50th ANNUAL LASER DAMAGE SYMPOSIUM
Proceedings

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LASER-INDUCED DAMAGE IN OPTICAL MATERIALS 2018

23–26 September 2018
Boulder, Colorado

Editors
Christopher Wren Carr, Gregory J. Exarhos, Vitaly E. Gruzdev, Detlev Ristau, M.J. Soileau

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Summary of Meeting

SPIE Laser Damage Symposium
50th Annual Symposium on Optical Materials for High Power Laser
23-26 September 2018

Vitaly E. Gruzdev
Department of Physics and Astronomy
University of New Mexico
Albuquerque, NM, 87131, USA

1. Abstract

These proceedings contain the papers presented as oral and poster presentations at the Anniversary 50th SPIE Laser Damage Symposium (aka Annual Symposium on Optical Materials for High-Power Lasers). The conference was held at Millennium Harvest House Hotel in Boulder, Colorado on 23-26 September 2018. The symposium was divided into oral and poster sessions following the traditional four major topics: thin films; surfaces, mirrors and contamination; fundamental mechanisms; materials and measurements. A mini-symposium was devoted to overview of the 50 years of history and achievements of the conference. A tutorial on laser-beam characterization was held by Bernd Eppich as a pre-symposium event on Sunday evening. The conference was opened by M. J. Soileau with an anniversary symposium welcome. A brief Tribute was devoted to Joan Guenther to remember her contribution to the conference as a wife and supporter of the conference co-founder Arthur Guenther, and as a conference treasurer. Gregory J. Exarhos of Pacific Northwest National Laboratory (USA), Vitaly Gruzdev of the University of New Mexico (USA), Christopher Wren Carr of the Lawrence Livermore National Laboratory (USA), Detlev Ristau of the Laser Zentrum Hannover e.V. (Germany), and M. J. Soileau of CREOL - The College of Optics and Photonics, University of Central Florida (USA) co-chaired the symposium. The founding organizers of the symposium are Dr. Arthur H. Guenther and Dr. Alexander J. Glass.

91 abstracts were submitted to the symposium, of which 89 were included into the conference program and 85 were presented at 12 oral and 4 poster sessions. No parallel sessions were held allowing the opportunity to discuss common research interests with all the presenters. With 170 attendees, 65 of which were authors, 21 – students, and 19 more - meeting co-chairs and program-committee members, the meeting holds a record attendance over last 30 years. As usually, the conference offered an outstanding opportunity to make many new acquaintances. Although held annually in the US, Laser Damage Symposium continues to be a true international conference with 51% of all presentations and 39% of the attendees coming from Europe and Asia this year. Following the active discussions, the Symposium was held at Boulder Millennium Harvest House Hotel in Boulder, Colorado for another year.

The 51st Annual Symposium of this series will be held in Omni Interlocken hotel in Boulder, Colorado, 22-25 September 2019. In response to multiple concerns of conference participants in 2018, the meeting will be held in another hotel. A traditional continuous effort will be made to ensure a close liaison between the high-energy, high-peak-power, and high-average-power laser communities. A mini-symposium of the 2019 meeting will be focused on manufacturing, properties, and laser-induced damage of diffraction gratings for laser systems.

The principal topics to be considered in 2019 do not appreciably deviate from those enumerated above. We expect to hear more about the impacts of surface contamination, debris, and surface treatment on the laser resistance of laser optics. Influence of various defects of optical materials continues to generate a significant interest over decades. Nonlinear and laser crystals, surfaces, and optical coatings continue to place major limitations on laser systems and remain the most active areas of laser-damage research and spirited debate. Recent progress in improvement and revision of the international standards on laser-induced damage will continue to attract significant attention of conference participants. Refinement of the mitigation strategy consisting of damage initiation followed by arresting damage growth through post-processing techniques while not creating downstream damage is also expected to be a continued focus. Laser damage by short-wavelength radiation stays an area of interest stimulated by the demand for laser-resistant UV optics utilized in laser-lithography applications. Short pulse (nanosecond and picosecond) laser

optics and damage phenomena surprisingly remain an active area of research over several decades. Constant progress in the fields of ultrashort-pulse (femtosecond) lasers and ultrafast laser-material interactions has become a substantial part of the conference. We also expect to hear more about new measurement techniques to improve our understanding of the fundamental damage mechanisms and to advance the manufacturing of optical materials and thin films for optical components. Thin films for a broad range of laser wavelengths and pulse durations continue to stay another hot topic of the meeting. Also, recent developments in the fields of surface nanostructuring, meta-optical materials, and related laser-damage issues will attract growing attention due to their intensive development and potential use in high-power lasers. Fundamental aspects of laser-induced damage including laser-induced ionization, scaling of damage threshold with laser and material parameters, dynamics of the damage processes, transient material responses, and various nonlinear effects continuously attract a lot of attention due to exploration of novel ranges of laser parameters.

As was initially established in 1992, several distinguished invited speakers will deliver keynote presentations of a tutorial and review nature in 2019. Invited contributors will cover recent breaking developments in the key areas of the research on laser-induced damage and optical materials for lasers. A tutorial on optical coatings and related laser-damage issues will be held as a pre-symposium event on Sunday evening.

The purpose of this series of symposia is to provide an international platform for information exchange about optical materials for high-power / high-energy lasers, fundamental mechanisms of the laser-solid interactions, improvement of optical coatings, studies of contamination effects, laser-damage standards, and a broad range of topics related to laser-induced damage in the materials. Co-chairs welcome relevant comments and criticism from interested readers.

Key words: laser damage, laser-material interaction, high-power lasers, high-energy lasers, optical components, optical fabrication, optical materials, thin film coatings, contamination, ultrafast laser-matter interactions.

2. Introduction

The anniversary Laser Damage Symposium - 50th Annual Symposium on Optical Materials for High-Power Lasers (a.k.a. the Boulder Damage Symposium, because of its Boulder, Colorado, venue) was held on 23-26 September 2018 in the atmosphere of celebration and busy conference schedule. This symposium continues to be the principal US and International forum for the exchange of information relative to laser-induced damage in all types of optical materials, and the interactions of intense laser light with optical media and components. This year, it was attended by 170 representatives of academia, industry, national research laboratories and centers (Fig. 1) from 11 countries that was about 14% increase in attendance compared to Laser Damage-2017 (Fig. 2). Countries of North America, Europe, and Asia were represented at the conference in 2018 with no participants from other continents (Fig. 3). 91 abstracts were submitted to the Symposium, 89 of them were included into the final program, and 85 were delivered within the traditional 3-day format of the meeting including 54 oral and 31 poster presentations. The large number of presentations has resulted in a very busy conference schedule addressed in feedbacks of meeting attendees. In response to the feedbacks, a limitation on the number of invited talks has been put starting from 2019. Also, extension of the poster sessions to Wednesday is under consideration of the conference co-chairs to provide more relaxed environment and enough time for discussions and communications during the conference.

