial film/interface contribution. Relevance of obtained data to the thin-film pulsed-laser damage was verified by conducting laser-induced–damage measurements and damage-morphology characterization.

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

***Keywords:*** *absorption, $Hf0_2$ and $Si0_2$ thin films, laser damage*

# Defect-initiated dielectric breakdown by nanosecond laser pulses in optical thin films studied by a single-shot laser damage test

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

**ABSTRACT TEXT:** The recently developed single-shot nanosecond damage technique [1] exhibits several advantages over traditional test methodologies – (i) it requires far fewer laser shots and subsequently sample surface, (ii) it provides spatial resolution, and (iii) the actual damage fluence and intensity are measured rather than just producing a "yes" or "no" result. We apply this technique to characterize thin film samples where damage is typically initiated by defects.

The technique works by identifying dielectric breakdown by monitoring the transmission and scatter of the laser pulse (1064 nm, 7.3 ns FWHM) with fast photodetectors. The moment of dielectric breakdown is identified by a strong spike in the scattering signal. This onset of scatter is often preceded by a small drop (~10%) in transmission and always followed by a strong drop (~90%) in transmission. The point of damage initiation within the beam profile (Gaussian) is identified by an in situ microscope that records an image from the laser light scattered off the growing laser-induced plasma. With these data we calculate the intensity and accumulated fluence at the moment of dielectric breakdown at the probed sample site. This 1-on-1 measurement is repeated by raster scanning the excitation pulse across the sample region of interest. The pulse fluence is chosen so as to initiate breakdown with each shot.

The result is a spatial map of damage fluences and intensities. After appropriate binning, the film can be characterized by defect (area) density as a function of the damage parameter (fluence and intensity) without assuming a defect model[2]. This new information can be used to compare films and explore the physical origin of defects.

REFERENCES

1. Y. Xu, L. A. Emmert, D. Patel, C. S. Menoni, and W. Rudolph, "1-on-1 pulse nanosecond laser-damage studies of thin films using time-resolved transmission," XLV Annual Symposium on Optical Materials for High Power Lasers, Boulder, CO, USA, September 22-25 (2013).
2. J.-Y. Natoli, L. Gallais, H. Akhouayri, and C. Amra, "Laser-Induced Damage of Materials in Bulk, Thin-Film, and Liquid Forms." Appl. Opt. 41, pp. 3156–3166 (2002).

***Keywords:*** *optical coatings, laser damage test, defect density, nanosecond pulse, damage precursor, dielectric breakdown*

## 9237-27, SESSION 8

# Silica laser damage mechanisms, precursors, and their mitigation *(Keynote Presentation)*

**Jeffrey D. Bude,** Lawrence Livermore National Lab. (United States)

**ABSTRACT TEXT:** We will review important optical damage precursors in silica up to UV fluences as high as 50J/cm$^2$ (3ns) along with studies of the damage mechanisms involved and processes to mitigate damage precursors. One key recent finding is that a variety of nominally transparent materials in trace quantities can act as surface damage precursors. We show that by minimizing the presence of precipitates during chemical processing, we can reduce damage density in silica at high fluence by more than 100 times while shifting the fluence onset of observable damage by about 7 J/cm$^2$.

This work was performed under the auspices of the U. S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344. LLNL-ABS-653732

## 9237-28, SESSION 8

# Microstructure variation of intrinsic defects and voids in fused silica after exposure to low-fluence laser pulse at 355nm

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

**SPEAKER BIOGRAPHY:** Dr. Chunhong Li obtained his Ph.D for a thesis on high power laser-induced damage in fused silica optics in 2011 from University of Science and Technology Beijing. His research interest was focused on the field of high power laser-induced damage in key optics such as fused silica and KDP/DKDP crystal optics. He also pay attention to the application of nuclear methods and synchrotron radiation methods in the study of laser damage mechanism.

**ABSTRACT TEXT:** This paper was designed to study the material stability of fused silica under low fluence laser irradiation (< 50 % Fth) in view of the structure variation of intrinsic defects and voids. The size and concentration variation of intrinsic defects and voids was successfully characterized by positron annihilation lifetime spectroscopy. The volume size of the vacancy clusters which is revealed by the second lifetime $\tau2$ and $\tau2$-$\tau b$ increases with the laser fluence. Particularly, the size of the vacancy clusters increased about 14.5 % after irradiated by pulsed 355 nm laser at F=14 $J/cm^2$ (50 % Fth). Results revealed that the void size calculated from the o-Ps lifetime $\tau3$ increase slightly with laser irradiation, while the voids concentration decreases sharply with laser fluence. Laser excited Raman spectroscopy was employed to characterize the angle change of the Si-O-Si bridging bond angle. Results suggested that the bond angle of the Si-O-Si bridging bond in bulk silica slightly reduced with the laser fluence. Pulsed UV Laser induced local densification, density non-uniformity and low degree of network polymerization in fused silica glass. Fracture of the Si-O-Si bridging bond induced by Laser photolysis process and the short range rearrange process of (Si-O)n membered rings induced by laser irradiation were suggested to be responsible for the microstructure variation of intrinsic defects and voids in bulk silica. The revealed data provide important information to study material stability and lifetime of fused silica optics for high power laser system.

***Keywords:*** *laser matter interaction, fused silica, intrinsic defects, microstructure variation, vacancy cluster, structure voids*

## 9237-29, SESSION 8

# The effects of subsurface defects on laser damage performance for fused silica optics

**Hongjie Liu, Jin Huang, Fengrui Wang, Xinda Zhou, Xiaodong Jiang,**
China Academy of Engineering Physics (China)

**ABSTRACT TEXT:** Highly absorptive contaminants and subsurface damage (SSD) are two main kinds of defects that are responsible for igniting laser damage of fused silica. These precursors decrease the laser-induced damage threshold by either high absorption of UV laser or reduction of the mechanical strength or enhancement of the local optical field. The understanding of damage phenomena requires a comprehensive way to detect defects as extensive as possible. Surface contaminations and SSD are detected by Time-of-Flight Secondary Ion Mass Spectrometry (TOF-SIMS) and Fluorescence microscopy respectively. Optical thermal absorption and laser induced damage performance of fused silica surface are also measured. We analyze the correlations existing between defects and laser induced damage. The results suggest that SSD and Ce element are mainly ignitor induced laser damage at present process technology of fused silica optics. It is interesting for comprehensive analysis of correlation between multi-factor defects and damage performance at the same time.

***Keywords:*** *contamination impurity, subsurface damage, optical thermal absorption, laser induced damage, fused silica optics*

# Tuesday Poster Viewing and Refreshment Break • Rooms 1 & 2

## Materials and Measurements

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

**Research on laser damage of final optics assembly on high-power laser facility**, Dongfeng Zhao, Shanghai Institute of Optics and Fine Mechanics (China) and Univ. of Chinese Academy of Sciences (China); Rong Wu II, Zunqi Lin, Jianqiang Zhu, Shanghai Institute of Optics and Fine Mechanics (China). . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . [9237-68]

**Development of an automated absorption measurement instrument (a "turn-key" system) for optical thin film coatings**, Jingtao Dong, Jian Chen, Zhouling Wu, ZC Optoelectronic Technologies, Ltd. (China) . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . [9237-70]

**Fabrication of long-period fiber gratings using focused 266nm laser irradiation without occurrence of the laser-induced damage**, Takuya Kiriyama, Yuta Kuroki, Yoshiki Kasahara, Yuki Tamura, Masaharu Nisioka, Hidehumi Hata, Haruki Nakagawa, Tomosumi Kamimura, Hisami Nishi, Osaka Institute of Technology (Japan) . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . [9237-72]

**Investigation of binary coating material mixtures using grazing incidence XUV-reflectometry**, Istvan Balasa, Laser Zentrum Hannover e.V. (Germany); Xavier Neiers, Lab. de Chimie Physique (France); Mathias Mende, LASEROPTIK GmbH (Germany); Lars O. Jensen, Detlev Ristau, Laser Zentrum Hannover e.V. (Germany) . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . [9237-73]

**Toward separation of bulk and interface defects: damage probability analysis of thin film coatings**, Linas Smalakys, Gintare Bataviciute, Egidijus Pupka, Andrius Melninkaitis, Vilnius Univ. (Lithuania) . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . [9237-74]

**Station for LIDT tests of optical components under cryogenic conditions**, Jindrich Oulehla, Josef Lazar, Institute of Scientific Instruments of the ASCR, v.v.i. (Czech Republic) . . . . . . . . . . [9237-75]

**Detection of the laser-damage onset in optical coatings by the photothermal-deflection method**, Katsuhiro Mikami, Osaka Univ. (Japan) and Univ. of Rochester (USA); Semyon Papernov, Univ. of Rochester (USA); Shinji Motokoshi, Osaka Univ. (Japan); Stephen D. Jacobs, Univ. of Rochester (USA); Takahisa Jitsuno, Osaka Univ. (Japan) . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . [9237-76]

**The microstructural origins of features observed in oxide films by third-harmonic microscopy**, Luke A. Emmert, Cristina Rodriguez, The Univ. of New Mexico (USA); Dinesh Patel, Drew D. Schiltz, Elzbieta Jankowska, Carmen S. Menoni, Colorado State Univ. (USA); Wolfgang Rudolph, The Univ. of New Mexico (USA) . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . [9237-77]

**An empirical investigation of the laser survivability curve: V**, Jonathan W. Arenberg, Northrop Grumman Aerospace Systems (USA); Wolfgang Riede, Deutsches Zentrum für Luft- und Raumfahrt e.V. (Germany); Jonathan H. Herringer, Arrow Thin Films, Inc. (USA) . . . . . . . . . [9237-78]

**Analysis of the laser damage characteristics of a production lot**, Jonathan W. Arenberg, Northrop Grumman Aerospace Systems (USA); Detlev Ristau, Lars O. Jensen, Laser Zentrum Hannover e.V. (Germany). . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . [9237-79]

**Study of laser-induced fatigue effects in synthetic fused silica in the UV**, Céline Gouldieff, Institut Fresnel (France) and Institut de Physique de Rennes (France); Frank R. Wagner, Jean-Yves Natoli, Institut Fresnel (France) . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . [9237-80]

**Controllable liquid spread speed in the groove using femtosecond laser**, Jiawen Li, Guoqiang Li, Yanlei Hu, Bing Xu, Jiaru Chu, Wenhao Huang, Univ. of Science and Technology of China (China). . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . [9237-81]

**Laser damage test-bench with ultrashort pulses down to 10 fs**, Olivier P. Utéza, Pierre Blandin, Raphael G. C. R. Clady, Nicolas Sanner, Marc L. Sentis, Lasers, Plasmas et Procédés Photoniques (France); Yu Li, Shen Yan Long, Northwest Institute of Nuclear Technology (China). . [9237-82]

**Development of an automated scanning white-light interferometer for optical coating dispersion measurements**, Matthew S. Kirchner, Greg Taft, Christopher S. Wood, Kapteyn-Murnane Labs., Inc. (USA) . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . [9237-91]

## Surfaces, Mirrors, and Contamination

**In-situ laser-induced contamination monitoring using long-distance microscopy**, Paul Wagner, Helmut B. Schröder, Wolfgang Riede, Deutsches Zentrum für Luft- und Raumfahrt e.V. (Germany) . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . [9237-83]

**Mechanisms of laser resist stripping without occurring the laser damage to Si wafer**, Yuta Kuroki, Takuya Kiriyama, Hirokoi Muraoka, Keita Kawasaki, Takuma Murakami, Hiroyuki Kuramae, Osaka Institute of Technology (Japan); Hideo Horibe, Osaka City Univ. (Japan); Tomosumi Kamimura, Osaka Institute of Technology (Japan) . . . . . . . . . . . . . . . . . . . . . . . . . . [9237-84]

**Ultraviolet laser damage tests of scratches repaired by carbon dioxide laser on fused silica optics**, Philippe Cormont, Sandy Cavaro, Commissariat à l'Énergie Atomique (France); Thomas Doualle, Institut Fresnel (France); Gael Gaborit, Commissariat à l'Énergie Atomique (France); Laurent Gallais, Institut Fresnel (France); Laurent Lamaignère, Jean-Luc Rullier, Commissariat à l'Énergie Atomique (France) . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . [9237-85]

**A study of ps-laser-induced-damage-threshold in hybrid metal-dielectric mirrors**, Vaclav Skoda, CRYTUR spol s.r.o. (Czech Republic); Jan Vanda, Institute of Physics of the ASCR, v.v.i. (Czech Republic) . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . [9237-86]

**Coming clean: understanding and mitigating optical contamination in advanced LIGO**, Kaitlin E. Gushwa, California Institute of Technology (USA); Calum I. Torrie, California Institute of Technology (USA) and Scottish Univ. Physics Alliance (United Kingdom) . . . . . . . . . . . . . . . . . . [9237-87]

