42nd ANNUAL LASER DAMAGE SYMPOSIUM
Proceedings

LASER-INDUCED DAMAGE IN OPTICAL MATERIALS: 2010

26–29 September 2010
Boulder, Colorado

Editors
Gregory J. Exarhos, Vitaly E. Gruzdev, Joseph A. Menapace, Detlev Ristau, M. J. Soileau

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International Program Committee

The cochairs of this series of symposia rely heavily on an International Program Committee to ensure their awareness of significant research in the broad field of laser-induced damage throughout the world. Its members are also frequently the source of suggestions for invited speakers and mini-symposium topics and leaders. The committee performs a vital service as an outreach for the conference on a global scale. Individuals with suggestions for the meeting are requested to contact any committee member (next page) who is either an acquaintance or in close proximity. The committee is ably led by Detlev Ristau, International Program Committee Chair.

Gregory J. Exarhos (greg.exarhos@pnl.gov)
Vitaly E. Gruzdev (gruzdevv@missouri.edu)
Joseph A. Menapace (menapace1@llnl.gov)
Detlev Ristau (dr@lzh.de)
M. J. Soileau (mj@mail.ucf.edu)

International Program Committee

Symposium Welcome

Joseph A. Menapace

Lawrence Livermore National Laboratory (United States)
menapace1@llnl.gov

On behalf of my fellow co-chairs, Greg Exarhos, Vitaly Gruzdev, Detlev Ristau, and M. J. Soileau, I would like to welcome all presenters and participants to the 42nd Annual Symposium on Optical Materials for High-Power Lasers! For the past forty-two years the NIST facility in Boulder, Colorado, has been our venue for hosting an international forum overflowing with spirited discussions amongst scientists, scholars, and engineers, from industrial companies, universities, and research institutes. The number of oral and poster contributions scheduled for this year's event clearly points to the continued interest in the field of laser damage and related topics from our scientific community. Contributions from investigators around the world continue to advance our knowledge of laser-induced damage on optical materials and thin films, of novel processes to measure, characterize, and mitigate contamination and damage, of advanced methods to produce laser-damage resistant optics and coatings, and in unraveling the details of the mechanisms responsible for damage initiation and growth. This series of the Proceedings of SPIE is a testament to the strength and importance of the field, and serves as one of the major resources compiled for laser damage research and development. The extraordinary efforts of the authors to persevere and overcome the difficulties encountered during their investigations and to prepare the manuscripts and posters are gratefully recognized.

This year we are also celebrating the 50th anniversary of the invention of the laser and it is exciting to say that there are few people in modern society who have not been affected by this device. With the course of the laser technology development towards ever increasing output power and beam quality, laser-induced damage in optical materials is continuing to be one of the key issues in fundamental research, technological development, and industry. Today, laser systems are found in nearly every advanced product or application, and the enormous potential of laser technology is far from being exhausted. State-of-the-art telecommunication systems used today are made possible by laser beams traveling through fiber optics thinner than a human hair that carry more than a half a million telephone conversations or thousands of computer connections and television channels. Even more astonishing is that without the laser, the internet would simply not exist. In the areas of business, manufacturing, and entertainment, we have supermarket checkout scanners, compact discs (CDs), digital video devices (DVDs), laser holograms for security on credit cards, and laser printers that are just a few of the countless consumer products that rely on lasers. Industrial lasers cut, drill, and weld materials ranging from paper and cloth to diamonds and exotic alloys far more efficiently and precisely than metal machining tools. Lasers are also used in millions of medical procedures every year to reduce the need for general anesthesia, to deliver pain free surgery, and when used with optical fibers, to deliver laser beams inside the body to reduce the need for more invasive surgery. In the areas of energy and science, the completion of the National Ignition Facility (NIF), the world's most powerful and only megajoule class laser system, sets the stage for scientists to investigate nuclear fusion technology that will open the door to the world's future energy needs and will allow us to better understand the makeup of stars in our universe and planets both within and outside our solar system. The SPIE Laser Damage Symposium is a key contributor and indicator to this progress, having featured many superb efforts of the scientific community over the last forty-two years.