Although, held annually in the US, this is a truly International conference with 39% of the attendees and 51% percent of the presentations coming from abroad this year (Fig. 3). Historically, the meeting has been divided into four broad categories: thin films; fundamental mechanisms; materials and measurements; and surfaces, mirrors, and contamination. Starting from 1992, a mini-symposium is held to highlight hot research topics and areas of active research and special interest in the fields related to high-power/high-energy lasers, laser-induced damage, and optical materials. Starting from 2014, a traditional pre-symposium event – a Round-Table discussion held on Sunday evening – was replaced with a tutorial. This year it featured methods of measurement and characterization of laser-beam parameters and was entitled “Laser Beam Characterization”. The tutorial was delivered by Dr. Bernd Eppich (Ferdinand-Braun-Institut, Leibniz-Institut für Höchstfrequenztechnik, Germany) on Sunday. The tutorial attracted almost half of the total number of conference participants and was accepted very well. The conference began on Monday, 24 September 2018 with a welcome talk delivered by Dr. M. J. Soileau (CREOL – the College of Optics and Photonics, University of Central Florida, USA). The talk addressed the 50th anniversary of the conference. A Tribute was devoted to Joan Guenther to remember her contribution to the conference as a wife and supporter of the conference co-founder Arthur Guenther, and as a conference treasurer who suddenly passed away on April 12, 2018.

Fig. 1. A group photo of participants of the Anniversary 50th Laser Damage Symposium taken in front of the National Center for Atmospheric Research in Boulder, Colorado on September 25, 2018.

3. Symposium Cochairs

The Boulder Damage Symposium was founded by Dr. A. H. Guenther and Dr. Alexander Glass. Over the last 49 years many prominent leaders within the high-power laser community have contributed significantly as Co-Chairs to this conference. A historical timeline of their contributions is listed below:

1969	A. H. Guenther, and A. J. Glass (C. M. Stickley)
1979	add H. E. Bennett and B. E. Newnam
1981	add D. Milam; A. J. Glass departs
1987	add M. J. Soileau
1988	D. Milam departs
1989	add L. L. Chase
1994	add M. R. Kozlowski; L. L. Chase departs
1997	add G. J. Exarhos and K. L. Lewis; H. E. Bennett and B. E. Newnam depart
2001	add C. J. Stolz
2002	add N. Kaiser; M. R. Kozlowski departs
2004	N. Kaiser departs
2005	add D. Ristau
2007	A. H. Guenther deceased
2008	K. L. Lewis departs
2009	add V. E. Gruzdev
2010	add J. A. Menapace; C. J. Stolz departs
2017	add C. W Carr; J. A. Menapace departs.
2018	add C. Menoni; G. J. Exharhos departs; M. J. Soileau departs and becomes a honorary co-chair.

4. Pre-symposium event: tutorial

Symposium Tutorial is the newest Symposium event introduced for the first time in 2014. That year, the tutorial was focused on the basics of thin films under the topic “Fundamentals of Growth and Characterization of Amorphous Thin Films for Interference Coatings” and was held by Dr. Carmen Menoni (Colorado State University, USA) and Dr. Wolfgang Rudolph (University of New Mexico, USA). Following highly positive response of tutorial attendees, another Tutorial was held again in 2015 as a pre-symposium event on Sunday evening. It was prepared and held by Dr. Laurent Gallais (Institut Fresnel, France) and featured defect-induced laser damage under the topic “Defect-Induced Damage in Nano- and Femtosecond Regime”. In 2016, the Tutorial entitled “Advanced Materials for High Laser-Damage Resistance” was prepared and delivered by Dr. Marco Jupe (Laser Zentrum Hannover, Germany). The lecture part was focused on the interplay of three major topics of this Symposium: optical materials, thin films for optical coatings, and fundamental mechanisms of ultrafast laser-material interactions. In 2017, the Tutorial was entitled “Femtosecond Laser Damage: Past, Present, and Future” and was delivered by Dr. Enam Chowdhury (The Ohio State University, USA). It was focused on overview of the fundamental research on mechanisms and major effects of the ultrafast laser-induced damage to transparent optical materials, optical coatings, and metal surfaces.

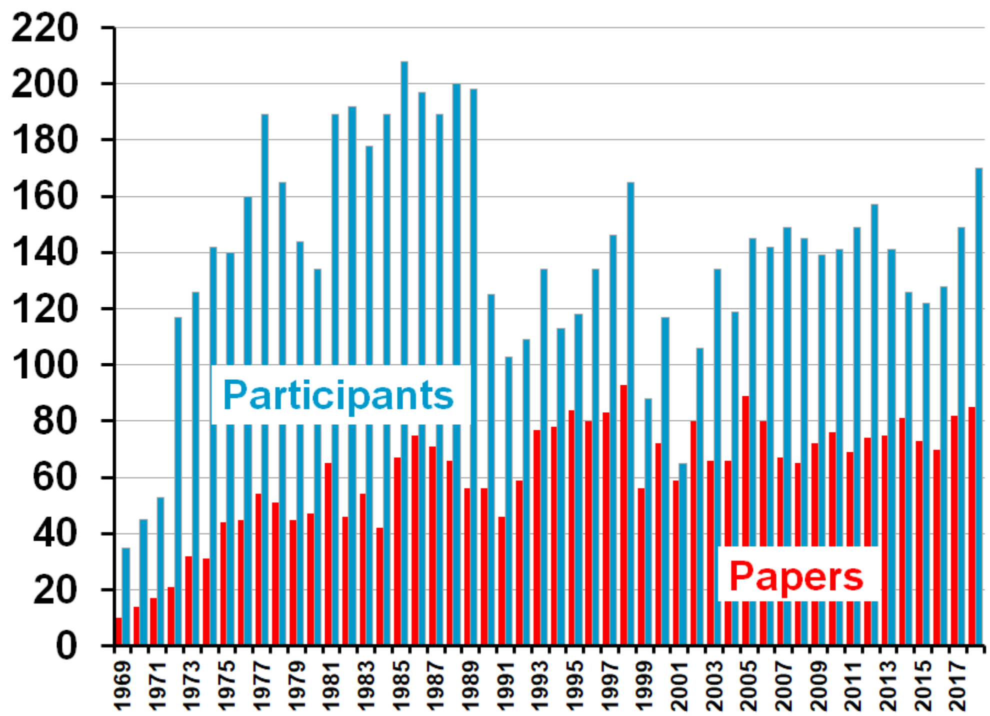

Fig. 2. Registered participants (blue columns) vs number of presented papers (red columns) vs year from 1969 through 2018 inclusive. The vertical axis shows absolute number of participants/presentations.

The global topic of that tutorial resulted in extended duration of the presentation (about 1.5 hour) that was addressed by attendees in their responses. In 2018, the Tutorial featured basic and advanced approaches to characterize laser beams and measure their basic parameters. It was entitled “Laser Beam Characterization”. The tutorial was prepared and held by Dr. Bernd Eppich (Ferdinand-Braun-Institut, Leibniz-Institut für Höchstfrequenztechnik, Germany). At the beginning, the tutorial was attended by some 65-70 participants of the conference, but more people joined it soon after finishing the registration.