**Laser-induced damage tests under multiple wavelength irradiation of ATLID TXA optics for ESA-Satellite Mission EarthCare**, Uwe Leinhos, MicroLiguids GmbH (Germany); Klaus Mann, Wilhelm Huettner, Julian Sudradjat, Laser-Lab. Göttingen e.V. (Germany); Georgios D. Tzeremes, European Space Agency (Netherlands). . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . [9237-88]

**Cleaning practices and facilities for the Nation Ignition Facility**, James A. Pryatel, Akima Infrastructure Services (USA); William H. Gourdin, Gerald S. Ruble, Susan C. Frieders, Lawrence Livermore National Lab. (USA) . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . [9237-89]

**Surface damage correction, and atomic level smoothing of optics by accelerated neural atom beam (ANAB) processing**, Michael Walsh, Kiet Chau, Sean Kirkpatrick, Richard Svrluga, Exogenesis Corp. (USA) . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . [9237-90]

# 9237-68, SESSION PS3

## Research on laser damage of final optics assembly on high-power laser facility

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**SPEAKER BIOGRAPHY:** Education: Sep.1992 ~ Jul. 1996 The No.1 Middle School of Yushan County, Jiangxi Province; Sep.1996 ~ Jul. 2000 Changchun University of Science and Technology Basic University Degree of Optoelectronic technology; Sep.2004~ Jul. 2007 Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Sciences, Master Degree of Optical Engineering. Work Experience: 2000.7Shanghai Institute of Optics and Fine Mechanics, Jiading, Shanghai; Major in high power laser technology, for example the final optical assembly design

**ABSTRACT TEXT:** The Shenguang-II Upgrade (SG-IIU) is an under-constructed high-power laser driver, with a 8-beam, 24KJ, 3ns, ultraviolet laser output energy in Shanghai Institute of Optics and Fine Mechanics, China. The function of Final Optics Assembly (FOA), one of the most important parts of SG-IIU facility, consists of :1) vacuum sealing to both the target chamber and the air, 2) frequency conversion from the 1ω to the 3ω light, 3) color separation, 4) focusing the whole beam to target surface, 5) beam sampling for 3ω energy diagnostics, 6) target debris shielding, and 7) keeping FOA dynamically inner-environment clean and the temperature stable. In order to improving laser damage resistance, simulation analysis have been done for on ghost images to the 4th order for 1ω, 2ω, 3ω, and for the antireflected light from the target surface. The optimization of the optics parameters has been investigated. The panels of ground glass scatter ghost laser around the FOA walls and the panels of architectural glass absorb the 1th order energy. And the appearance of smoothing fused silica surface defect and the effect of wiping off etching contamination are researched on HF-based etching processes under ultrasonic. And the experimental parameters are definite with SEM microscopy and atomic force microscopy to recode face appearance and with one pulse laser incidence to measure laser damage threshold. This presentation addresses the optical configuration of the FOA, the simulation analysis of ghost and the way of ground glasses absorbing energy and the result of laser damage resistance of fused silica on HF-based etching processes under ultrasonic. In May, experimental research of the FOA will plan to do on the one of beams SG-IIU facility.

***Keywords:*** *laser damage, fine optics assembly, high power laser, ultraviolet laser, HF-based etching, ultrasonic, surface defect*

## 9237-70, SESSION PS3

# Development of an automated absorption measurement instrument (a “turn-key” system) for optical thin film coatings

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

**ABSTRACT TEXT:** In this paper, we present the progress in the development of an automated measurement instrument for optical thin film coatings. Based on the laser-induced surface thermal lensing effect, the instrument shows a measurement sensitivity of absorbance down to 10 ppb, and it provides user-friendly operation of the whole absorption measurement process. Compared with a typical bench-top system, the instrument requires little special skills from the operators and is therefore more reliable and reproducible.

The specific applications of this instrument include measuring weak absorption, detecting local absorption defects, and monitoring laser-coating-interaction dynamics. The measurement results show that such a high sensitive automated instrument is an effective diagnostic tool for the optimization of optical thin film coatings with desired optical properties.

***Keywords:*** *weak absorption, optical thin film coatings, high sensitivity, photothermal effect, automated instrument, a turn key system*

## 9237-72, SESSION PS3

# Fabrication of long-period fiber gratings using focused 266nm laser irradiation without occurrence of the laser-induced damage

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**ABSTRACT TEXT:** Long period fiber gratings (LPFG) have been used in many applications such as passive optical devices for fiber-optic telecommunications, sensors for strain and temperature, and refractive index measurement. The ultraviolet (UV) laser irradiation is one candidate of the LPFG fabrication. However, an UV laser irradiation to fiber through the periodic metal mask restricts fabrication flexibility. In this study, fabrication of LPFG without the mask was investigated by using the scanning focused UV laser. The photosensitive optical fiber (THORLBAS-GF1) was placed on the focal point of laser beam. The beam scanning and shifting process was carried out 50 times. In the case of irradiation of focused 213nm laser with pulse width 8ns, the cladding of the optical fiber was damaged. In contrast, in the case of focused 266nm laser with pulse width 33ns, no damage was observed at the irradiated fiber. LPFG with a larger attenuation of 20dB was successfully fabricated in this study.

***Keywords:*** *long period fiber gratings, ultraviolet laser, laser irradiation, photosensitive optical fiber, laser induced*

## 9237-73, SESSION PS3

# Investigation of binary coating material mixtures using grazing incidence XUV-reflectometry

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**ABSTRACT TEXT:** Being of special interest in thin film technology for a long time already, even nowadays mixtures of coating materials are in the focus of research aiming for highest performance in high power as well as in ultra-short pulse laser applications. On the one hand, coating material combinations allow customizing the coating for a certain application by modifying advantageously the refractive index or the band gap energy. On the other hand, that technology is essential in the production of Rugate-filters, using gradually varied refractive index profiles. It is therefore of special interest to get insight into the composition of such mixed layers, not only in terms of refractive index and absorption coefficient, but to evaluate the fractions of materials involved for gaining a better understanding, and therefore to reach highest possible reproducibility for production of such kind of thin films.

In this work, single layers of binary mixtures of aluminum oxide, aluminum fluoride, and silica are studied with respect to their composition using XUV-reflectometry (XUV-R). As the penetration depth of XUV radiation under grazing incidence is only a few tens of nanometers, this noninvasive measurement technique is sensitive to the near surface composition of the film. Therefore it allows investigating the layer material separated from the substrate on which it was deposited. Using specific absorption edges in the XUV of the involved materials, an empirical correlation between XUV response and mixture ratio is developed and compared to the deep ultraviolet (DUV) absorption edges of the mixture materials.

***Keywords:*** *XUV/EUV, metrology, binary optical thin films, ultrafast laser optic, high power laser, contamination*

## 9237-74, SESSION PS3

# Toward separation of bulk and interface defects: damage probability analysis of thin film coatings

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**ABSTRACT TEXT:** Laser damage in transparent materials induced by pulses of nanosecond duration is driven by absorption of nanometer sized defects inherent to manufacturing process. So called Beilby layer containing residuals of abrasive materials as well as subsurface cracks are good examples of defects in conventional polishing process. Deposition of thin films adds another dimension of complexity by introducing new types of bulk defects. Thus optimization of laser optics manufacturing technologies towards higher optical resistance becomes a challenging task. Furthermore deposition process can change the properties of existing defects. As the criterion of quality Laser induced Damage Threshold (LIDT) is often considered. However, even improvement of some manufacturing steps such as defect density minimization could not always lead to the improvement of LIDT because of screening factors such as interference effects and distinct materials used. So far there is lack of scientific tools and techniques that could identify if damage was initiated within the coating or at the interface. Herewith theoretical and experimental efforts were made in order to distinguish between polishing and deposition defects by analyzing curves of damage probability. Polarization and angle of incidence effects were taken into account by investigating in single- and multi-layer coatings containing defects located both in bulk and at interfaces between different layers. The first result show that manipulation of irradiation conditions combined with theoretical modeling could help to identify origins of defects limiting maximal fluence.

***Keywords:*** *LIDT, defect density, polishing process, thin film coatings, laser damage, contamination of optical components, surface and bulk defects, laser damage in new high power laser systems*

# Station for LIDT tests of optical components under cryogenic conditions

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

**ABSTRACT TEXT:** In this contribution we present a technology for deposition and testing of interference coatings for optical components designed to operate in power pulsed lasers. The aim of the technology is to prepare components for high power laser facilities such as ELI (Extreme Light Infrastructure) or HiLASE. ELI is a part of the European plan to build a new generation of large research facilities selected by the European Strategy Forum for Research Infrastructures (ESFRI). These facilities rely on the use of diode pumped solid state lasers (DPSSL). The choice of the material for the lasers' optical components is critical. Some of the most important properties include the ability to be antireflection and high reflection coated to reduce the energy losses and increase the overall efficiency. As large amounts of heat need to be dissipated during laser operation, cryogenic cooling is necessary. We designed and built a LIDT test station consisting of a vacuum chamber and a cooling system. The samples were placed into the vacuum chamber which was evacuated and then the samples were cooled down to approximately 120K and illuminated by a pulsed laser. Pulse duration was in the nanosecond region. Multiple test sites on the sample's surface were used for different laser pulse energies. We used optical and electron microscopy to inspect the coatings before and after the conducted experiments. The obtained information was used to optimize the optical coating designs which are used by our SYRUSpro 710 coating system. Also spectrophotometric measurements were conducted to determine the temperature dependence of refractive indices of the materials used during the coating production process.

***Keywords:*** *thin film coatings, cryogenic cooling, PIAD evaporation, LIDT, laser damage*

## 9237-76, SESSION PS3

# Detection of the laser-damage onset in optical coatings by the photothermal-deflection method

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**SPEAKER BIOGRAPHY:** Dr. Katsuhiro Mikami received Engineering Ph. D. degree on Mar. 2013 from Osaka University, JAPAN. He is a research fellow at Japan society for the promotion of science (JSPS) and studying in Institute of Laser Engineering (ILE), Osaka University. He was with Laboratory for Laser Energetics (LLE) at University of Rochester as visiting research associate from Sep. 2013 to Aug. 2014. His field of the research is laser-induced damage of high-power laser optics, specifically the temperature dependence of the laser damage threshold.

**ABSTRACT TEXT:** Defects and contamination in optical devices behave like laser-damage precursors whose presence can be estimated through absorption measurements. Many optical components for high-power lasers have shown laser-damage-threshold enhancement after underthreshold laser irradiation. This phenomenon is known as laser conditioning and can be associated with contamination cleaning and/or defect ejection. To reveal the laser-conditioning mechanism, it is essential to monitor absorption behavior during the laser-conditioning process. In this study, varying optical coating absorption during N-on-1 damage tests was evaluated by the photothermal-deflection (PD) method. A continuous-wave Nd:YAG laser (1064-nm wavelength ) and He–Ne laser were used as a pump and probe laser, respectively. A single-mode Nd:glass laser (1053-nm wavelength and 1.4-ns pulse width ) was used as a damage-testing laser. The study showed a decrease in absorption after sample irradiation with low, underthreshold laser pulse fluence. However, absorption definitely increased when the laser pulse fluence approached the damage-threshold value, thereby signifying laser-damage onset. These experimental results indicate modification of optical coatings by subthreshold laser irradiation and render PD as a viable method for the detection of the laser-damage onset.

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***Keywords:*** *laser damage, photo-thermal deflection, optical coatings, laser conditioning*

## 9237-77, SESSION PS3

# The microstructural origins of features observed in oxide films by third-harmonic microscopy

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**ABSTRACT TEXT:** Third harmonic microscopy (THM) with circularly polarized illumination has been shown to reveal material anisotropy in thin films owing to suppression of optical signals from isotropic media [1]. This is useful for optical coatings because these are ideally amorphous and defects might show up as anisotropic domains. For example, features were observed in $Sc_2O_3$ and $HfO_2$ films in regions where Nomarski microscopy failed to produce contrast. Since $HfO_2$ films are known to have nanocrystalline regions [2], one hyposthesis for the contrast observed with THM was that these nanocrystallites were responsible.

We present a comparative study of microstructure and THM contrast. We show correlations between the THM features and the average crystallinity. To this end we annealed oxide films up to and above their crystallization temperature and characterized them by x-ray diffraction. The connection between the microstructure and THM images is shown through electron microscopy.