Laser Damage 2010 is divided into four core topical areas: thin films; surfaces, mirrors and contamination; fundamental mechanisms; materials and measurements. The international program committee has been instrumental in promoting these topical areas worldwide, attracting contributions from scientists and engineers from 14 different countries. Currently, the international program committee consists of 15 representatives from China, France, Germany, Japan, Russia, the United Kingdom, and the United States. This year we have invited talks in all topical areas with the series consisting of 43 oral presentations and 39 posters. To encourage scientific dialogue in up-and-coming research areas, Laser Damage 2010 also hosts a mini-symposium dedicated to the fundamentals of laser ablation comprised of an invited talk and two oral presentations on femtosecond laser experiments and applications. The symposium has been

designed to maximize attendee participation and interaction amongst researchers through the use of sequential sessions, question and answer periods at the end of oral presentations, and poster sessions for more direct dialog between colleagues. This approach contributes to the strength of the meeting and, indeed, promotes international exchanges in the laser-damage and related technical communities.

The co-chairs appreciatively recognize the tireless efforts of the SPIE staff and Artika Lal, Symposium Assistant from Lawrence Livermore National Laboratory, whose hard work in planning and execution made the event possible. The organizers also value the efforts of Kent Rochford, NIST Technical Coordinator, who directed facility activities and audio/video capabilities at the symposium site. Financial support for Laser Damage 2010 has been graciously provided by the meeting co-sponsors: Lawrence Livermore National Laboratory, Pacific Northwest National Laboratory, Spica Technologies, Inc., and the Office of Naval Research. We also thank Laser Zentrum Hannover e.V., the National Institute of Standards and Technology, CREOL & FPCE, College of Optics and Photonics, University of Central Florida, and the University of Missouri-Columbia for providing the much needed managerial support during planning and event operations. We express sincere gratitude and a "hats off" to RMI Laser and CVI Melles Griot for providing refreshment services during the event and to Saint-Gobain Crystals and Precision Photonics Corp. for hosting the open houses and evening receptions. We also especially thank Mike Thomas and his staff at Spica Technologies, Inc., who donated their time and facilities to perform the damage tests for the thin film UV antireflection laser damage competition. This outstanding effort is appreciated by the community and the organizers.

The city of Boulder and the surrounding areas provide spectacular views of the Rocky Mountains rich with "Old West" history, excellent hiking and other outdoor activities, and great restaurants. The co-chairs hope this setting provides a great opportunity to relax with old friends and perhaps establish new research opportunities. On behalf of my co-chairs and the International Program Committee, we wish you a productive and enjoyable stay in Boulder and look forward to seeing you next year.

Symposium Cosponsors

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Summary of Meeting

SPIE Laser Damage
42nd Annual Symposium
on Optical Materials for High Power Laser
26-29 September 2010

Vitaly E. Gruzdev
Department of Mechanical and Aerospace Engineering
University of Missouri
Columbia, MO, 65211, USA

1. Abstract

These proceedings contain the papers presented as oral and poster presentations at the 42nd Annual Symposium on Optical Materials for High-Power Lasers. The conference was held at the National Institute of Standards and Technology facility in Boulder Colorado on 26-29 September 2010. The symposium was divided into the traditional sessions devoted to the following topics: thin films; surfaces, mirrors and contamination; fundamental mechanisms; materials and measurements; and finally, a mini-symposium on fundamentals of laser ablation. The conference was opened by Dr. Joseph A. Menapace with a symposium welcome. Dr. Gregory J. Exarhos of Pacific Northwest National Laboratory (United States), Dr. Vitaly Gruzdev of the University of Missouri, Columbia (United States), Dr. Joseph A. Menapace of the Lawrence Livermore National Laboratory (United States), Dr. Detlev Ristau of the Laser Zentrum Hannover e.V. (Germany), Dr. M. J. Soileau of the University of Central Florida (United States) co-chaired the symposium. The founding organizers are Dr. Arthur H. Guenther and Dr. Alexander J. Glass.