5. Thin Films

Due to the tremendous range of applications of optical multilayer coatings for modifying the optical performance of elements (e.g., reflectivity, wavelength sensitivity, polarization, or simply protection), this category continued to be one of the largest parts of the meeting and received very significant attention. Thin films and optical coatings are known to demonstrate the lowest thresholds of laser-induced damage compared to those of bulk materials. Besides damage thresholds or sensitivity of particular coatings to high-power laser radiation, the topics of 2018 included improvement of film structure and film design, novel film and substrate materials, film response to aging, influence of substrate preparation on film quality, film contamination and defects, use of porous materials for production of coatings, specific features of damage morphology on various optical coatings, fatigue effects in single-layer coatings, influence of water vapors and argon on coating quality, and numerous reports on improvement of film-deposition techniques including use of plasma-assisted evaporation, reactive magnetron sputtering, electron and ion beam sputtering. Oxide films including hafnia and silica continued to attract major attention in the field of thin-film materials, but this year we also heard about use of MgF_2. Major attention was traditionally paid to coatings at 1064 nm, 532 nm, 355 nm, but coatings for mid-infrared also received increasing attention. Damage of multilayer mirrors and anti-reflection coatings by ultrashort pulses were another significant focus of this section. This year we heard about effect of films stresses on laser-induced damage. Among novel approaches, there was reported development of anti-reflection adaptive mixed thin films based on use of porous thin films.

Dense thin films offer the benefit of environmental stability, and a significant research is proceeding in this direction in the field of thin films. Laser interaction studies uncover areas where dense films offer advantages over traditional e-beam coatings. Also, as shown from the thin film damage competition, there are a number of companies that are manufacturing dense coatings by a variety of deposition techniques to deliver very high laser resistance. As before, thin-film laser damage competition was one of the major events of the Thin Film section.

Defects and interfaces continued to be a traditional area of high interest. They were approached by deposition optimization to minimize defect density, optimization of film composition, specific vacuum conditions, and laser-conditioning mitigation techniques. We continued to see interest in defect detection and characterization in various films and coatings. This year, invited talk of Dr. Michel Lequime (Institut Fresnel, France) emphasized optimization of multi-layer design to achieve active functionality of the coatings including all-optical switching, high-efficiency frequency conversion, and controlling of spectral properties of the coatings by laser radiation. With total of 15 oral and 11 poster presentations in conference program, the Thin Film section was the second largest in the 2018 meeting and confirmed a strong interest of the optical-coating community to laser-damage issues.

6. Thin-film laser damage competition

This year, the eleventh thin-film damage competition was organized by Dr. Raluca Negres and Dr. Christopher Stolz of Lawrence Livermore National Laboratory (USA). The competition started in 2008 to sample the government, industrial, and academic sectors producing high laser resistant optical coatings. In parallel with the 50th anniversary of the conference, this annual event celebrated 10 years of the competition history. Motivated by this fact, this year's competition was focused on the same multilayer mirrors tested in 2008 when this event was first launched to track progress in this specific field over the 10 years. Zero-degree-of-incidence high reflecting coatings were tested using a raster scan method at 1064 nm wavelength with 5-ns laser pulses at 10 kHz repetition rate in a single longitudinal mode regime. The mirror specifications exactly reproduced those announced in 2008. The participants from the USA, Europe, and Asia selected coating materials coating design, and deposition method on their own. The samples were tested at the same damage-testing facility of Spica Technologies Inc. (USA) that was utilized for the damage tests in 2008 to enable direct and reliable comparison among the participants. Details of the testing procedure and major results of the tests were delivered by Raluca A. Negres on Wednesday morning (September 26) in the talk entitled "1064-nm Mirror Thin Film Damage Competition".

The table below summarizes the 11 damage-test competitions performed from 2008 to 2018 inclusive.

2008	HR mirrors for Nd-YAG lasers, wavelength 1064 nm, 0-degree incidence, nanosecond pulses
2009	HR mirrors for Ti-sapphire lasers, wavelength 780 nm, femtosecond pulses
2010	AR coatings for excimer lasers, wavelength 351 nm, nanosecond pulses
2011	HR mirrors for excimer lasers, wavelength 193 nm, nanosecond pulses
2012	Brewster-angle thin film polarizer, wavelength 1064 nm, nanosecond pulses, p-polarization
2013	Brewster-angle thin film polarizer, wavelength 1064 nm, nanosecond pulses, s-polarization
2014	Narrow-bandwidth Fabry-Perot transmission filters, wavelength 1064, nanosecond pulses
2015	Broadband low-dispersion mirror, wavelength 773 nm, picosecond pulses
2016	Broadband low-dispersion femtosecond mirror, wavelength 773 nm, 45 degrees AOI, p-polarization
2017	HR laser mirrors at wavelength 355 nm, nanosecond pulses
2018	HR mirros for Nd-YAG lasers, wavelength 1064 nm, 0-degree incidence, nanosecond pulses

7. Fundamental Mechanisms

This section traditionally deals with the fundamental effects and mechanisms of the interactions of high-intensity light with matter. The traditional topics include laser-induced ionization, nonlinear behavior and effects of material response, self-focusing and other nonlinear propagation effects, modeling of thermal and non-thermal processes, and experimental data reduction protocols (e.g. effects of pulse width, repetition rate, spot size, wavelength, temperature, ionizing radiation, and other basic environmental effects). Also, of great interest are all types of scaling relationships between laser-induced damage thresholds and material/laser/environment parameters that not only afford insight into the fundamentals of the interaction process, but allow extrapolations for engineering and cost-benefit practical evaluations. In many areas, these insights are based on real-world, systems-level tests, as opposed to a frequently pristine laboratory environment. The fundamental mechanisms of defect-initiated laser damage is of high interest for a large part of the laser-damage community.

This year, 7 of 11 Fundamental Mechanisms submissions were devoted to ultrafast laser-material interactions and ultrashort-pulse laser effect. They considered bulk and surface effects including formation of damage craters, generation of periodic surface ripples on ZnSe surface, modification of optical properties in bulk glasses, a transition from intrinsic to defect-driven damage morphology in multilayer high reflectors, ablation of TiO_2 films by few-cycle laser pulses, variations of nonlinear absorption by high-repetition-rate femtosecond laser pulses, first-principle simulations of damage by ultrashort near- and mid-infrared laser pulses. Materials under consideration included multilayer stacks, but also typical dielectrics and semiconductors. Novel simulation approaches, e. g., first-principle simulations by modified particle-in-cell method were reported and demonstrated remarkable agreement between the simulation results and experimental data. This year's presentations also featured specific ultrafast damage effects in mid-infrared range of optical spectrum. Continuous efforts were made to characterize the fundamental mechanisms of laser damage in fused silica, hafnia, and titania as the most popular optical materials. The invited talk by Peter Herman (University of Toronto, Canada) was focused on confined ultrafast modification of bulk glasses and thin films by controlled beam shapes. It considered 3D nanostructuring of those optical materials including generation of nanogratings and nanocavity structures to deliver optical elements with novel optical responses. With 9 oral and 2 poster presentations listed in the conference program, this area is rather stable over last decade.