REFERENCES

1. R. A. Weber, C. Rodriguez, D. N. Nguyen, L. A. Emmert, D. Patel, C. S. Menoni, and W. Rudolph, “Third harmonic microscopy of intrinsic and induced material anisotropy in dielectric thin films,” Opt. Eng. 51, 121807 (2012).
2. C. V. Ramana, K. Kamala Bharathi, A. Garcia, and A. L. Campbell, “Growth behavior, lattice expansion, strain, and surface morphology of nanocrystalline, monoclinic HfO2 thin films,” J. Phys. Chem. C 116, 9955-9960 (2012).

***Keywords:*** *optical thin films, nonlinear microscopy, damage precursors, microstructure, electron miroscopy*

## 9237-78, SESSION PS3

# An empirical investigation of the laser survivability curve: V

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**Wolfgang Riede,** Deutsches Zentrum für Luft- und Raumfahrt e.V. (Germany);
**Jonathan H. Herringer,** Arrow Thin Films, Inc. (United States)

**SPEAKER BIOGRAPHY:** Jonathan Arenberg is the Chief Engineer for the James Webb Space Telescope program at Northrop Grumman Aerospace Systems. Dr. Arenberg has been with Northrop Grumman since 1989 having begun his career with Hughes Aircraft Company in 1982. His work experience includes optical, space and laser systems. Dr. Arenberg has worked on such astronomical programs as the Chandra X-ray Observatory, James Webb Space Telescope and helped develop the New Worlds Observer concept for the imaging of extra-solar planets. He has worked on several major high-energy and tactical laser systems, laser component engineering and metrology issues. He is a US delegate to the ISO sub-committee charged with writing standards for laser and electro-optic systems and components, SPIE, American Astronomical Society and AIAA. Dr. Arenberg holds a BS in physics and an MS and PhD in engineering, all from the University of California, Los Angeles

**ABSTRACT TEXT:** In this paper, we report on a continuing multi-year empirical investigation into the nature of the laser survivability curve. The laser survivability curve is the onset threshold as a function of shot number. This empirical investigation is motivated by the desire to design a universal procedure for the measurement of the so-called S on 1 damage threshold. In last year's report, we applied maximum likelihood methods to determine the probability of damage curve as a function of fluence. Under the assumption of the probability of damage on each shot being independent of irradiation history, a projection of laser survivability curve was then made. This year, we define a procedure to make such measurements and report on their predictive efficacy.

***Keywords:*** *laser damage testing, S on 1 testing*

## 9237-79, SESSION PS3

# Analysis of the laser damage characteristics of a production lot

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**SPEAKER BIOGRAPHY:** Jon Arenberg is the Chief Engineer for the James Webb Space Telescope program at Northrop Grumman Aerospace Systems. Dr. Arenberg has been with Northrop Grumman since 1989 having begun his career with Hughes Aircraft Company in 1982. His work experience includes optical, space and laser systems. Dr. Arenberg has worked on such astronomical programs as the Chandra X-ray Observatory, James Webb Space Telescope and helped develop the New Worlds Observer concept for the imaging of extra-solar planets. He has worked on several major high-energy and tactical laser systems, laser component engineering and metrology issues. He is a US delegate to the ISO sub-committee charged with writing standards for laser and electro-optic systems and components, SPIE, American Astronomical Society and AIAA. Dr. Arenberg holds a BS in physics and an MS and PhD in engineering, all from the University of California, Los Angeles.

**ABSTRACT TEXT:** This paper reports on the analysis of laser damage measurements made on an entire lot of approximately identically processed and coated samples. Each sample's test data is analyzed to determine its probability of damage curve, pi. The probability of damage curves are further processed to derive the defect distribution, fi, for each sample. The individual fi are then examined to determine if they are likely to have come from a single parent distribution, f, which represents the performance of the manufacturing process. It is expected that this paper will show how a damage test on a single sample is an acceptable predictor for the performance of a lot.

***Keywords:*** *lot sampling, laser damage measurements, defect distribution, parent defect distribution*

# Study of laser-induced fatigue effects in synthetic fused silica in the UV

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**Frank R. Wagner, Jean-Yves Natoli,** Institut Fresnel (France)

**SPEAKER BIOGRAPHY:** Céline Gouldieff obtained her Master Degree in Engineering from the Ecole Centrale Marseille in 2010 and her Research Master degree in 2010 from the Aix-Marseille University.

From October 2010 to November 2013, she worked as a PhD student in the Institut Fresnel (Marseille, France) on experimental and theoretical aspects of laser-induced damage in optical materials for UV wavelengths. She obtained her PhD in Physics from Aix-Marseille University in November 2013. Since January 2014, she works as a post-doctoral student in the Institut de Physique de Rennes (IPR, Rennes, France) on the development and the characterization of polymer microstructures for integrated photonic applications.

**ABSTRACT TEXT:** In the last decades, the resistance to high-power laser flux was largely improved in most of optical components insofar as 1-on-1 measurements are concerned. Another challenge lies in improving their resistance to multiple laser shots for high-power laser applications. Indeed, in multi-pulse irradiation, a decrease of the laser-induced damage threshold with increasing number of pulse was observed in various optical materials as in glasses, crystals, and thin-films. This effect, commonly denominated “fatigue” effect, is a limiting factor in many applications where optics have to be long-lifetime, as for example for space applications.

Representing the laser damage probability as a function of pulse number for a given fluence allows to distinguish statistical pseudo-fatigue and fatigue which is due to cumulative material modifications. Investigating on the fatigue effects in the bulk of synthetic fused silica (Suprasil 1®) for different wavelengths, we evidenced that fatigue effects was due to statistical pseudo-fatigue when irradiated at 1064 nm while the fatigue effect at 355 nm came from cumulative material modifications.

The current work is dedicated a more detailed study of fatigue effects in Suprasil 1®, testing the influence of the beam size and the UV-wavelength on the fatigue effects. Moreover, an estimation of the lifetime of the created defects is performed using a destructive technique.

***Keywords:*** *synthetic fused silica, laser induced fatigue, long lifetime, UV wavelength, laser damage, multiple laser irradiation*

## 9237-81, SESSION PS3

# Controllable liquid spread speed in the groove using femtosecond laser

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**SPEAKER BIOGRAPHY:** Dr. Jiawen Li is a lecturer of University of Science and Technology of China. He received his Ph.D from University of Science and Technology of China in 2011 and then spent two year in postdoctoral research. His major interests include femtosecond laser fabrication, structural color.

**ABSTRACT TEXT:** The capillary-driven flow in micro groove has attracted much attention because it can be used as a passive power source in microfulidic devices. In recent years, some researchers have used the capillary force to deliver liquids in micro groove and found liquid spread distance is linear to the square of spread time in experiment. This kind of spread speed will limit the application of capillary-driven method in the field of microfluidics because the accurate volumes of liquids should be displaced with controllable flow speeds. In this paper, we investigated the feasibility of controllable flow speeds by the gradient microstructure on groove surface which are constructed using femtosecond laser. Firstly, we used femtosecond laser to fabricate different microstructures on glass groove surfaces with different laser pulse overlaps. Then, the liquids were dropped at the end of grooves with different surface structure. It was found the flow speed in groove increased when the femtosecond laser pulse overlap increased, though the liquid spread distance was linear to the square of spread time. Lastly, according to simulation, we designed gradient microstructure along the groove in order to obtain the constant spread speed. The variable pulse overlaps were used to obtain the expected gradient microstructure along the groove. The experiment showed the constant spread speed was obtained. We also obtained the other expected flow behavior by this method. It can be concluded the expected spread speed can be controlled by constructing the microstructure using femtosecond laser.

***Keywords:*** *capillary-driven, spread speed, microstructure, femtosecond laser*

## 9237-82, SESSION PS3

# Laser damage test-bench with ultrashort pulses down to 10 fs

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**SPEAKER BIOGRAPHY:** Dr Olivier UTEZA is currently a senior CNRS researcher in the Laboratory Lasers, Plasmas and Photonic Processes of the University Aix-Marseille, France. After 10 years of research on excimer lasers and development of high peak power hybrid femtosecond laser system, his main research interests deal today with femtosecond laser – matter interaction at mid-intensities, especially in the field of laser ablation and damage.

**ABSTRACT TEXT:** Operation of large scale intense laser facilities as well as the industrial implementation of laser-based micromachining applications requires the characterization of the response of material and optical components to different levels of laser exposure, ranging from laser damage evaluation for safe day-to-day operation of laser systems to the determination of laser ablation characteristics for micromachining processes. Measuring and improving the knowledge of laser – matter interaction thus appears to be essential to the development of any controlled and optimized laser systems and processes [1-3].

Additional complexity arises when considering pulses of extremely short pulse duration down to few optical cycles. Such pulses have extremely broad spectrum difficult to manipulate and are highly subject to beam distortions due to their high intensity rapidly yielding to deleterious phase modulations. The difficulty to manipulate them severely increases in dense media and can also take place in air [4]. The use of ultrashort pulses needs benchmarking to boost their implementation in the industry and related applications and also for providing precise data on damage and ablation of any material of interest.

The purpose of this work is thus to measure reliably the laser-induced damage threshold (LIDT) at the surface of materials exposed to single pulses down to ? 10 fs pulse duration (using 1on1 protocol), providing feedback to builders and suppliers of intense laser infrastructures. We also aim to determine laser-induced ablation threshold (LIAT) of materials and related characteristics (like morphology and affected zone) to help the development of micromachining processed based on ultrashort lasers. Our presentation will first be devoted to the description of a laser test-bench operated in air and able to study laser – matter interaction with femtosecond pulses down to pulse duration of a few optical cycles (? 10 fs). We then characterize the propagation of ultrashort pulses to estimate the onset of nonlinear effects in air (with measurement of the nonlinear index n2) and to determine the exact conditions in which the LIDT and LIAT thresholds are measured. Finally, we illustrate the accuracy of our approach by measuring LIDT and LIAT fluences of materials extensively used in optics and photonics (like for instance fused silica).

REFERENCES

1. B. C. Stuart, M. D. Feit, S. Herman, A. M. Rubenchik, B. W. Shore, and M. D. Perry, Nanosecond-to-femtosecond laser-induced breakdown in dielectrics, Phys. Rev. B 53, 1749 (1996)
2. B. Chimier, O. Utéza, N. Sanner, M. Sentis, T. Itina, P. Lassonde, F. Légaré, F. Vidal, and J. C. Kie?er, Damage and ablation thresholds of fused silica in femtosecond regime: relevant physical criteria and mechanisms, Phys. Rev. B 84, 094104 (2011)
3. M. Lebugle, N. Sanner, O. Utéza, M. Sentis, Guidelines for efficient direct ablation of dielectrics with single femtosecond pulses, Appl. Phys. A 114 (1), 129-142 (2014)
4. D.E. Laban, W.C. Wallace, R.D. Glover, R.T. Sang, D. Kielpinski, Self-focusing in air with phase-stabilized few-cycle light pulses, Opt. Lett. 35 (10), 1653 (2010)

***Keywords:*** *laser damage, ultrashort pulse, test bench, laser ablation, nonlinear index, dielectrics, 10fs, micromachining*

## 9237-91, SESSION PS3

# Development of an automated scanning white-light interferometer for optical coating dispersion measurements

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We present an automated scanning white light interferometer for simple dispersion measurements of optical coatings in reflection and transmission with typical GDD precision of $5fs^2$ and measurement range of 500-1650nm. Diode lasers with relatively long coherence lengths enable alignment of the test optic before switching to a white light source. A He-Ne laser collinear with the white light beam provides calibration of the scanning reference arm while also minimizing the effects of vibration. Pairs of silicon or InGaAs detectors simultaneously measure s and p polarizations. Selection of the scanning range controls the spectral resolution and noise in the measurements.

## 9237-83, SESSION PS4

# In-situ laser-induced contamination monitoring using long-distance microscopy

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**ABSTRACT TEXT:** Operating high power space-based laser systems in the visible and UV spectral range is problematic due to the occurrence of laser-induced contamination. Organic materials are outgassing into vacuum or artificial atmospheres and can lead to deposits accumulating on irradiated optical components. Besides absorption, these ultrathin layers of contaminants can strongly reduce the laser-induced damage threshold of the corresponding components. Hence, the reliability of space-based laser systems depends on the optical components quality and their resistance to such deposit build-up.

In this paper contamination-induced damage on high-reflective coated optics is investigated for UV irradiation of 355 nm with naphthalene as contamination material under high-vacuum conditions. Naphtalene was selected as contamination material due to its simplicity in handling and omnipresence in contaminant mixtures. Three different kinds of high-reflective coated optics fabricated by Electron Beam Deposition, Magnetron Sputtering and Ion Beam Sputtering technique were investigated. The contamination test procedure was designed to perform laser-induced contamination tests on 45° high-reflective coated optics. In-situ observation of contamination induced damage was performed using a long distance microscope with a resolution of a few µm. Additionally the onset and evolution of deposit formation and contamination induced damage of optical samples was observed by in-situ laser-induced fluorescence and reflectivity monitoring. Ex-situ characterization of deposits and damage morphology was performed by differential interference contrast and fluorescence microscopy.