All told, 76 papers were presented, including oral and poster presentations plus a mini-symposium. No parallel sessions were held, allowing the opportunity to discuss common research interests with all the presenters. With 138 participants attending, the meeting offered an opportunity to make many new acquaintances. Although held annually in the US, this is a truly International conference with 40 percent of the attendees and 60 percent of the presentations coming from abroad. As usual, the National Institute of Standards and Technology in Boulder, Colorado, offered a setting conductive to interchanges between individuals working in closely related and complementary fields. We look forward to future opportunities to come together again in this setting.

The 43d Annual Symposium of this series will be held in Boulder, Colorado, 18-22 September 2011. A continuous effort will be made to ensure a close liaison between the high-peak-power and high-average-power laser communities, as well as to include damage issues related to various research efforts and commercial laser applications. A mini-symposium related to the subject of deep-UV lasers and damage to deep-UV optics is anticipated. Invited talks are also anticipated to open the four major topical areas and the mini-symposium.

The principal topics to be considered as contributed papers in 2011 do not differ drastically from those enumerated above. We expect to hear more about the impacts of contamination on the laser resistance of optical components and the impacts of defects since both of these topics continue to generate significant interest. High-energy laser windows, crystals, and transparent ceramics continue to place limitations on laser systems and so remain an active area of research and spirited debate. 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 as a large number of laser-resistant UV optics are manufactured for large-aperture fusion lasers. Short pulse laser optics and damage phenomena remain an active area of research. Recently increased activity in the field of ultrashort-pulse (femtosecond) laser-material interactions is expected to be one of growing topics of the future symposium. We also expect to hear more about new measurement techniques to improve our understanding of the different damage mechanisms or to improve the manufacturing of optical materials and thin films for optical components of greater laser damage resistance. Fundamental aspects of laser-induced damage including multiphoton

and avalanche ionization, scaling of damage threshold with laser and material parameters continue to attract much attention

As was initially established in 1992, several distinguished invited speakers will make presentations of a tutorial or review nature. In addition other contributors will cover late-breaking developments of interest to the attendees.

The purpose of this series of symposia is to exchange information about optical materials for high-power/high-energy lasers. The editors welcome comments and criticism from all interested readers relevant to this purpose.

Key words: laser damage, laser interaction, optical components, optical fabrication, optical materials and properties, thin film coatings, contamination.

2. Introduction

The SPIE Laser Damage—42nd Annual Symposium on Optical Materials for High-Power Lasers (a.k.a. the Boulder Damage Symposium, because of its Boulder, Colorado, venue) was held 26-29 September 2010. This symposium continues to be the principal United States and international forum for the exchange of information relative to the interaction of intense laser light with optical media and components. This year, it was attended by 138 representatives of academia, industry, national research laboratories and centers from 11 countries. Among 89 paper submittals, 76 presentations were delivered including 40 oral and 36 poster presentations. Although held annually in the US, this is a truly international conference with 40 percent of the attendees and 60 percent of the presentations coming from abroad this year. Historically, the meeting has been divided into four broad categories: thin films; fundamental mechanisms; materials and measurements; and surfaces, mirrors, and contamination. Starting in 1992 a Mini-Symposium is held to highlight hot research topics and areas of active research and special interest in the research fields related to high-power/high-energy lasers, laser-induced damage, optical materials, laser-material interactions. Starting in 2009, a Round-Table discussion is held on Sunday evening as a pre-symposium event. This year it featured the fundamental aspects of laser-induced damage under the topic "Multiphoton Ionization vs. Avalanche (Impact) Ionization in LID of Transparent Materials". The discussion was moderated by Dr. M. J. Soileau and Dr. V. E. Gruzdev and involved 33 participants of the conference.

3. Symposium Cochairs

The Boulder Damage Sympsoium was founded by Dr. Arthur H. Guenther and Dr. Alexander J. Glass. Over the last 42 years many prominent leaders within the high-power laser community have contributed significantly as cochairs 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. Gruzdev
2010	add J. A. Menapace; C. J. Stolz departs

4. Thin Films

Because of the tremendous range of applications of optical multilayer coatings for modifying the optical performance of elements (e.g., reflectivity, wavelength sensitivities, polarization, or simply protection), this category continues to receive significant attention. Besides damage thresholds or sensitivity, topics include advanced thin deposition technologies (ion-beam sputtering and e-beam evaporation), film structure, film design, film response to environmental attack and aging, and numerous reports on important film properties such as adhesion, thermal conductivity, absorption, stability. Special attention is paid to coatings at 1064 nm, 532 nm, 355 nm, and deep-UV coatings.