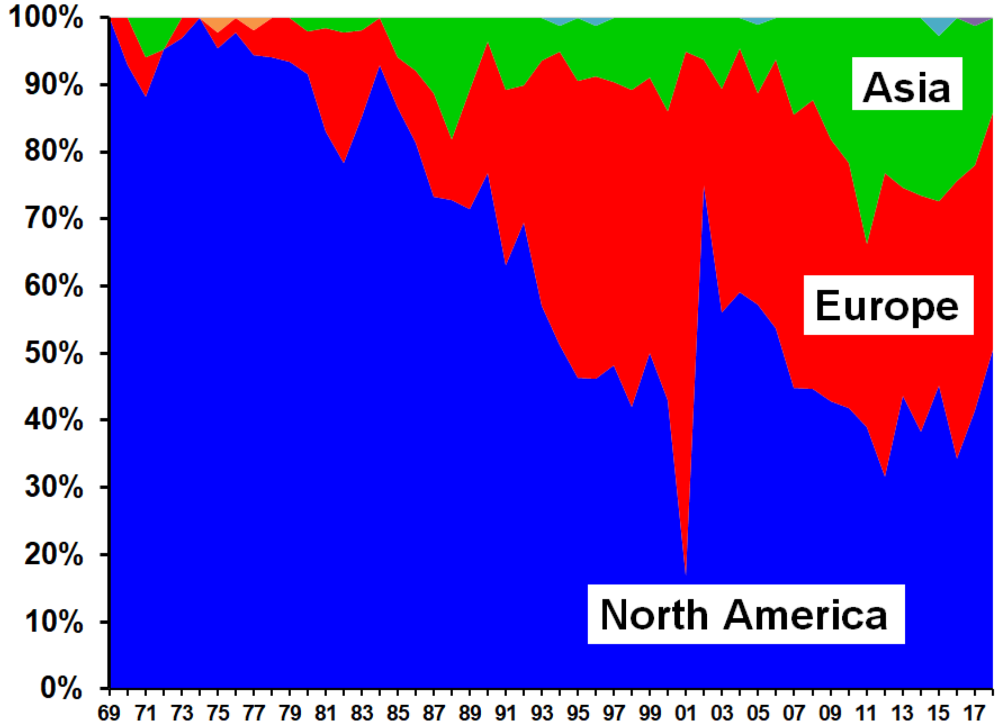

Fig. 3. Continent-distribution chart of the presentations delivered at the conference vs year from 1969 through 2018 inclusive. Tiny areas at the top part of the chart depict minor representations from Africa and Australia.

8. Surfaces and Mirrors

Presentations of this category are devoted to surface preparation, subsurface damage characterization, surface roughness, scattering, environmental degradation, surface aging, substrate material properties including cooling techniques, surface-damage measurement, and cleaning of surfaces. The crux of the contamination problem is fundamentally that damage experiments done in controlled clean laboratory settings do not necessarily yield the same results as laser operations in less pristine real-life environments. A novel aspect of this field is the research on surface degradation of space optic that is to transfer millions-to-billions of laser pulses. There is a significant amount of work needed in understanding what contamination is acceptable, what contamination is a threatening issue for optic survivability, and how fluence-limiting or lifetime-limiting contamination can be eliminated or mitigated.

This year, presentations were devoted to treatment of surfaces by various finishing techniques for improvement of laser-damage thresholds, anti-reflection sub-wavelength surface nanostructures, laser-damage performance of final optics of high-power laser systems, mitigation of novel phase-defect-induced laser damage, studies of laser-induced contamination, interaction of laser pulses with contaminants on glass surfaces, studies of damage growth on exit surfaces of transparent materials, and use of laser cleaning to remove contaminants from high-power laser-system diffraction gratings. A remarkable amount of papers dealt with surface micro- and nano-structuring to suppress or enhance surface reflection without depositing any kind of optical coatings. Fair amount of papers was focused on surface damage and damage mitigation of optics for high-power laser facilities. Invited talk by Denny Wernham (European Space Research and Technology Center, the Netherlands) featured the life-time issues associated with laser-induced damage and laser-induced contamination of optics in ALDIN laser system for the AEOLUS project of the European Space Agency. The laser is to deliver millions of 20-nanosecond pulses at 355 nm and pulse energy about 80 mJ or more. With 12 oral and 3 poster presentations, this key area shows increased representation in 2018 compared to 2017.

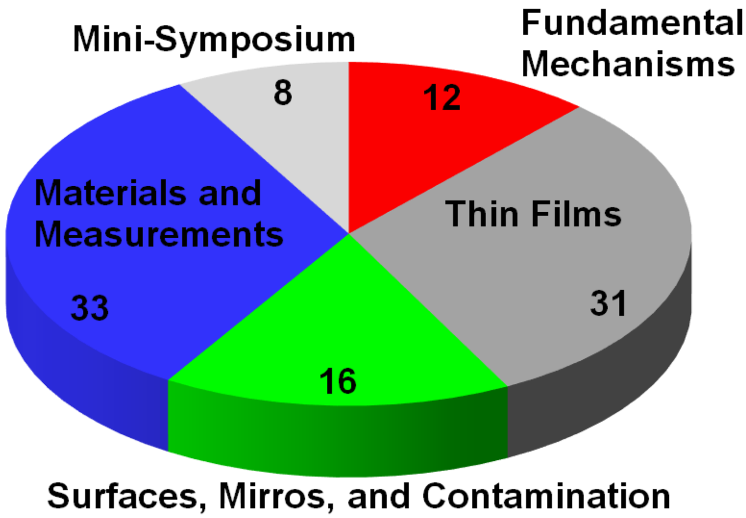

Fig. 4. Distribution of presentations of the 49th Laser Damage Symposium (2018 only) by key topics. Numbers show percentage of presentations of specific topics.

9. Materials and Measurements

Among the four main sections of the conference, this one continuously stays the largest over the last decade (Figs. 4 and 5). In general, this section deals with protocols and setups for measurements of laser damage to the bulk of transparent optical media whether amorphous, polymeric, polycrystalline, or crystalline; reports on material properties of importance for their optical function and/or the damage process, e.g., linear and nonlinear absorption, thermal conductivity, stress-optic coefficients, moduli, scattering, and various defects. Also included are new techniques for measuring these quantities, which stay a continuing challenge as materials are improved in quality and diversity. There is always a strong interest in improved measurement systems or new instruments particularly in the areas of non-destructive characterization and defect detection. Laser damage measurements are difficult, and work continues on developing tests that address large area versus small area and the difficulties of obtaining data with high space resolution.