At a partial pressure of naphthalene in the range of 10-5 mbar a drastic reduction of the laser-induced damage threshold up to a factor of 10 compared to values obtained without contamination was observed, dependent on the coating process, fluence and contaminant pressure. Contamination-induced surface damage was found to originate from distinct localized sites. As a general rule, the merging of this localized sites and the corresponding increase in the surface area affected by contamination led to a loss in reflectivity. The onset time and the slope of this loss were found to be different for the coating types investigated.

In conclusion the in-situ observation with long distance microscopy was found to be a valuable tool for understanding the onset and later stages of the contamination-induced surface degradation

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***Keywords:*** *laser induced contamination, UV laser irradiation, damage morphology investigation with long distance microscope, high reflective optics, coating techniques, damage threshold, LIC, naphthalene*

## 9237-84, SESSION PS4

# Mechanisms of laser resist stripping without occurring the laser damage to Si wafer

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**ABSTRACT TEXT:** In semiconductor manufacturing, the conventional resist removal process needs a lot of environmentally unfriendly chemicals and consumes much ultra-pure water.

The removal with the laser irradiation instead of chemicals has the advantage of reducing environmental load. In our past research, an advanced laser resist stripping method for the positive-tone diazonaphthoquinone / novolak resist was successfully developed without occurring laser damage to the Si wafer. The efficiency of resist stripping is drastically improved by changing the laser irradiation environment from air to water. However, the mechanism of the resist stripping occurring without laser damage is not made sure.

In this study, dynamic thermal stress simulation which couples heat transfer and stress analyses during the laser irradiation was performed with a finite element method. At the pulsed laser irradiation, the resist coated on the Si wafer had thermal stress concentration at the interface between resist and Si wafer because of the difference of material properties such as coefficient linear thermal expansion and Young's modulus. In the case of laser removal in water, since cooling effect of the resist surface is larger than in air due to the large heat transfer coefficient of water, large stress occurs at the interface between resist and Si wafer. In the case of atmospheric laser radiation, thermal stress concentration is not enough because of the small temperature gradient through resist to wafer. The resist is slightly stripped from the Si wafer surface, but laser damage occurs to the Si wafer surface simultaneously. Therefore, resist removal efficiency was improved in water. From these results, the irradiation of pulsed laser to the resist in water enables resist stripping from the Si wafer without occurring laser damage.

***Keywords:*** *resist stripping, novolak resist, laser irradiation, laser induced damage, dynamic thermal stress simulation*

## 9237-85, SESSION PS4

# Ultraviolet laser damage tests of scratches repaired by carbon dioxide laser on fused silica optics

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

**ABSTRACT TEXT:** Fusion class power laser facilities such as National Ignition Facility (NIF) or Megajoule laser (LMJ) need large optical components with high wavefront quality and high resistance to laser-induced damage. Scratches on optics surface have been identified as a major contributor to laser damage.

Most of the scratches are generated during polishing and the usual way to remove them is to polish again. So it is not a deterministic process. A couple of years ago, we suggested a deterministic polishing process by using a $CO_2$ laser to remove scratches. A $CO_2$ laser was used to locally melt the silica in the scratched area. We have applied this process to an optic of large size which has been polished according to the LMJ standard. Indeed we succeeded to remove a 16 µm deep scratch and to increase the laser damage threshold from 4 J/cm$^2$ to 16 J/cm$^2$.

We present here the characterizations after scratch removal including details of laser damage test but also roughness evolution after each step of the process.

***Keywords:*** *fused silica, laser damage mitigation, $CO_2$ laser, optics surface defects*

## 9237-86, SESSION PS4

# A study of ps-laser-induced-damage-threshold in hybrid metal-dielectric mirrors

**Vaclav Skoda,** CRYTUR spol s.r.o. (Czech Republic);
**Jan Vanda,** Institute of Physics of the ASCR, v.v.i. (Czech Republic)

**SPEAKER BIOGRAPHY:** Václav Škoda received his MS degree in Physics from the Charles University in Prague, Faculty of Mathematics and Physics in 1975, PhD. degree in 1990 from the Czech Technical University in Prague, Faculty of Nuclear Science and Physical Engineering. He has been working as thin film specialist in Crytur Ltd. in Turnov, Czech Republic. He is member of SPIE.

**ABSTRACT TEXT:** Laser-induced-damage-threshold of two types of metal-dielectric hybrid mirrors was tested using a laser apparatus working at 800 nm wavelength with 1 ps pulse length at 1 kHz repetition rate and in 106-on-1 test mode. The laser beam diameter used for measurements was in range of 0.1 mm. Four sets of mirror samples with different layer system designs using multilayer $Ta_2O_5/SiO_2$ coating centered at 800 nm or 1030nm on silver or gold metal layer were manufactured. Both BK7 and fused silica substrate materials were used for manufacturing of samples. The measured damage thresholds at 45 deg incidence and P-polarization were compared with computed properties of layer systems. The laser damage was detected by observation using Nomarski microscope. Samples were coated in a high-vacuum chamber by electron-beam deposition process partly at elevated temperature. Ion-assisted-deposition method with oxygen as reactive gas was used. Metal layers were deposited from resistive heated tungsten boats. A comparison of measured damage threshold of samples in dependence on material and quality of substrates, used metal layer, and central design wavelength of dielectric layer system was carried out.

***Keywords:*** *LIDT, metal dielectric mirrors, hybrid mirrors, laser mirrors*

## 9237-87, SESSION PS4

# Coming clean: understanding and mitigating optical contamination in advanced LIGO

**Kaitlin E. Gushwa,** California Institute of Technology (United States);
**Calum I. Torrie,** California Institute of Technology (United States) and Scottish Univ. Physics Alliance (United Kingdom)

**ABSTRACT TEXT:** The Advanced Laser Interferometer Gravitational-Wave Observatory (LIGO) consists of two ground-based observatories, operated in unison with the aim of directly detecting gravitational waves. The L-shaped interferometers have 4 km long arms comprised of ultra-high vacuum chambers that house suspended optical components and connecting beamtubes. LIGO's fused silica optics are extremely sensitive to optical scattering and absorption losses induced by both particulate and hydrocarbon contamination. During operation at full power, the optical surfaces are illuminated with up to 200 $kW/cm^2$. Additionally, the round-trip test mass cavity loss budget from all sources is limited to 70 ppm. Even low-level contaminants can result in laser damage to the optics during operation, and the unacceptable reduction of overall detector sensitivity.

The problem has been approached from several angles, the successes and failures of which are described. Initial efforts concentrated on quantifying the extent of contamination, identifying sources, improving cleanroom practices to decrease the generation of particulates, and developing non-contact cleaning methods for installed optics in air. Current research focuses on correlating cleanliness levels and materials with laser-induced damage threshold (LIDT) tests, and designing techniques to quantify and remove optical contamination in-situ while under vacuum. As a result of these ongoing efforts, we now have a better understanding of the extent and origin of contamination in the vacuum system. Significant improvements to methods of controlling contamination, and subsequently protecting the optics from losses and laser damage have been made; however further work is needed to reach ultimate performance requirements.

Dr. Calum Torrie's invited presentation, Protecting Optics Installed in Advanced LIGO from Particulate Contamination, will include a top-level overview of these approaches and the status of current research and development work being carried out in this field. His talk will also include an introduction to gravitational waves, methods used to detect them, and a summary of the status of Advanced LIGO. This talk (Kaitlin Gushwa's talk) will discuss the tools and techniques used to quantify contamination in greater detail. This will include a presentation of the data collected thus far, damage testing results, and practices implemented to mitigate contamination.

***Keywords:*** *LIGO, fused silica optics, contamination control, cleanliness, laser damage, LIDT, particle size distribution*

## 9237-88, SESSION PS4

# Laser-induced damage tests under multiple wavelength irradiation of ATLID TXA optics for ESA-Satellite Mission EarthCare

**Uwe Leinhos,** MicroLiguids GmbH (Germany);
**Klaus Mann, Wilhelm Huettner, Julian Sudradjat,** Laser-Lab. Göttingen e.V. (Germany);
**Georgios D. Tzeremes,** European Space Agency (Netherlands)

**ABSTRACT TEXT:** The ESA mission EarthCARE is projected in order to make global observations of clouds, aerosols and infrared radiation. The satellite will be launched in 2015 and operate at an altitude of around 400 km. Part of the satellite is an atmospheric UV-LIDAR operating at 355nm wavelength. Since the exact knowledge of laser-induced damage thresholds (LIDT) is extremely important for space-borne laser operation, optical elements for the EarthCARE mission are investigated in cooperation between ESA and Laser-Laboratorium Göttingen.

A setup was developed at Laser-Laboratorium that allows determination of LIDT data under simultaneous 1064nm, 532nm and 355nm irradiation, in order to investigate the influence of (unwanted) combined irradiation of specific elements with multiple wavelengths. Utilizing a fully characterized test laser beam and a well defined sample environment, 10.000-on-1 LIDT data of high-reflecting mirrors (AOI 45°) in vacuum were determined both at multiple wavelengths and at 355nm alone. A considerably lower threshold (7 J/cm$^2$) is registered for multiple wavelength irradiation compared to single UV wavelength data (10.3 J/cm$^2$). From characteristic damage curves end of life thresholds were extrapolated. In addition, a test optics (HR355, 45°, ambient conditions) was irradiated for 150 million pulses at multiple wavelengths at a fixed fluence of 2 J/cm$^2$ as a certification test.

# 9237-89, SESSION PS4

## Cleaning practices and facilities for the Nation Ignition Facility

**James A. Pryatel,** Akima Infrastructure Services (United States);
**William H. Gourdin, Gerald S. Ruble, Susan C. Frieders,**
Lawrence Livermore National Lab. (United States)

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

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

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

## 9237-90, SESSION PS4

# Surface damage correction, and atomic level smoothing of optics by accelerated neural atom beam (ANAB) processing

**Michael Walsh, Kiet Chau, Sean Kirkpatrick, Richard Svrluga,**
Exogenesis Corp. (United States)

**ABSTRACT TEXT:** Surface damage and surface contamination of optics has long been a source of problems for laser, lithography and other industries. Nano-sized surface defects may present significant performance issues in optical materials for deep UV and EUV applications. The effects of nanometer sized surface damage (scratches, pits, and organics) on the surface of optics made of traditional materials and new more exotic materials is a limiting factor to high end performance. Angstrom level smoothing of materials such as calcium fluoride, spinel, zinc sulfide, BK7 and others presents a unique set of challenges. Exogenesis Corporation, using its proprietary Accelerated Neutral Atom Beam (ANAB) technology, is able to remove nano-scale surface damage and contamination and leaves many material surfaces with roughness typically around one angstrom. This process technology has been demonstrated on nonlinear crystals, and various other high-end optical materials. This paper describes the ANAB technology and summarizes smoothing results for various materials that have been processed with ANAB. All surface measurement data for the paper was produced via AFM analysis.