This year the third thin-film damage competition was organized by Dr. Christopher Stolz of Lawrence Livermore National Laboratory (United States). Two years ago, it started to sample the industrial, government, and academic sectors producing high laser resistant optical coatings. This year, 351 nm antireflection coatings from 11 companies and institutes from the US, Europe, China, and Japan were tested with 7.5 ns pulses at the laser-damage test facility of Spica Technologies Inc. (United States). The most laser resistance was demonstrated by samples manufactured by sol-gel technology with porous silica. A multitude of deposition processes, coating materials, and manufacturing techniques submitted to this competition provided some interesting results that will likely lead to some interesting future research.

Dense thin film processes offer the benefit of environmental stability so much of the research in the field of thin films is proceeding in this direction. Laser interaction studies are uncovering areas where dense films offer advantages over traditional e-beam coatings. Also as shown in the thin film damage competition where are a number of companies that are manufacturing dense coatings from a variety of deposition techniques with very high laser resistance.

Coating defects continue to be an area of active interest in both process optimization to minimize defect formation as well as mitigation techniques such as laser conditioning. This year we continued to see interest in short-pulse, ultra-short pulse, and DUV coatings.

5. Fundamental Mechanisms

This area deals with the interaction of light with matter – where real system experience is presented. Topics include laser-induced ionization, nonlinear behavior and effects, self-focusing, thermal modeling, and experimental data reduction protocols (e.g. effects of pulse width, repetition rate or duty cycle, spot size, wavelength, temperature, ionizing radiation, and other environmental effects), as well as all types of experimental or material variable scaling relationships that not only afford insight into the fundamentals of the interaction process, but allow extrapolations for engineering and cost-benefit evaluations. In many areas, these insights are based on real-world, systems-level tests, as opposed to a frequently pristine laboratory environment.

A significant amount of experimental and simulation work is now being done in the femtosecond regime as exemplified by the significant number of submitted papers on ultrafast phenomena. This year's presentations demonstrate stable growth of scientific interest and research activity in that field. A significant number of presentations also focuses on the fundamental influence of defects on laser-induced damage threshold, linear and non-linear absorption, and material response to high-power laser action.

6. Surfaces and Mirrors

Presentations of this category are devoted to surface preparation (including MRF technology for large-aperture optics, plasma pre-treatment, aqueous HF-based etching), subsurface damage characterization, roughness and scattering, environmental degradation and aging, as well as substrate material properties, including cooling techniques, and, of course, damage measurement and the 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 operating environments. There is a significant amount of work needed in understanding what contamination is acceptable, what contamination is threatening to optic survivability, and how fluence-limiting or lifetime-limiting contamination can be eliminated or mitigated from operating laser systems.

A fair amount of papers deals with laser-damage mitigation demonstrating pronounced success in that field. Decontamination and refining of optical surfaces and the impact of contamination on laser resistance still stay the topics of active research and discussion.

7. Materials and Measurements

Among the four main sections of the conference, this one continuously stays the largest over several last years. This section deals with measurement of laser damage to the bulk of transparent optical media whether amorphous, polymeric, polycrystalline, or crystalline; reports of material properties of importance for their optical function and/or the damage process, e.g., linear and nonlinear absorption coefficients, thermal conductivity, stress-optic coefficients, moduli, scattering, and various defects. Also included are new techniques for measuring these quantities, which present a continuing challenge as materials are improved in quality and diversity.

There is always interest in improved measurement systems or new instruments particularly in the area of non-destructive characterization and defect detection instrumentation. Laser damage measurements are difficult and work continues on developing tests that address large area versus small area and the difficulties of obtaining high resolution data. Significant efforts are reported on investigation of damage precursors, damage initiators, their identification and elimination. Impressing reports are delivered on automated programmable systems for defect identification and blocking for mitigating laser-induced damage.