This year, significant attention was paid to characterization of nonlinear refraction and absorption of optical fibers, thin films, and magneto-optical materials; predictions and measurements of fatigue laser damage; international standards on characterization of optical properties and thresholds of laser-induced damage. Multiple presentations were devoted to measurements of laser-damage thresholds in various materials including crystalline coatings, anti-reflection coated YAG crystals, calcium fluoride windows, nematic liquid crystals, fused silica, various optical glasses, and polymer optical fibers. We heard about studies of defect density in hafnia thin films, statistical analysis of distribution of the laser damage threshold, optical signatures of multilayer diffraction gratings, spectrally resolved wave-front measurements on dielectric coatings, machine learning and image processing for studies of LID morphology, accelerated testing of coated optics, damage-free removal of resist, damage size analysis for lifetime damage-threshold measurements, automated repair of laser damage on National Ignition Facility, multi-mode fiber optics for UV lasers, defect analysis in calcium fluoride windows, and models to specify defects with regards to generation of hot spots in high-power laser beams. The major range of laser parameters of interest includes nano-second pulses at 1064, 1030, 355, and 213 nm. Substantial attention was paid to UV lasers this time. Among novel methods, STERIO-LID was reported for detection of damage precursors and defects at interfaces of thin films. The invited talk delivered by Detlev Ristau (Laser Zntrum Hannover e. V., Germany) featured standardization in several relevant fields with emphasis on international standards on determination of laser-induced damage threshold (ISO 21254), optical absorption (ISO 11551), total scattering (ISO 13696), and losses and transfer functions (ISO 13142). Associated measurement procedures were discussed, and future developments and standardization projects were outlined. With 13 oral and 16 poster presentations, this section of the conference was the largest in the conference program of 2018.

10. Mini-Symposium

This year, the Mini-Symposium was focused on history and overview of the 50 years of this conference. It was organized by M. J. Soileau of University of Central Florida, USA as a senior co-chair of the conference and was coordinated by Vitaly Gruzdev of University of New Mexico, USA. With 8 invited talks of which 7 were presented, the Mini-Symposium spread over two oral sessions on Monday and Tuesday mornings. Presentations of Martin Stickley, Michael Bass, Leonid Glebov (presented by M. J. Soileau), and Brian Newnam were focused on the history of laser-damage research in the USA and former Soviet Union as well as on establishing and early years of the conference. Invited talk of Hans-Peter Berlien (Evangelische Elizabeth Klinik, Germany) overviewed laser-damage applications in medical laser systems. Christopher Stolz (Lawrence Livermore National Laboratory, USA) summarized ten years of laser-damage thin-film competition of the Laser Damage symposium. Scott Diddams (National Institute of Standards and Technology, USA) overviewed the history and current status of high-resolution laser spectroscopy and its applications. The Mini-Symposium attracted large attendance and became one of the brightest events of the 50th Anniversary celebration.

The Mini-Symposium of Laser Damage Symposium-2019 will be devoted to diffraction gratings and their laser-induced damage. It will be organized and chaired by Terrance Kessler of University of Rochester, USA. A brief summary of the past mini-symposium topics starting from 1992 and the organizing chairs is listed below.

Year	*Chair*	*Topic*
1992	Brian Newnam	Damage Issues for Lithographic Optics
1993	Karl Guenther	Quest for the Invincible Laser Coating – Critical Review of Pulse Laser-Induced Damage to Optical Coatings: Causes and Cures
1994	Claude Klein	Diamond for Optics Applications in Adverse Environment
1995	Floyd Hovis	Contamination and the Laser Damage Process
1996	Robert Setchell	Laser-Induced Damage in Optical fibers
1997	David Welch	Damage and Lifetime Issues for Laser diodes
1998	Norbert Kaiser	Optics for Deep UV
1999	David Sliney	Laser Damage Processes in the Eye and Other Biological Tissue
2000	Mark Kozlowski Hideo Hosono	Defects in Glass
2001	Mark Kozlowski	Optical Materials for Telecommunications
2002	Detlev Ristau	Optics characterization – joint with 7th International Workshop of Laser Beam and Optics characterization
2003	William Latham	Understanding Optical Damage with Ultra-short Laser Pulses
2004	Keith Lewis	Damage Issues in Fiber Laser systems
2005	Leon Glebov	Petawatt Lasers
2006	Alan Stewart	Optics in a Hostile Environment
2007	Stan Peplinski	Lifetime Issues for CW and Quasi-CW Lasers
2008	Christopher Stolz Herve Bercegol	Fused Silica
2009	Wolfgang Rudolph	Femtosecond Laser-Induced Damage
2010	Klaus Sokolowski-Tinten	Fundamentals of Laser Ablation
2011	Holger Blashke, Carmen Menoni	Deep-UV Optics
2011	Michelle Shin	Meta-Optics/Photonic Band Gap Materials
2012	Stavros Demos	Laser-Induced Plasma Interactions
2013	Leonid Glebov	High-Power Fiber Lasers

2014	Stavros Demos	Applications Related to Laser Damage
2015	Vladimir PErvak	Laser-Induced Damage to Multilayers in Femtosecond Regime
2016	Stefan H. Borneis Christopher J. Stolz	Review of Large-Scale, High-Power Laser Facility Projects
2017	Vitaly Gruzdev	Frontiers of Ultrafast Science: Sources, Basic Effects, and Mechanisms of Ultrafast Laser-Matter Interactions
2018	M. J. Soileau	50th Anniversary Conference Overview

11. Keynote and Invited Presentations

As usually, the 50th Laser Damage Symposium was highlighted by four keynote presentations in the major areas:

1. "Recent advances on light-matter interaction in layered media", **Michel Lequime,** Institut Fresnel (France) – area of Thin Films.
2. "Getting a high-power UV laser into space: the story of the Aladin laser development for the European Space Agency's Aeolus Satellite", **Denny Wernham**, European Space Research and Technology Center, (The Netherlands) – the area of Surfaces, Mirrors, and Contamination.
3. "Shaping nonlinear ultrafast laser interactions: gateway to novel bulk glass and intra-film devices", **Peter R. Herman**, University of Toronto (Canada)– the area of Fundamental Mechanisms.
4. "Standardization in optics characterization", **Detlev Ristau**, Laser Zentrum Hannover e. V. and Leibniz University Hannover (Germany) – the area of Materials and Measurements.