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

## NOTES

# NOTES

# Wednesday AM • 17 September

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

## Wed 8:20 am to 9:40 am • SESSION 9

## Fundamental Mechanisms II

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

8:20 am: **Measurement of femtosecond laser damage thresholds at mid-IR wavelengths**, Drake Austin, Kyle Kafka, Cosmin Blaga, Louis F. Dimauro, Enam Chowdhury, The Ohio State Univ. (USA) . . . . . . . . . . [9237-30]

8:40 am: **Modeling the material properties at the onset of damage initiation in bulk potassium dihydrogen phosphate crystals**, Stavros G. Demos, Michael D. Feit, Lawrence Livermore National Lab. (USA); Guillaume Duchateau, Univ. Bordeaux 1 (France) . . . . . . . . . . [9237-31]

9:00 am: **Using particle-in-cell simulations to model femtosecond pulse laser damage of metals and dielectrics**, Robert A. Mitchell III, Douglass W. Schumacher, Enam Chowdhury, The Ohio State Univ. (USA) . . . . . . . . . . [9237-32]

9:20 am: **Optic damage modeling and analysis in the National Ignition Facility**, Zhi M. Liao, Brett A. Raymond, Jessie M. Gaylord, Robert N. Fallejo, Jeffrey D. Bude, Paul J. Wegner, Lawrence Livermore National Lab. (USA) . . . . . . . . . . [9237-33]

Refreshment Break . . . . . . . . . . Wed 9:40 am to 10:10 am

### 9:40 am to 10:10 am • Refreshment Break

# Wednesday AM continued • 17 September

## 10:10 am to 12:10 pm • SESSION 10

### Materials and Measurements I

Session Chairs: **James E. Andrew,** AWE plc (United Kingdom);
**Semyon Papernov,** Univ. of Rochester (USA)

10:10 am: **Experimental tools for nonlinear spectroscopy: absorption and refraction** *(Keynote Presentation)*, Eric W. Van Stryland, Trenton R. Ensley, Matthew C. Reichert, David J. Hagan, CREOL, The College of Optics and Photonics, Univ. of Central Florida (USA) . . . . . . . . . . [9237-35]

10:50 am: **Thermal lensing of laser materials**, Mark J. Davis, Joseph S. Hayden, SCHOTT North America, Inc. (USA) . . . . . . . . . . [9237-48]

11:10 am: **Femtosecond damage threshold at kHz and MHz pulse repetition rates**, Benedek J. Nagy, Lénárd Vámos, Daniel Oszetzky, Peter Rácz, Peter Dombi, Wigner Research Ctr. for Physics of the H.A.S. (Hungary) . . . . . . . . . . [9237-37]

11:30 am: **Research on limiting of high-power laser radiation in nonlinear nanomaterials**, Alexandr Y. Gerasimenko, Mikhail S. Savelyev, National Research Univ. of Electronic Technology (Russian Federation) . . . . . . . . . . [9237-38]

11:50 am: **Spectral and temperature-dependent infrared emissivity measurements of painted metals for improved temperature estimation during laser damage testing**, Sean M. Baumann, National Air and Space Intelligence Ctr. (USA); Michael A. Marciniak, Glen P. Perram, Air Force Institute of Technology (USA) . . . . . . . . . . [9237-39]

Lunch Break and NIST Tours. . . . . . . . . . . Wed 12:10 pm to 2:10 pm

## 12:10 pm to 2:10 pm • Lunch Break and NIST Tours

### 12:10 pm to 12:55 pm · 2 tours offered • NIST Facility Tours

NIST has generously offered to provide 2 limited tours of the facility, including the NIST-F1/NIST-F2 Atomic Clocks and to Josh Hadler's Laser Welding Lab. A sign-up sheet will be at the registration desk.

## 9237-30, SESSION 9

# Measurement of femtosecond laser damage thresholds at mid-IR wavelengths

**Drake Austin, Kyle Kafka, Cosmin Blaga, Louis F. Dimauro, Enam Chowdhury,**
The Ohio State Univ. (United States)

**SPEAKER BIOGRAPHY:** A leading expert in the field of short pulse lasers, ultra-intense and high energy density laser matter interaction, Prof. Chowdhury led the design and construction of the 500 TW SCARLET laser system at the Ohio State University. He also heads an AFOSR funded Femtosecond Solid Dynamics Laboratory (FSD Lab) in OSU Physics with short pulses of lasers operating with wavelengths from 200 – 10,000 nm and pulsewidth from 5 – 500,000 femtoseconds. This lab is dedicated to studying the fundamental mechanisms of damage caused to materials exposed to intense laser pulses.

**ABSTRACT TEXT:** Introduction: There has been a tremendous interest in studying femtosecond laser matter interaction in mid IR wavelength ranges, because of enhancement of electron ponderomotive energy at longer wavelengths due to ?^2 scale [1], and its promise to generate XUV attosecond pulses at multi keV [2]. Mid IR femtosecond interaction with solids is interesting in its own right for several reasons. First, systematic measurement of Mid-IR femtosecond laser damage threshold has never been performed before, because of lack of well characterized mid IR femtosecond sources. Second, for traditional insulators, the reduced individual photon energies at mid IR wavelengths should exhibit a transition from multiphoton to tunneling ionization, when compared to similar interactions with UV-VIS-near IR femtosecond pulses. Semiconductors like Si and Ge are transparent ‘high band gap’ semiconductor at mid IR wavelengths. With fluence near damage threshold, when sufficient electron population transfer into conduction band occurs and all insulators become metal-like, mid IR frequencies present and interesting paradigm, i.e. much larger ponderomotive energies of electrons (compared with near IR wavelengths) which may be very sensitive to alignment of laser polarization direction along different lattice axes of symmetry. When this high non-thermal ponderomotive energy exceeds combined binding energy of the material, it may give rise to material damage characteristics not apparent at near IR wavelengths.

Experimental Setup: The details of damage testing methodology and basic setup are described in a previous paper by Poole et. al. [3]. Femtosecond laser damage testing was performed using 800, 1900 and 3600 nm laser at 45 degree angle of incidence with p-polarized light. The mid IR wavelengths were generated by two separate OPA’s which are BBO (1900 nm)and KTA (3600 nm) based, and are pumped by Ti:Sapphire based regenerative amplifiers producing 3 mJ TEM00 pulses @ 800 nm with pulsewidth of 60 fs. The laser modes and focal spots were characterized with mid IR cameras, and damage spots were studied with optical microscopes and scanning electron microscopes.

Results and discussion: S on 1 ( single shot to 105 shots) LDT peak fluences for Si, Ge and CaF2 obtained from laser damage probability curves fits, and each point represents 0% damage probability at maximum peak fluence (fluence error 20%). LDT at small number of pulses approach single shot LDT, and are consistently higher than that for large no. of shots, where heat accumulation, melting and roughening of surface seem to decrease LDT. The LDT trend of insulator CaF2 with bandgap of ~10.8 eV, showed significantly reduced LDT at 3600 nm (5 J/cm2, 100 shots) compared with that of 800 nm (8 J/cm2, 100 shots). This is most likely because of a change in initial ionization mechanism from multi-photon to tunnel ionization, because Keldysh parameters are 0.23 and 1 for 3600 nm and 800 nm respectively. Another important contribution to laser damage comes from avalanche ionization, which is determined by energy available to conduction electrons to impact ionize valence electrons further. Si and Ge LDT for 10 shots fall in a range between 0.3 – 0.6 J/cm2 for wavelengths 800, 1900 and 3600 nm, and does not follow prediction from two temperature model as described by [4] as monotonically increasing function of wavelength.

Acknowledgement: This work was supported by the Air Force Office of Scientific Research, USA under grant no. # AFPSR-FA9550-12-1-0454.

REFERENCES:

[1] Ghimire et. al., Nature Physics 7, 138–141 (2011)

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

[3] Poole et. al. Optics Express, Vol. 21, Issue 22, pp. 26341-26351 (2013).

[4] Gamaly, E. G. et al. Phys. Plasmas 9, 949 (2002)

***Keywords:*** *fundamental mechanism, mid-infrared laser damage threshold, laser damage of insulator, laser damage of semiconductors, femtosecond laser damage, two temperature model, optical parametric amplification*

# 9237-31, SESSION 9

# Modeling the material properties at the onset of damage initiation in bulk potassium dihydrogen phosphate crystals

**Stavros G. Demos, Michael D. Feit,** Lawrence Livermore National Lab. (United States); **Guillaume Duchateau,** Univ. Bordeaux 1 (France)

**SPEAKER BIOGRAPHY:** Stavros G. Demos is an experimental physicist and has been involved in the field of Laser Damage since he joined Lawrence Livermore National Laboratory in 1997. Stavros has served in the organizing committees for numerous conferences including CLEO and Photonics West. He has coauthored over 110 journal publications and 100 conference proceedings and 20 patents in the fields of laser-defect interactions in optical and laser materials, laser damage, optical characterization/diagnostics instrumentation, and biomedical photonics.

**ABSTRACT TEXT:** A key feature of laser-induced damage is that it transforms a nominally transparent non-absorbing material into a plasma with temperatures on the order of 1 eV and pressures on the order of 10 GPa, which are in the regime of warm dense matter (WDM). This transformation occurs while the physical properties of the material are rapidly modified while hydrodynamic expansion effects can play an important role. KDP (and DKDP) crystals are suitable candidate material for modeling the transient material properties at the onset of damage initiation because: (a) it exhibits a low melting point (on the order of 400 K), so phase transition and damage related processes occur at a lower temperature with limited influence of hydrodynamic effects; (b) there is significant prior work documenting its damage initiation behaviors as well as experimental results that probed the electronic structure of the damage precursors.

Extensive recent work aiming in revealing the electronic structure of the damage precursors in KDP has suggested a multi-level electronic structure and provided estimates of the transition rates between the electronic states. Specifically, nanometric defects incorporated in the crystal lattice induce electronic states located in the band gap that can facilitate excitation of valence electrons into the conduction band through sequential one-photon absorption events, thus, a priori providing the mechanism for energy deposition and heating in the course of the interaction with the laser pulse. These findings were used as the foundation for developing a model that reproduces the well-documented behaviors of laser damage in KDP crystals.

The model involves two phases. During phase I, the model assumes a moderate localized initial absorption that is strongly enhanced during the laser pulse via excited state absorption and thermally driven generation of additional point defects in the surrounding material. The model suggests that during a fraction of the pulse duration, the host material around the defect cluster is transformed into a strong absorber that leads to increase of the local temperature. During phase II, the model results suggest that the excitation pathway mainly consists of one photon absorption events within a quasi-continuum of short-lived vibronic defect states spanning the band gap generated after the initial localized heating of the material. The width of the transition (steps) between different number of photons is governed by the instantaneous temperature, which was estimated using existing experimental data. The model also suggests that the critical parameter prior to initiation of breakdown is the conduction band electron density.

The model was developed and tested using as a benchmark its ability to reproduce the well documented damage initiation behaviors but most importantly, the salient behavior of the wavelength dependence of the damage threshold. Our semi empirical approach leads to good agreement between predicted trends and the corresponding experimental observations using a very small number of fitting parameters, which suggests the reliability of both the physical scenario and the associated modeling assumptions.

This work was performed in part under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344. LLNL-ABS-653198

## 9237-32, SESSION 9

# Using particle-in-cell simulations to model femtosecond pulse laser damage of metals and dielectrics

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

**ABSTRACT TEXT:** We present novel Particle-In-Cell (PIC) simulations of the full laser damage process and the resulting damage spot morphology. At the heart of these simulations is the implementation, for the first time, of a Lennard-Jones pair potential model (LJPPM) for PIC codes. PIC facilitates the first ab initio treatment of realistic target sizes while the LJPPM allows a PIC code to treat a system of particles as a medium which can ablate, melt, and resolidify. Combining these two approaches, we model the effect of a femtosecond-pulse laser on metal and dielectric targets near and above the damage threshold and compare to recent experimental results. PIC simulations integrate the Maxwell and Lorentz equations of motion for "macroparticles", each representing a collection of electrons or ions, with continuously varying positions and momenta that interact with electromagnetic fields on a discretized grid. PIC simulations are ideal for treating intense interactions between lasers and matter and the flow of material after heating. The basic PIC approach does not treat particle-particle interactions within a grid cell correctly, but the effect of such interactions can be added to the PIC integration cycle. The resulting algorithm retains the strengths of PIC including self-consistent treatment of the laser-particle interaction and subsequent generation of plasma waves and electron heating.

Molecular dynamics simulations (MDS) provide the current state-of-the-art for ab initio treatment of laser damage, but computational costs limit MDS to only treating a small portion (e.g. 10 nm square) of the target area. PIC simulations using ~5-10 nm cells can readily treat the entire damage spot morphology. The challenge is to implement a LJPPM that permits use of such large cells, but still retains the average effect of the particle-particle interactions. Previously, we described initial results from our first approach to implementing a LJPPM [1]. Although damage spot formation was obtained, the use of a first-order algorithm, among other issues related to approximating a short-range force on such a large spatial scale, caused significant distortion of the effect of inter-particle interactions. Our current implementation uses a second-order algorithm and applies corrections to remove this distortion while maintaining excellent energy conservation over the nanosecond time-scale required for a damage spot to form.

To demonstrate the LJPPM technique, we modified the PIC code LSP [2] in 2D(3V) geometry to simulate the laser-target interaction and the subsequent target evolution. The laser interaction simulations run for ~2 ps and are performed implicitly using ~8 nm cells and ~2500 particles/cell, with a typical laser pulse of 100 fs duration and 2 um spot size at various intensities and wavelengths. These results are then used to initialize a second simulation with ~10 nm cells and ~1000 particles/cell using an implicit algorithm optimized for large time steps that is run for ~2 ns. Conducting targets were modeled using copper or gold ions and electrons and dielectric targets were modeled using silicon and oxygen atoms. In both cases targets are initialized at room temperature, a binary collision operator is used, and ionization is modeled. Using this approach we observe laser absorption, target heating profile, damage evolution, and ultimately a resolidified damage spot, all consistent with other approaches. We discuss extension of this approach to 3D geometries.

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

REFERENCES

1 R. A. Mitchell, D. W. Schumacher, and E. A. Chowdhury, "Modeling femtosecond pulse laser damage on conductors using Particle-In-Cell simulations," Proc. SPIE 8885, 88851U (2013).