8. Mini-Symposium on Fundamentals of Laser Ablation

This year the meeting was concluded with a mini-symposium dealing with the topic of Fundamentals of Laser Ablation. The basic processes of initiating and early-stage development are similar for laser ablation and surface damage and include laser-induced ionization, energy transfer from electron to phonon sub-system, and atomic motion away from the ablated surface. This fact makes very considerations of the fundamental effects of laser ablation of particular interest for the laser-damage community. This year the mini-symposium was opened by an invited talk delivered by Dr. Herbert M. Urbassek (Germany). The other talks presented experimental techniques (application of time-resolved coherent XUV scattering to investigate ultrashort-pulse laser-induced melting and ablation) and theoretical results (simulation of laser-induced ionization and its dependence on material parameters) of studies of the fundamental processes of laser ablation. The mini-symposium was organized this year by Dr. Klaus Sokolowski-Tinten from the University of Duisburg-Essen (Germany).

A brief summary of the past mini-symposium topics staring 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

9. Plenary Talks

As usually, the 42nd Boulder Damage Symposium is highlighted by several invited presentations:

1. "Advances in ion beam sputtered optical interference coatings", C. S. Menoni, Colorado State University (United States), 784202.

2. "Imaging the early material response associated with exit surface damage in fused silica", S. G. Demos, Lawrence Livermore National Laboratory (United States), 78420M.

3. "Insight from molecular dynamics simulation into ultrashort-pulse laser ablation", H. M. Urbassek, Technische Universität Kaiserslautern (Germany), 784214.

4. "Multiscale analysis: a way to investigate laser damage precursors in materials for high power applications at nanosecond pulse duration", J.-Y. Natoli, Institut Fresnel (France), 784217.

5. "Developing MRF technology for the manufacture of large-aperture optics in mega-joule class laser systems", J. A. Menapace, Lawrence Livermore National Laboratory (United States), 78421W.

10. 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)).

There were several outstanding posters and oral papers, however, the following papers were selected:

Best oral paper:
"Frequency dependence in the initiation of ultrafast laser-induced damage", J. R. Gulley, Kennesaw State University (United States), 78420U.
Best poster paper:
"Femtosecond pulse S on 1 LIDT in dielectric materials: comparison of experiment and theory", L. A. Emmert, M. Mero, D. N. Nguyen, W. Rudolph, the University of New Mexico (United States); D. Patel, E. M. Krous, C. S. Menoni, Colorado State University (United States), 784211.

11. In Conclusion

The location in Boulder, Colorado, during autumn at the venue of the National Institute of Standards and Technology and its outstanding facilities and support staff were appreciated by all. The 138 attendees were easily accommodated with ample opportunity to mingle and socialize.

This year the sunny and warm weather in Boulder encouraged taking a group picture of all symposium participants by the staircase of the National Institute of Atmospheric Research (Boulder, CO) (Fig. 1) where the traditional Wine and Cheese Reception was held on Tuesday, September 28.

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, again with no parallel sessions.

We must also note the tireless assistance of SPIE staff 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, and on-line document service, to which we may add the social functions–thanks to them, "A good time was had by all."