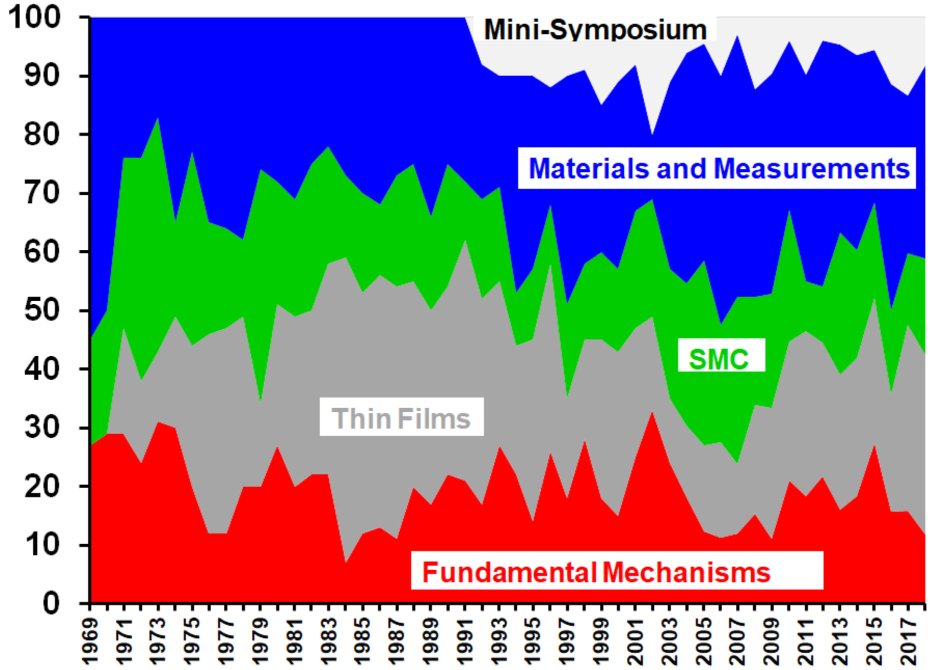

Fig. 5. Distribution of presentations over four major topics and mini-symposium vs year from 1969 through 2018 inclusive. The vertical axis shows percentage of presentations of the major conference section.

Also, the Mini-Symposium hosted 8 plenary talks this year. The talk of the conference co-founder Alex Glass "Damage phenomena in high-power lasers: early studies" was transferred to 2019 due to excised absence of the speaker. The other 7 talks of the Mini-Symposium were delivered:

Martin Stickley (retired from DARPA, BDM, AFCRL, CREOL/UCF, USA), "The Laser Damage meeting: early years";

Michael Bass (CREOL - The College of Optics and Photonics, University of Central Florida, USA), "When everything damaged and we didn't know why";

Hans-Peter Berlien (Evangelische Elizabeth Klinik, Germany), “Test methods for laser-induced damage threshold of medical laser delivery and applications systems”;
Leonid B. Glebov (CREOL - The College of Optics and Photonics, University of Central Florida, USA), “Early laser-damage research at State Optical Institute in Leningrad”;
Brian E. Newnam (Los Alamos National Laboratory, USA), “Highlights from the 2nd and 3rd decades of the Laser Damage Symposia”;
Christopher J. Stolz (Lawrence Livermore National Laboratory, USA), “Trends observed in ten years of the BDS Thin film Laser Damage Competition”;
Scott A. Diddams (National Institute of Standards and Technology, USA), “The history and presence of high-resolution laser spectroscopy and its applications”.

12. Conference Awards

Beginning with the meeting in 2000, the organizers instituted a best paper award in the oral and poster categories. The awards appropriately take the form of laser-induced art in an optical glass plaque. (see, e.g., paper by I. N. Trotski, Proc. SPIE 4679, 392-399 (2001)). All the awarded papers can be found in this volume of Laser Damage Proceedings.

Starting from 2017, Co-Chairs of this Symposium expanded the award categories and establish three awards:
- Alexander Glass Best Oral Presentation Award;
- M. J. Soileau Best Student Paper Award;
- Arthur Guenther Best Poster Award.

There were several outstanding posters and oral papers nominated for those awards. However, this year the two top nominations for the Best Oral Presentation Award were rejected because of lack of the manuscripts submitted to the conference proceedings. As a result, the following papers were selected by Co-Chairs for the 2018 awards:

Alexander Glass Best Oral Presentation Award:
“Revisiting of the laser-induced filamentation damage conditions in fused silica for energetic laser systems”, Eyal Feigenbaum, Wade H. Williams, Raluca A. Negres, Mary A. Norton, Chrostopher F. Miller, Gabriel Mennerat, Clay Widmayer, Christopher W. Carr, Jean-Michel G. Di Nicola, Jeffrey D. Bude, Lawrence Livermore National Laboratory (USA); SPIE paper number [10805-24].

M. J. Soileau Best Student Paper Award:
“Femtosecond laser-induced modifications of frequency tripling mirrors (FTMs)”, Amir Khabbazi Oskouei, Luke A. Emmert, Wolfgang Rudolph, The University of New Mexico (USA); SPIE paper number [10805-66].

Arthur Guenther Best Poster Award:
“The nonlinear refractive index of thin films and substrates as various wavelengths and pulse durations”, Morten Steinecke, Tarik Kellermann, Marco Jupe, Lars O. Jensen, Laser Zentrum Hannover e. V. (Germany); Detlev Ristau, Laser Zentrum Hannover e. V. and Leibniz University Hannover (Germany); SPIE paper number [10805-75].

13. Publications

Concerns were previously expressed by Laser Damage authors regarding copyright issues appeared when results presented at Laser Damage Symposium and published in the Symposium Proceedings were submitted for publication in non-SPIE peer-reviewed journals. To address those concerns, Vitaly Gruzdev and Michelle Shinn volunteered as guest editors of Special Section on Laser Damage published in the flagman peer reviewed SPIE journal *Optical Engineering*. The first Special Section was published in volume 51, issue 12:
https://www.spiedigitallibrary.org/journals/optical-engineering/volume-51/issue-12#SpecialSectiononLaserDamage
and contained 18 papers selected by peer-reviewers for publication out of 21 submitted manuscripts (Table 1). The papers covered various aspects of laser damage including fundamental mechanisms, influence of defects, measurements of laser-damage thresholds, statistical laws of damage threshold, damage of thin films and optical coatings. Many of those publications were based on the results presented at Laser Damage and on manuscripts published in the Proceedings of Laser Damage Symposium. Other manuscripts were submitted independently via general submission procedure of SPIE journals.

That Special Section was recognized as highly successful with multiple downloads and many citations (Fig. 6). That fact motivated the International Program Committee of Laser Damage Symposium to coordinate another Special Section on Laser Damage with editors of *Optical Engineering*. Result of that effort is the Special Section on Laser Damage II that was published in volume 53, no. 12 of *Optical Engineering* in December 2014:
https://www.spiedigitallibrary.org/journals/optical-engineering/volume-53/issue-12#SpecialSectiononLaserDamageII
It contained 16 papers selected out of 21 submissions and covers a broad spectrum of topics related to laser-induced damage. Due to increasing requirements to scientific quality and content of submitted manuscripts, 5 manuscripts were rejected during preparation of that Special Section (Table 1).