2 D. R. Welch, D. V. Rose, M. E. Cuneo, R. B. Campbell and T. A. Mehlhorn, Physics of Plasmas 13, 063105 (2006).

***Keywords:*** *modeling, particle-in-cell, femtosecond, damage threshold, laser induced damage, ablation, short pulse*

## 9237-33, SESSION 9

# Optic damage modeling and analysis in the National Ignition Facility

**Zhi M. Liao, Brett A. Raymond, Jessie M. Gaylord, Robert N. Fallejo, Jeffrey D. Bude, Paul J. Wegner,** Lawrence Livermore National Lab. (United States)

**SPEAKER BIOGRAPHY:** Zhi attended University of Rochester where he obtained his B.S., M.S. and PhD in optical engineering, working under Dr. Govind Agrawal on nonlinear fiber optics before joining Lawrence Livermore National Laboratory (LLNL) in 2001.

Zhi's expertise is in nonlinear optics, adaptive optics, and laser-induced damage in optics. He has contributed to many of LLNL's successful laser projects over the years such as the Fiber Laser Guide Star, Alkali Laser, ARC, the Mercury Laser, and NIF (National Ignition Facility). Currently, Zhi is working on developing models for predicting optic lifetime for NIF which he has authored/presented peer-reviewed scientific publications covering these topics. Zhi was also the co-PI for the team that won 2006 R&D award for high-average-power frequency conversion using YCOB crystal.

**ABSTRACT TEXT:** Comprehensive modeling of laser-induced damage in optics in National Ignition Facility (NIF) has been performed on all fused silica final optics installed with a metric that compares the damage performance to online inspections. The results indicated that the damage models are successful in tracking the performance of the fused silica final optics when properly accounting for various optical finishes and mitigation processes. This validates the consistency of our damage model and allows us to further monitor and evaluate different system parameters that can potentially affect optics performance.

This work was performed under the auspices of the U. S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344. (LLNL-ABS-652852)

## 9237-35, SESSION 10

# Experimental tools for nonlinear spectroscopy: absorption and refraction *(Keynote Presentation)*

**Eric W. Van Stryland, Trenton R. Ensley, Matthew C. Reichert, David J. Hagan,**
CREOL, The College of Optics and Photonics, Univ. of Central Florida (United States)

**SPEAKER BIOGRAPHY:** His current research interests are in the characterization of the nonlinear optical properties of materials and their temporal response as well as the applications of these nonlinear materials properties for optical switching, beam control etc. He developed the Z-scan technique and established the methodology for applying Kramers-Kronig relations to ultrafast nonlinearities and developed the field of cascaded second-order effects. The Journal of Quantum Electronics publication on Z-scan has been noted as the most highly cited paper in the journal's 30 year history by a factor of 2. He is a fellow of the Optical Society of America (OSA), IEEE, SPIE and APS, a past member of the OSA and LIA Boards of Directors, and former co-chair of the OSA Science and Engineering Council. He also served as a topical editor for Optics Letters. He was elected President of the OSA for 2006. He was awarded the R.W. Wood Prize of the OSA in 2012.

**ABSTRACT TEXT:** We have long been developing and refining techniques to measure the sign and magnitude of both nonlinear absorption and nonlinear refraction. In this talk we will give an update on our progress in developing an automated nonlinear spectrometer and give a summary of the most recent techniques we have developed. The nonlinear spectroscopy we are performing is aimed at giving both the spectra of nonlinear absorption and dispersion of nonlinear refraction over at least two octaves of wavelength range. We have interest in measuring both frequency degenerate and nondegenerate nonlinearities. We will also discuss two new methods of performing nonlinear measurements. In particular we will discuss the dual-arm (DA) Z-scan and an optical beam deflection experiment with remarkable sensitivity. The DA Z-scan is a differential technique that allows us to differentiate the nonlinear signal of a thin film from that of the substrate or, for solution measurements, the solute from that of the solvent. This has increased our signal-to-noise for measuring the thin-film/solute nonlinear refraction by an order of magnitude.

The beam deflection technique we have developed borrows from photothermal beam deflection spectroscopy which has been used for measuring extremely small linear-absorption-induced phase distortions. Here we use ultrashort pulses in a pump probe geometry where the refractive index gradient induced by a strong pump pulse deflects a weak probe pulse onto a quad-segmented photodetector. The advances in these quad photodetectors that are designed to measure small beam displacements make this technique sensitive to phase shifts as small as lambda/20,000. It is also capable of separately measuring the nonlinear absorption. Since this is a two-beam technique it can also give information on the temporal dependence of the nonlinearity in which a single beam Z-scan cannot.

We will report experiments using these techniques on a variety of materials.

***Keywords:*** *nonlinear optics, spectroscopy, nonlinear refraction, nonlinear absorption*

## 9237-37, SESSION 10

# Femtosecond damage threshold at kHz and MHz pulse repetition rates

**Benedek J. Nagy, Lénárd Vámos, Daniel Oszetzky, Peter Rácz, Peter Dombi,**
Wigner Research Ctr. for Physics of the H.A.S. (Hungary)

**SPEAKER BIOGRAPHY:** Benedek Nagy is assistant research fellow at the Wigner Research Centre for Physics in Hungary. He is currently a Ph.D. student. He earned his master degree in applied physics at the Budapest University of Technology and Economics. He got involved into laser physics during his master thesis work and he is responsible for the laser induced damage threshold measurements and their development in the Wigner RCP.

**ABSTRACT TEXT:** Femtosecond laser-induced damage threshold (LIDT) measurements for different optical components are well studied for a set of laser pulse repetition rates spanning the range between 1 Hz and 1 kHz [1, 2]. These results are valuable for the development of chirped pulse amplified laser systems at these repetition rates. Recent years saw the advent of high-repetition-rate femtosecond systems (beyond 1 kHz, up to some MHz) with relatively high pulse energy, including, for example, fiber lasers [3], various other Yb-based lasers and high-repetition-rate optical parametric amplifiers. In those cases it is an important laser engineering issue to determine the necessary beam expansion throughout the amplifier chain, as determined by the femtosecond LIDT of different interfaces and optical components.

As an initial study in this direction, we performed several femtosecond LIDT measurements on typically used ultrafast optical elements with different Ti:sapphire laser systems having substantially different pulse repetition rates (a 1 kHz regenerative amplifier and a 3.6 MHz long-cavity oscillator [4]). The concept of these measurements was to achieve easily comparable LIDT values measured at different repetition rates but at the same wavelength, pulse length and focal spot size with a process based on the ISO standard. To this end, we performed damage tests with an equal (90 fs) pulse length from both laser sources and the damage spot size was decreased to approximately 10 ?m which was necessary due to the low pulse energy of the long-cavity oscillator. This can be compensated for by taking into account the known LIDT scaling with spot size which is assumed to be valid in the femtosecond domain, too [5].

Upon these measurements, we found a remarkably large difference between kHz and MHz LIDT the origin of which requires further investigation. We took measurements on protected silver and high reflector (HR) mirrors designed for 800 nm. The LIDT for the protected silver mirror is 0.97 J/cm$^2$ and 0.13 J/cm$^2$ and the LIDT of the HR mirror is 0.42 J/cm$^2$ and 0.10 J/cm$^2$ for the kHz and the MHz repetition rates respectively. We also observed thermal effects during our tests the systematic study of which is a first step to investigate this new phenomenon. Further experiments with chirped mirrors are underway to confirm the observed differences and find an explanation of the observed strong repetition rate dependence of LIDT in the novel pulse repetition rate range between the kHz and MHz domains.

REFERENCES

[1] Mer?, M. et al. Optical Engineering 44(5), 051107 (2005).
[2] Bonse, J. et al. Thin Solid Films 408(1-2), 297–301 (2002).
[3] Eidam, T. et al. Opt. Lett. 35, 94–96 (2010).
[4] Dombi, P. and Antal, P. Laser Physics Letters 4(7), 538 (2007).
[5] DeShazer, L. G. et al. Applied Physics Letters 23(11), 607–609 (1973).

***Keywords:*** *laser induced damage threshold, repetition rate, femtosecond lasers*

# Research on limiting of high-power laser radiation in nonlinear nanomaterials

**Alexandr Y. Gerasimenko, Mikhail S. Savelyev,**
National Research Univ. of Electronic Technology (Russian Federation)

**SPEAKER BIOGRAPHY:** A. Gerasimenko - Senior Researcher, Associate Professor Department of Biomedical Systems: Interests - nonlinear optics, biophotonics, nanomaterials. M. Saveliev - postgraduate department of biomedical systems: Interests - nonlinear optics, optical tomography, mathematical modeling

**ABSTRACT TEXT:** The usage of high power laser systems promotes damage to the eyes and optical sensors. This generates a need for limiters of high power laser radiation (LR). Widely used absorbent and interference filters operate in narrow wavelength bands, and have a low linear transmittance. For these reasons, they can not be used for solving the problem of limiting LR. The function of materials of LR limiters is based on nonlinear optical mechanisms (nonlinear absorption, nonlinear refraction, induced scattering). Such materials will provide laser protection without disrupting the quality and color of the transmitted image. The task of creating such optical materials is yet remains unsolved. As well there is a problem of comparing these materials in order to determine the most effective due to the different experimental conditions (wavelength, pulse duration and shape, energy, waist radius of radiation, etc.).

Passage of pulsed radiation through the material with nonlinear absorption can be described by the radiation transport equation [1]. Usually nonlinear absorption which depends on the laser pulse intensity, is characterized by two parameters: the linear absorption coefficient and nonlinear absorption coefficient (thresholdless model) [2]. However the microscopic mechanisms of interaction of laser pulses with nonlinear material often possess threshold character, i.e. are activated at intensities above a certain threshold value. It is therefore advisable to consider a model in which the absorption coefficient has a threshold (threshold model):

- in the case of the intensity LR to be less than the threshold value, the absorption coefficient is determined by the linear absorption coefficient;
- in the case of the intensity LR to be larger than the threshold value, the absorption coefficient is determined by two parameters: the linear absorption coefficient and nonlinear absorption coefficient.

If threshold value equally zero, the threshold model becomes thresholdless model. Therefore, thresholdless model is a special case of threshold model.

Using the Z-scan technique with an open aperture the investigation of dispersed materials was performed for multi-wall carbon nanotubes (MWCNTs) in dimethylformamide (DMF), MWCNTs in tetrahydrofuran (THF) and single-walled carbon nanotubes (SWCNTs) in THF using lasers with pulse duration 7, 16 ns, wavelengths 532, 1064 nm and pulse energy up to 800 mJ.

Is was determined that the threshold model more accurately describes the experimental Z-scan data compared to the thresholdless model for all investigated dispersed materials of CNTs. This indicates the threshold character of microscopic mechanisms of interaction of laser pulses with these materials. The difference in the obtained values of nonlinear absorption coefficient is probably due to the boiling temperature of the solvents: 153 degrees Celsius for DMF and 66 degrees Celsius for THF.

Thus, the probability of shock boiling and formation of local inhomogeneities, which determine the intensity of laser light scattering, and hence the nonlinearity of dispersed materials of carbon nanotubes (CNTs) in THF is higher than in DMF.

The paper presents a new threshold model for calculating the intensity threshold value and nonlinear absorption coefficient s according to the Z-scan data.

Comparison of nonlinear optical characteristics of the above mentioned materials based on CNTs and materials based on ZnSe, porphyrin-graphene Graphene-TPP, fullerene-graphene Graphene C60, polyethylene oxide with MWCNTs, organic polymethine dyes PD-792, PD-7098 and pyran dyes DCM-627, DCM-684 [2] was performed.

For the first time the comparison of different nonlinear materials under identical conditions by constructing the output characteristics of laser radiation limiters was made. Change of the pulse shape after passing of laser radiation through various nonlinear dispersed materials is shown.

Studies indicate the possibility to apply the dispersed materials based on CNTs in comprising the limiters of the high power laser radiation. This work was supported by grant (SP-2477.2012.4).

REFERENCES

1. Tereshchenko S.A., Podgaetsky V.M. Determining the parameters of the laser radiation intensity limiter based on a time-dependent equation of radiative transfer in a nonlinear medium // Quantum electron. 2011. V. 41. N. 1. P. 26.
2. Tereshchenko S.A., Podgaetskii V.M., Gerasimenko A.Yu., Savel'ev. M.S. Investigation of nonlinear characteristics of Intensity limiters of high-power laser radiation // Optics and Spectroscopy. 2014. V. 116. N. 3. P. 454.