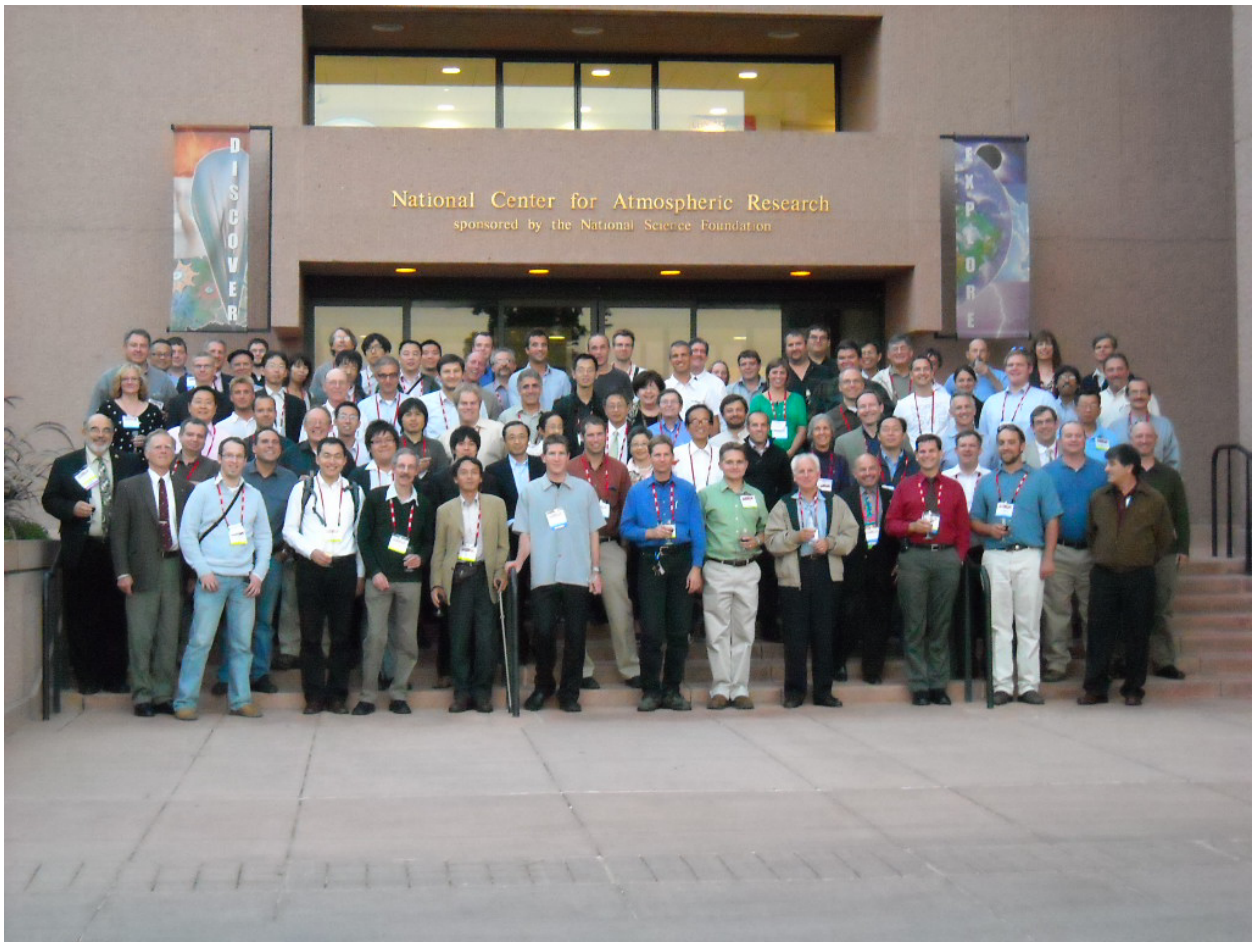

Fig. 1. Participants of SPIE Laser Damage Symposium by the staircase of the National Institute of Atmospheric Research (Boulder, CO). 28 September 2010.

12. Acknowledgments

A number of volunteers help tirelessly with some of the administrate duties necessary to put on a conference of this magnitude. Artika Arpana Lal from Lawrence Livermore National Laboratory assisted at the registration desk and helped with the thin-film competition. SPIE staff took care of the administrative planning and on-site tasks including registration, setup, and general questions; as well as program and proceedings preparation, invitation letters for international participants, and provided much on-line support for the conference and publishing all the manuscripts herein. The conference co-chairs appreciate their valuable help and assistance.

This year we acknowledge support from local Colorado companies: Rocky Mountain Instrument Co.; CVI Melles Griot; Saint-Gobain Crystals; and Precision Photonics Corp. for supporting social events of this meeting. They are separately acknowledged in this volume of conference proceedings.

Of course, we are all indebted to Kent Rochford, Division Chief of the Optoelectronics Division, who was the prime contact at NIST, for his continued support and encouragement, and Wendy Ortega, also of NIST, who together made it possible to hold a seamless meeting. On behalf of all the organizers and attendees, we thank them for their tireless efforts.

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