Strong interest of the Laser-Damage community and success of the two previous Special Sections on Laser Damage motivated Vitaly Gruzdev and Michelle Shinn to volunteer again in editing another Special Section on Laser Damage III. That Special Section was published in January 2017 in volume 56, no. 1:
https://www.spiedigitallibrary.org/journals/optical-engineering/volume-56/issue-01#SpecialSectiononLaserDamageIII
It contains a record-high number of submissions (33 total) of which 28 were published. This success of the Special Section on Laser Damage III was partly due to the highly fruitful cross promotion with High Power Laser Ablation conference (HPLA) in 2016-2017. Of the 28 published papers, 8 were submitted by the HPLA authors. Of the entire Special Section, the paper of Stefan Scharring et al "Laser-based removal of irregularly shaped space debris":
https://www.spiedigitallibrary.org/journals/Optical-Engineering/volume-56/issue-01/011007/Laser-based-removal-of-irregularly-shaped-space-debris/10.1117/1.OE.56.1.011007.full
was featured by the journal and appreciated among the best downloads.

In 2018, another Special Section on Laser Damage IV was prepared in the connection with the 50th anniversary of the conference. It was published by *Optical Engineering* in volume 57, no. 12:
https://www.spiedigitallibrary.org/journals/optical-engineering/volume-57/issue-12#SpecialSectiononLaserDamageIV
Guest Editors of that Special Section were Vitaly Gruzdev and Jonathan Arenberg. Of the 12 submissions to that Special Section, 10 were published including 3 review papers: "Laser-induced damage of nodular defects in dielectric multilayer coatings" by Jinlong Zhang et al
https://www.spiedigitallibrary.org/journals/Optical-Engineering/volume-57/issue-12/121909/Laser-induced-damage-of-nodular-defects-in-dielectric-multilayer-coatings/10.1117/1.OE.57.12.121909.short
"Ten year summary of the Boulder Damage Symposium annual thin film laser damage competition" by Christopher Stolz and Raluca Negres:
https://www.spiedigitallibrary.org/journals/Optical-Engineering/volume-57/issue-12/121910/Ten-year-summary-of-the-Boulder-Damage-Symposium-annual-thin/10.1117/1.OE.57.12.121910.short
and "Discussing defects related to nanosecond fatigue laser damage: a brief review" by Frank Wagner et al:
https://www.spiedigitallibrary.org/journals/Optical-Engineering/volume-57/issue-12/121904/Discussing-defects-related-to-nanosecond-fatigue-laser-damage--a/10.1117/1.OE.57.12.121904.full

Table 1. Submission overview of the three Special Sections of *Optical Engineering* on Laser Damage.

Special Section issue	Total submissions	Published	Rejected
Laser Damage (v. 51, no. 12, 2012)	21	18	3
Laser Damage II (v.53, no. 12, 2014)	21	16	5
Laser Damage III (v. 56, no. 1, 2017)	33	28	5
Laser Damage IV (v. 57, no. 12, 2018)	12	10	2

14. In Conclusion

The location in Boulder, Colorado, USA at the Boulder Millennium Harvest House Hotel, its facilities and support staff were appreciated. While attendees of the 50th Laser Damage Symposium were accommodated with ample opportunity to mingle and socialize, multiple concerns were expressed regarding that conference venue. To address them, the 51st Symposium will be held in Omni Interlocken Hotel in Boulder, Colorado, USA in September 2019. The organizers hope the new venue will be highly supportive for addressing the concerns from conference attendees received in 2018. Also, the hotel-type venues allow fixing the repeating problems with access of registered conference participants to the Boulder NIST facilities that forced the organizers to depart from the NIST in 2016.