***Keywords:*** *nonlinear optics, limiting, high power, laser radiation, nanomaterials*

# 9237-39, SESSION 10

# Spectral and temperature-dependent infrared emissivity measurements of painted metals for improved temperature estimation during laser damage testing

**Sean M. Baumann, National Air and Space Intelligence Ctr. (United States); Michael A. Marciniak, Glen P. Perram,** Air Force Institute of Technology (United States)

**SPEAKER BIOGRAPHY:** Dr. Marciniak is an Associate Professor of Physics at the Air Force Institute of Technology (AFIT). He received his PhD from AFIT in 1995 and has been on faculty there since 1999. His research interests include various aspects of light-matter interaction, including (1) polarimetric scatterometry of nanostructured materials, such as photonic crystals, plasmonic materials, and optical meta-materials; (2) bidirectional reflectance distributions for optical signatures; and (3) high-energy laser damage assessment. He has published over 23 refereed and 53 other publications, and chaired 5 PhD and 47 MS thesis committees. He is a retired USAF Lt Col with 22 years of service.

**ABSTRACT TEXT:** A database of spectral, temperature-dependent emissivities was created for a range of painted-aluminum laser damage testing targets with the purpose of improving the accuracy with which temperature on front and back target surfaces may be estimated during laser damage testing. Previous temperature estimates had been made by fitting an assumed gray-body radiance curve to the radiance measured from the back surface via a Telops imaging Fourier transform spectrometer. In this work, temperature-dependent spectral emissivity measurements of the samples were made using an SOC-100 hemispherical directional reflectometer and Nicolet Fourier transform infrared spectrometer. Of particular interest was a high-temperature matte-black enamel paint used to coat the rear surfaces of the aluminum samples. The paint had been assumed to have a spectrally flat and temperature-invariant emissivity. However, the collected data showed both spectral variation and temperature dependence. The uncertainty in back-surface temperature estimation during laser damage testing made by using the measured emissivities was improved from ±25 degrees-C to ±5 degrees-C away from the beam center. At beam center, temperatures exceeded the capabilities of the SOC-100 reflectometer, so measured radiance fits reverted to gray-body fits and the uncertainty in estimated temperature increased commensurately. Accurate temperature measurements in laser damage testing are useful in informing a predictive model for future high-energy-laser weapon engagements.

***Keywords:*** *laser lethality, temperature dependent emissivity, spectral emissivity, infrared imaging Fourier transform spectroscopy*

## 9237-48, SESSION 10

# Thermal lensing of laser materials

**Mark J. Davis, Joseph S. Hayden,** SCHOTT North America, Inc. (United States)

**ABSTRACT TEXT:** A ubiquitous byproduct of lasing in solid-state media is the production of heat. While means exist (e.g., near-resonant pumping, clever system architecture) to mitigate potential detrimental effects from heating, the impact on the optics of gain media can be significant. This presentation focuses on the main three effects that can induce wave-front distortion: 1) thermo-optic (dn/dT); 2) stress-optic; and 3) surface deformation (e.g., "end-bulging" of a laser rod). Considering the simple case of a side-pumped cylindrical rod which is air- or water-cooled along its length, the internal temperature distribution has long been known to assume a simple parabolic profile (e.g., Foster and Osterink, 1970; Koechner, 1970). Resulting from this are two induced refractive index variations due to thermo-optic and stress-optic effects that also assume a parabolic profile, but generally not of the same magnitude, nor even of the same sign. Finally, a small deformation on the rod ends can induce a small additional lensing contribution. The landmark 1970 papers noted above treated this case and arrived at analytical expressions relating pump energy, rod geometry, and physical properties to an effective (total) induced lensing. First applied to YAG, their treatment has found widespread usage throughout the solid-state laser community for many years. We had two goals in this study: a) using finite-element simulations (COMSOL), to verify the existing analytical expressions; and b) apply them to glasses from the SCHOTT laser glass portfolio. The first goal was a reaction to more recent work by Chenais et al. (2006) who claimed Koechner (2006) made an error in his analysis with regard to thermal stress, throwing into doubt conclusions within studies since 1970 which made use of his equations. However, our re-analysis of their derivations, coupled with our FE modeling, confirmed that the Koechner and Foster & Osterink treatments are correct, and that Chenais et al. made mistakes in their derivation of the thermally-induced strain. Finally, for a nominal laser rod geometry, we compared the thermally-induced optical distortions in LG-680, LG-750, LG-760, LG-770, APG-1, and APG-2. While LG-750, -760, and -770 undergo considerable thermo-optic lensing, their stress-optic lensing is nearly of the same magnitude but of opposite sign, leading to a small total thermal lensing signature.

REFERENCES

Chenais, S., F. Druon, S. Forget, F. Balembois, and P. Georges, On thermal effects in solid-state lasers: The case of ytterbium-doped materials, Progress in Quantum Electronics, 30 (4), 89-153, 2006.

Foster, J.D., and L.M. Osterink, Thermal effects in a Nd-YAG laser, Journal of Applied Physics, 41 (9), 3656-&, 1970.

Koechner, W., Thermal lensing in a Nd-YAG laser rod, Applied Optics, 9 (11), 2548-&, 1970.

Koechner, W., Solid-State Laser Engineering, edited by W.T. Rhodes, 747 pp., Springer, New York, 2006.

***Keywords:*** *laser glass, thermal lensing, characterization*

## NOTES

# Wednesday PM • 17 September

## 2:10 pm to 3:50 pm • SESSION 11

## Materials and Measurements II

Session Chairs: **Carmen S. Menoni,** Colorado State Univ. (USA);
**Jérôme Néauport,** Commissariat à l'Énergie Atomique (France)

2:10 pm: **Determination of multi-pulse damage thresholds from crater-size measurements**, Matthias Lenzner, Lenzner Research, LLC (USA); Zhanliang Sun, Wolfgang Rudolph, The Univ. of New Mexico (USA) . . . . . . . . . . . . [9237-40]

2:30 pm: **Laser-induced damage morphology in fused silica at 1064nm in the nanosecond regime**, Maxime Chambonneau, Romain Diaz, Commissariat à l'Énergie Atomique (France); Guillaume Duchateau, Univ. Bordeaux 1 (France); Pierre Grua, Commissariat à l'Énergie Atomique (France); Jean-Yves Natoli, Institut Fresnel (France); Jean-Luc Rullier, Laurent Lamaignère, Commissariat à l'Énergie Atomique (France) . . . . . . . . . . . . [9237-41]

2:50 pm: **Three-dimensional mapping of absorption defects at 355nm for potassium dihydrogen phosphate (KDP) used in high-power laser systems**, Jian Chen, Jingtao Dong, Qi Zhang, Zhouling Wu, ZC Optoelectronic Technologies, Ltd. (China)[9237-42]

3:10 pm: **A maximum likelihood method for the measurement of laser damage threshold**, Jonathan W. Arenberg, Northrop Grumman Aerospace Systems (USA); Micheal D. Thomas, Spica Technologies, Inc. (USA) . . . . . . . . . . . . [9237-43]

3:30 pm: **Adaptive characterization of laser damage from sparse defects**, Sam Richman, Alexander R. Martin, Quentin Turchette, Trey Turner, Research Electro-Optics, Inc. (USA) . . . . . . . . . . . . [9237-44]

### 3:50 pm to 4:20 pm • Refreshment Break

## 4:20 pm to 5:40 pm • SESSION 12

## Materials and Measurements III

Session Chairs: **Detlev Ristau,** Laser Zentrum Hannover e.V. (Germany);
**Vitaly E. Gruzdev,** Univ. of Missouri-Columbia (USA)

4:20 pm: **Harmonisation of two nanosecond laser-induced damage testing facilities at 1064nm in vacuum and ambient pressure**, Clemens Heese, Alessandra Ciapponi, European Space Research and Technology Ctr. (Netherlands); Jorge Piris, European Space Agency (Netherlands); Paul Allenspacher, Melanie Lammers, Wolfgang Riede, Deutsches Zentrum für Luft- und Raumfahrt e.V. (Germany); Toncho Ivanov, European Space Research and Technology Ctr. (Netherlands). . . . . . . . . . . . . [9237-45]

4:40 pm: **In-line quantitative phase imaging for damage detection and analysis**, Dam-Be L. Douti, Institut Fresnel (France); Sherazade Aknoun, Institut Fresnel (France) and Phasics S.A. (France); Laurent Gallais, Serge Monneret, Mireille Commandré, Institut Fresnel (France). . . . . . . . . . . . . [9237-46]

5:00 pm: **Laser-induced damage threshold of a hybrid mirrors designed for broadband operation in HiLASE beam distribution system**, Jan Vanda, Institute of Physics of the ASCR, v.v.i. (Czech Republic); Adrien Hervy, Ecole Nationale Supérieure de Techniques Avancées (France) and Aix-Marseille Univ. (France) and REOSC (France); Vaclav Skoda, CRYTUR spol s.r.o. (Czech Republic) . . . . . . . . . . . . [9237-36]

5:20 pm: **Mono-module disk laser**, Victor V. Apollonov, A. M. Prokhorov General Physics Institute (Russian Federation) . . . . . . . . . . . . [9237-49]

### 5:40 pm to 5:50 pm • Closing Remarks

## 9237-40, SESSION 11

# Determination of multi-pulse damage thresholds from crater-size measurements

**Matthias Lenzner,** Lenzner Research, LLC (United States);
**Zhanliang Sun, Wolfgang Rudolph,** The Univ. of New Mexico (United States)

**SPEAKER BIOGRAPHY:** Matthias Lenzner graduated from the Friedrich-Schiller-University of Jena, Germany with a Diploma degree in Physics in 1986 and Ph.D. in Physics in 1989, both on optoelectronic switching in semiconductors. He was with the semiconductor group of Vilnius University, Lithuania for 6 months and with the University of New Mexico in Albuquerque, NM for one year in 1991/92. From 1994-2000 he was working with the femtosecond laser group of the Vienna University of Technology, Austria, where his special research interest wa the investigation of ultrafast processes in laser-solid interaction.

Starting from 2001, he worked several years as R&D manager for a company in Berlin, Germany that developed and manufactured laser systems for refractive eye surgery. In September 2004, he joined the Physics Department of The City College of New York as a faculty member. Since 2010, he is working in Tucson, AZ as an independent researcher.

**ABSTRACT TEXT:** The determination of single pulse damage thresholds from measurements of the ablated crater area as a function of incident fluence is a straightforward and well established technique [J. M. Liu, Opt. Lett. 7 (1982) 196]. We show that the same technique can be applied to the determination of the multi-pulse laser-induced damage threshold (LIDT). Since the multi-pulse thresholds of dielectric and metallic materials are controlled by incubation effects, they depend on the illumination history. This threshold is therefore a function of the number of pulses N and where within the spot size (position r) the LIDT is exceeded: Fth=Fth(N,r). For this reason, it is not a priori clear whether A versus ln F is linear and can be extrapolated to find Fth. We generalized common incubation models for dielectric materials and metals and compared these to experimental data, concluding that multi-pulse LIDT measurements can be based on crater size measurements similar to 1-on-1 damage tests. This permits the determination of N-on-1 LIDTs with postillumination sample inspection, which is important in situations where in situ monitoring is not possible or unreliable.

***Keywords:*** *laser induced damage, measurement of damage threshold, LIDT, incubation effects on LIDT*

## 9237-41, SESSION 11

# Laser-induced damage morphology in fused silica at 1064nm in the nanosecond regime

**Maxime Chambonneau, Romain Diaz,** Commissariat à l'Énergie Atomique (France);
**Guillaume Duchateau,** Univ. Bordeaux 1 (France); Pierre Grua, Commissariat à l'Énergie Atomique (France); **Jean-Yves Natoli,** Institut Fresnel (France);
**Jean-Luc Rullier, Laurent Lamaignère,** Commissariat à l'Énergie Atomique (France)

**ABSTRACT TEXT:** The morphology of laser-induced damage sites at the exit surface of fused silica is tightly correlated to the mode composition of the nanosecond laser pulses at 1064 nm. In the single longitudinal mode (SLM) configuration, a molten and fractured central zone is surrounded by a funnel-shaped surface modification. Ring patterns surround the damage sites when these are initiated by multiple longitudinal modes (MLM) laser pulses. In this last mode configuration, the pulses temporal profiles as well as the damage ring patterns differ from pulse to pulse. The appearance chronology of the rings is found to be closely related to the temporal shape of the laser pulses. This supports that the damage morphology originates from the coupling of a laser-supported detonation wave propagating in air with an ablation mechanism in silica. In our experiments, the propagation speed of the detonation wave reaches about 20 km/s, and its scaling as the cube root of the laser intensity can be explained on the basis of hydrodynamic modeling. Additional experiments performed in vacuum and at lower wavelengths enable the understanding of the damage morphology in both SLM and MLM configurations.

***Keywords:*** *laser induced damage, morphology, silica, nanosecond, single longitudinal mode, multiple longitudinal modes, ring pattern, 1064nm*

## 9237-42, SESSION 11

# Three-dimensional mapping of absorption defects at 355nm for potassium dihydrogen phosphate (KDP) used in high-power laser systems

**Jian Chen, Jingtao Dong, Qi Zhang, Zhouling Wu,**
ZC Optoelectronic Technologies, Ltd. (China)

Potassium dihydrogen phosphate (KDP) is commonly used for frequency conversion and optical switching applications in many high-power laser systems. Such applications require high damage threshold of KDP crystals. Damage behavior of KDP has been investigated for many years, and the results show that intrinsic or extrinsic defects are responsible for highly localized absorption in KDP materials, and that in turn will cause the laser damage.

In this paper, we studied the absorption properties of KDP crystals at wavelengths of 355 nm by using a three-dimensional (3D) photothermal microscope. The advantage of the 3D photothermal microscope for defect characterization was discussed through comparison between the photothermal microscopic results and the results from other defect characterization methods, such as optical scattering mapping and laser induced fluorescence.

# 9237-43, SESSION 11

# A maximum likelihood method for the measurement of laser damage threshold

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

**SPEAKER BIOGRAPHY:** Jonathan Arenberg is the Chief Engineer for the James Webb Space Telescope program at Northrop Grumman Aerospace Systems. Dr. Arenberg has been with Northrop Grumman since 1989 having begun his career with Hughes Aircraft Company in 1982. His work experience includes optical, space and laser systems. Dr. Arenberg has worked on such astronomical programs as the Chandra X-ray Observatory, James Webb Space Telescope and helped develop the New Worlds Observer concept for the imaging of extra-solar planets. He has worked on several major high-energy and tactical laser systems, laser component engineering and metrology issues. He is a US delegate to the ISO sub-committee charged with writing standards for laser and electro-optic systems and components, SPIE, American Astronomical Society and AIAA. Dr. Arenberg holds a BS in physics and an MS and PhD in engineering, all from the University of California, Los Angeles.

**ABSTRACT TEXT:** Recently, we have shown that application of maximum likelihood (ML) techniques to the measurement of laser damage threshold shows promise as an unbiased solution to the problem of laser damage threshold measurement. In this year's report, we introduce a candidate test procedure for a ML for threshold measurement. The derivation of the probability of damage model, test fluence selection protocol and analysis method are discussed in some detail. The discussion concludes with a demonstration of the performance of the test procedure.

***Keywords:*** *laser damage testing, laser damage threshold, binary search, maximum likelihood*

## 9237-44, SESSION 11

# Adaptive characterization of laser damage from sparse defects

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

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

**ABSTRACT TEXT:** Standard techniques for characterizing laser damage are ill-suited to the regime in which sparse defects form the dominant mechanism. Previous work on this problem using REO's automated laser damage threshold test system has included linking damage events in HfO2/SiO2 high reflector coatings with visible pre-existing defects, and using a probability per defect based on size and local fluence to generate predictions of damage events in subsequent coating runs. However, in all this work the test sites were always in a predefined array, and the association of defects with damage events was done only after the fact. In an effort to make this process both more efficient and less susceptible to uncertainties, we have now developed an adaptive test strategy that puts defect identification and analysis into the loop. A map of defect locations and sizes on a test surface is compiled, and a set of test sites and corresponding fluences based on that map is then generated. With defects of interest now centered on the damaging beam, the problem of higher-order spatial variation in the beam profile is greatly reduced. Test sites in defect-free zones are also included. This technique allows for the test regimen to be tailored to the specific surface under consideration. We report on characterization of a variety of coating materials and designs with this adaptive method.

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***Keywords:*** *laser damage threshold, surface quality, sparse defects, damage testing protocol, adaptive test strategy, damage precursors, 1064nm*

# 9237-36, SESSION 12

## Laser-induced damage threshold of a hybrid mirrors designed for broadband operation in HiLASE beam distribution system

**Jan Vanda,** Institute of Physics of the ASCR, v.v.i. (Czech Republic);
**Adrien Hervy,** Ecole Nationale Supérieure de Techniques Avancées (France) and Aix-Marseille Univ. (France) and REOSC (France);
**Vaclav Skoda,** CRYTUR spol s.r.o. (Czech Republic)

**SPEAKER BIOGRAPHY:** Jan Vanda was born in 1980, Czech Republic. At 1999 he started at VSB-Technical University of Ostrava, where he done both his master and Ph.D. degrees in the field of electronics and telecommunications. At January 2009 he successfully defended his doctoral thesis on microstructured optical fibers. After short training in private companies, he took one year post-doctoral position in FORTH-IESL, Crete, Greece, where he worked on advanced utilization of superparamagnetic fluids in optical fibers. When project finished, he moved to the Czech Office for Standards, Metrology and Testing, where he represented Office in international organizations as permanent delegate in IEC and CENELEC. Since January 2012, he is working as junior researcher in HiLASE project at Institute of Physics, ASCR. His professional interest lies within optical fibers, microstructures, and applied optics.

**ABSTRACT TEXT:** Research and development of novel materials and novel measurement methods for optical coatings, mirrors, crystals and other components is highly desirable. Pulsed lasers in general and those operating with pulses shorter than 10 ps in particular evolved rapidly in the past years with respect to energy or average power they can provide. Purely scientific setups, originally designed for the fundamental research, have extended into many fields, as metrology, machining or medical devices. Utilizing of gathered knowledge and state-of-the-art then allowed construction of compact devices in applied research and industry, which can reach substantial output powers and energy densities. Such leap can be however achieved only by utilizing of solid state lasers, who are the only solution offering enough performance and scalability. Consequently, need for highly reliable, strong and durable optical components emerged and significant efforts are currently invested into development of such parts.

Other significant change is changing of interest in wavelength range. As in the past were most accessible and used solid state lasers based on titanium doped sapphire with wavelengths around 800 nm, demand from industrial and other applications created pressure to move towards longer wavelengths. This introduced another degree of complexity considering laser system components – it is very difficult to prepare structures based on dielectric thin films for wavelengths around 2 μm or longer. In the same manner requirements for broadband components with considerable damage threshold capable operating at longer wavelengths has arisen, as many wavelength tuning grown to be broadly available. Uses of metallic or metallic film based components are no longer an option, as they provide relatively low damage threshold and propensity towards damage. Promising solution of such challenge can be so-called hybrid components. Such devices, based on combination of metallic and dielectric thin films, connect advantages of both materials. Native application of hybrid thin film structure is hybrid mirror, where damage threshold of component can be, for certain band of wavelengths, significantly improved by introducing proper dielectric layers structure while broadband operation of mirror will be preserved. Consequently, the same beam distribution line can be safely used both for output of high energy pumping laser and for output of broadband wavelength tuning system. This approach leads to reduced complexity and increased reliability of the whole system.

Certain research project, as for example HiLASE, has important role in providing engineering background for the fundamental research as well as transfer scientific results from the field of the high average power lasers into application level. For this purpose, HiLASE is developing three Yb:YAG kW class thin-disk laser lines, delivering 1-2 picosecond pulses of energy 1 Joule with repetition rate up to 1 kHz and beam diameter 15 mm, and one Yb:YAG multislab system delivering 1-2 nanosecond pulses of energy 100 Joules with repetition rate up to 100 Hz and beam diameter 45 mm, both operating at 1030 nm. Thin disk system is further going to be equipped with wavelength conversion to provide spectrum of wavelengths in the near- and mid- infrared region whereby need for reliable, high performance broadband components for such wavelengths is formed. Following paper presents progress in LIDT of currently developed high damage threshold broadband hybrid mirrors, intended for use in laser system built within the HiLASE project as well as for the future deployment in the commercial systems.

***Keywords:*** *LIDT, laser, hybrid mirror*

# Harmonisation of two nanosecond laser-induced damage testing facilities at 1064nm in vacuum and ambient pressure

**Clemens Heese, Alessandra Ciapponi,** European Space Research and Technology Ctr. (Netherlands); Jorge Piris, European Space Agency (Netherlands); **Paul Allenspacher, Melanie Lammers, Wolfgang Riede**, Deutsches Zentrum für Luft- und Raumfahrt e.V. (Germany); **Toncho Ivanov,** European Space Research and Technology Ctr. (Netherlands)

**ABSTRACT TEXT:** The international standard for laser-induced damage threshold (LIDT) testing of optical coatings is built on regular inter-laboratory comparisons, so called round-robins. In 1983 and 1997 such experiments were conducted at the fundamental wavelength of the Nd:YAG laser under atmospheric conditions settling the international standard as it is known today.

In 2013 DLR, LZH, University of Vilnius and ESA extended this comparison to LIDT measurements in vacuum. One of the major contributors to the uncertainty of the measurements was the sample-to-sample variation of the same batch, as well as the different pulse durations used. Applying scaling laws seemed to be difficult, as they are not determined to the level of precision necessary.

To establish a higher level of confidence in the correlation of both DLR and ESA's LIDT measurement facilities, tests were conducted on the same sample at identical pulse duration of 10 ns at a wavelength of 1064 nm. Furthermore the same type of diode pumped, injection seeded laser was used. These measures limit the number of tests that we are able to directly compare, as each facility has to test a significant area on each samples (>100 sites).

Four samples have been compared with the S-on-1 method according to ISO21254-1, two AR1064/0° windows and two silicon wafer. The total variation of the 0% damage probability values after 10000 shots is less than 20%, which is well within the 2$\sigma$ uncertainty, both laboratories calculate individually.

The obtained level of agreement of the measurements is, to our best knowledge, the closest agreement of two ISO21254-1 nanosecond LIDT testing facilities. To achieve this high level of confidence both facilities did undergo a deep mutual review process of all used measurement and analysis methods. Within the scope of this review activity the ESA opto-electronics laboratory achieved ISO17025 accreditation and got the accreditation for measurement of "Laser Induced Damage Threshold Measurements" according to ISO21254 series accredited by RvA (Dutch accreditation council) under L412.

In this paper we will discuss the difficulties of performing comparable laser damage testing as well as a detailed analysis of the measurements conducted on the samples for this harmonisation activity.

***Keywords:*** *LIDT, ISO21254, ISO17025, laser, damage, coating, round-robin, inter-laboratory comparison*

# In-line quantitative phase imaging for damage detection and analysis

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**ABSTRACT TEXT:** Laser-induced damage is usually defined as any permanent modification of a material that has been induced by laser irradiation. The damage occurrence and hence the power or energetic threshold level of its occurrence is then directly related to the observation technique that is used for damage detection. The choice and implementation of this technique is a then critical issue when investigating the laser damage resistance of samples for practical or fundamental applications. Different detection systems have been tested and used in the community based on different techniques: scattering (dark field imaging or scattering measurement of a probe beam), imaging, plasma detection, spectrophotometry, photoacoustic effect,… The recommended technique by the ISO standard for surface damage detection is the use of a Nomarski microscope, which is sensitive to optical path length of the sample and can evidence otherwise invisible features (refractive index or topological modifications). Visual inspection under Nomarski microscope is often found to be the most reliable and sensitive technique.

In this work we investigate a new technique for laser damage detection based on phase imaging. A wavefront sensor based on quadriwave lateral shearing interferometry (QLSI) associated to a high magnification optical microscope has been used to observe samples irradiated by a femtosecond laser. By comparing a reference measurement done before irradiation to a post-irradiation measurement, a high resolution image of the change in the sample optical path induced by the laser irradiation is obtained. The technique has been applied to the analysis of bulk (fused silica) and thin film samples ($Nb_2O_5$, $Ta_2O_5$, $SiO_2$, $HfO_2$) irradiated by a 500fs laser in different conditions: single or multiple pulses, UV (343nm) or IR (1030nm) wavelength. The results are compared to ex-situ observations of the samples made with other techniques: Nomarski microscopy, Scanning Electron Microcopy, Atomic Force Microscopy. QLSI is found particularly suitable for damage detection since it realizes higher sensitivity, convenient use and can provide quantitative information on the refractive index or surface modification of the samples under test.

***Keywords:*** *laser damage detection, phase measurement*

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# Mono-module disk laser

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**ABSTRACT TEXT:** The mono-module disk laser concept is an effective design for diode-pumped solid-state lasers, which allows the realization of lasers with super-high output power, having very good efficiency and also excellent beam quality. Since the first demonstration of the principle in 1964the output power of mono-module disk has been increased to the level of few kW in continuous wave (CW) mode of operation. "Zig-Zag" disk laser geometry does not look like as a perspective one for further output parameters growing. The scaling laws for mono-module disk laser design show that the limits for CW mode of operation is far beyond 100 kW for output power. Due to the efficient porous cooling technology and possibility of amplified spontaneous emission (ASE) suppression the operation of the mono-module disk laser geometry is possible in CW and pulse-periodical (P-P) modes at extremely high output power.

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