Vol	Issue	Month	Paper #	Author(s)	Paper Type	Published Online	CID	Downloads	Citations
51	12	Dec-12	OE GED-DEC2012	Gruzdev and Shinn	Guest Editorial	11/9/12	121801	1,301	0
51	12	Dec-12	120400SSR	Palm (Marciniak)	Article	7/10/12	121802	747	3
51	12	Dec-12	120367SSPR	Cho	Article	7/10/12	121803	388	0
51	12	Dec-12	120366SSPR	Cho	Article	7/10/12	121804	303	0
51	12	Dec-12	120405SSPR	Gulley	Article	6/27/12	121805	557	6
51	12	Dec-12	120382SSPRR	Wagner	Article	7/13/12	121806	302	18
51	12	Dec-12	120493SSPR	Weber	Article	7/9/12	121807	260	6
51	12	Dec-12	120375SSRR	Apostolova	Article	8/3/12	121808	351	9
51	12	Dec-12	120381SSR	Han (Li)	Article	7/19/12	121809	652	7
51	12	Dec-12	120406SSPR	Brenk (Rethfeld)	Article	8/22/12	121810	383	4
51	12	Dec-12	120468SSR	Manenkov	Article	9/18/12	121811	518	7
51	12	Dec-12	120401SSPRR	Muehlig	Article	9/14/12	121812	306	7
51	12	Dec-12	120411SSRR	Nikiforov	Article	9/20/12	121813	99	1
51	12	Dec-12	120377SSRR	Lu	Article	9/26/12	121814	404	5
51	12	Dec-12	120396SSPRRRR	Ahsan	Article	9/26/12	121815	337	9
51	12	Dec-12	120620SSPR	Komolov	Article	10/10/12	121816	329	3
51	12	Dec-12	120486SSPRR	Shen	Article	10/10/12	121817	578	23
51	12	Dec-12	120617SSPR	Stolz	Article	11/28/12	121818	567	3
51	12	Dec-12	120616SSPRR	Arenberg	Article	12/10/12	121819	103	3
							TOTAL	8485	114
53	12	Dec-14	OE-2014-1208-GED	Gruzdev and Shinn	Guest Editorial	12/22/14	122501	829	0
53	12	Dec-14	140177SSPR	Carreon	Article	6/11/14	122502	200	2
53	12	Dec-14	140405SSPR	Balasa	Article	7/1/14	122503	141	4
53	12	Dec-14	140509SSPR	Papernov	Article	6/25/14	122504	2,033	4
53	12	Dec-14	140527SSR	Lu (Ma)	Article	7/1/14	122505	308	7
53	12	Dec-14	140398R	Rubenchik (Wu)	Article	7/17/14	122506	372	8
53	12	Dec-14	140456SSPR	Mitchell	Article	7/23/14	122507	361	3
53	12	Dec-14	140541SSPR	Muehlig	Article	8/11/14	122508	127	0
53	12	Dec-14	140718SSR	Douti (Gallais)	Article	8/6/14	122509	319	10
53	12	Dec-14	140531SSR	Baumann (Perram)	Article	8/12/14	122510	167	4
53	12	Dec-14	140437SSPRR	Hildenbrand (Petrov)	Article	8/21/14	122511	333	11
53	12	Dec-14	140532SSPR	Gonschior (Klein)	Article	9/2/14	122512	126	1
53	12	Dec-14	140540SSR	Stratan(Zorila)	Article	10/8/14	122513	207	5
53	12	Dec-14	140712SSRR	Ding(Wang)	Article	10/6/14	122514	187	0
53	12	Dec-14	140793SSR	Gruzdev	Article	10/27/14	122515	386	0
53	12	Dec-14	140754SSPRR	Field	Article	11/6/14	122516	1,735	4
53	12	Dec-14	140756SSR	Arenberg	Article	12/2/14	122517	634	1
							TOTAL	8465	64
56	1	Jan-17	OE-2017-0111-GED	Shinn and Gruzdev	Guest Editorial	1/23/17	011000	628	0
56	1	Jan-17	151769SSR	Hervy (Gallais)	Article	6/30/16	011001	576	1
56	1	Jan-17	160321SSPR	Field	Article	7/8/16	011002	1,203	0
56	1	Jan-17	160429SSPRR	Zhu	Article	7/11/16	011003	255	0
56	1	Jan-17	160551SSPR	Papernov	Article	7/15/16	011004	238	0
56	1	Jan-17	160320SSPR	Field	Article	7/15/16	011005	989	0
56	1	Jan-17	160594SSPR	Muehlig	Article	7/18/16	011006	118	0
56	1	Jan-17	160631SSR	Scharring	Article	8/1/16	011007	3,952	6
56	1	Jan-17	160697SSPR	Negres	Article	8/1/16	011008	1,458	5
56	1	Jan-17	160565SSRR	Shen (Jiang)	Article	8/3/16	011009	183	0
56	1	Jan-17	160739SSR	Lorbeer	Article	8/15/16	011010	1,059	1
56	1	Jan-17	160549SSR	Han (Feng)	Article	9/8/16	011011	194	0
56	1	Jan-17	160635SSPRR	Bellum	Article	8/25/16	011012	1,099	6
56	1	Jan-17	160694SSR	Phillips (Perram)	Article	8/26/16	011013	127	2
56	1	Jan-17	160835SSR	Bardy	Article	8/29/16	011014	274	7
56	1	Jan-17	160848SSR	Raemer	Article	9/8/16	011015	207	0
56	1	Jan-17	160617SSPR	Demos	Article	9/8/16	011016	702	2
56	1	Jan-17	160914SSR	Bauer (Perram)	Article	9/20/16	011017	109	1
56	1	Jan-17	160686SSPR	Field	Article	9/21/16	011018	1,515	4
56	1	Jan-17	160810SSRR	Xu (Emmert)	Article	10/12/16	011019	176	1
56	1	Jan-17	160636SSPRR	Bellum	Article	10/12/16	011020	742	2
56	1	Jan-17	161045SSPR	Jiao	Article	10/13/16	011021	114	2
56	1	Jan-17	160864SSR	Doualle (Gallais)	Article	10/17/16	011022	171	2
56	1	Jan-17	160796SSR	Gehring	Article	10/25/16	011023	105	1
56	1	Jan-17	160863SSPR	Durak (Velpula)	Article	11/4/16	011024	177	0
56	1	Jan-17	161048SSR	Saripalli	Article	11/7/16	011025	101	1
56	1	Jan-17	160970SSRR	Sun	Article	11/30/16	011026	237	2
56	1	Jan-17	160821SSRR	Ma (Cheng)	Article	12/8/16	011027	126	1
56	1	Jan-17	160855SSPR	Qiu	Article	10/24/16	011108	696	1
							TOTAL	17531	48
57	12	Dec-18	180121SSPRR	Zhu	Article	9/11/18	121902	42	0
57	12	Dec-18	180229SSRR	Gebrayel	Article	9/11/18	121903	60	0
57	12	Dec-18	180630SSR	Wagner	Article	9/13/18	121904	75	0
							TOTAL	177	0

Figure 6. Download and citation data for the Special Sections on Laser Damage according to the data as of September 19, 2018.

This year the nice weather in Boulder encouraged to take a group picture of all symposium participants outside the National Institute of Atmospheric Research (Boulder, CO) where the traditional Wine and Cheese Reception was held on Tuesday, September 25.

The organizers of the Boulder Damage Symposium look for opportunities to join with other related groups for joint meetings in the future. For example, in 2002 we had a joint meeting with the 7th International Workshop on Laser Beam and Optics Characterization (LBOC), again with no parallel sessions. Also, starting from 2009, Pacific Rim Laser Damage (PLD) symposium is held annually in spring with the topics and the scope completely similar to the topics and scopes of Laser Damage Symposium. We are looking forward to develop fruitful collaboration with PLD meeting in order to join our efforts for better serving the laser-damage community worldwide.

We must also note tireless assistance of SPIE who handle the administrative functions of the symposium. Their presence, experience, resources, and professionalism clearly were made manifest with on-line reservations, payment by credit cards, badges, preparation of the abstract book and pocket programs, preparation and printing this volume of Symposium Proceedings, and on-line document service, to which we may add the social functions – thanks to them, “A good time was had by all.” This year, special thanks are forwarded to SPIE for the tremendous efforts in creating the bright celebration atmosphere at the conference.

15. Acknowledgments

A number of volunteers help tirelessly with some of the administrate duties necessary to put on a conference of this magnitude. Diane Cline from SPIE took care of all the administrative planning and on-site tasks including setup, registration, and general questions. Bobbie Williams of Lawrence Livermore National Lab helped with the registration pick up and at front desk through the entire meeting. Pat White from SPIE took care of program preparation, invitation letters for international participants, and provided much on-line support for the conference. Joel Shields also from SPIE was responsible for preparation of this volume of the conference proceedings and the publication of the manuscripts into it. Assistance of James Bell (meeting manager) and Jeff Braswell (Marketing) of SPIE is greatly appreciated by organizers of this Laser Damage meeting.

We especially acknowledge generous support of the conference co-sponsors this year: Lawrence Livermore National Laboratory (USA); Spica Technologies Inc. (USA); Materion; ZC Optoelectronic Technologies Corporation (USA), and Laser Components (USA). Sponsor support of refreshment breaks by Laser Components; LIDARIS LIDT Service (Lithuania); and Northrop Grumman Corporation (USA) is especially appreciated. Support of the welcome and social mixer on Sunday evening by Edmund Optics (USA) is specially acknowledged. The contribution of Spica Technologies for performing the laser damage tests for the annual laser-damage thin-film competition is greatly appreciated. A generous support of the Wine and Cheese tasting on Tuesday evening by Arrow Thin Films (USA) is appreciated by all conference participants. Advanced Thin Films (USA) is acknowledged for the Open House and reception host on Monday evening. They are separately acknowledged in this volume of conference proceedings.

We acknowledge the cooperating organizations: Pacific Northwest National Laboratory (USA); School of Optics – CREOL and FPCE, College of Optics and Photonics, University of Central Florida (USA); Laser Zentrum Hannover (Germany); University of Missouri, Columbia (USA); The University of New Mexico (USA).

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