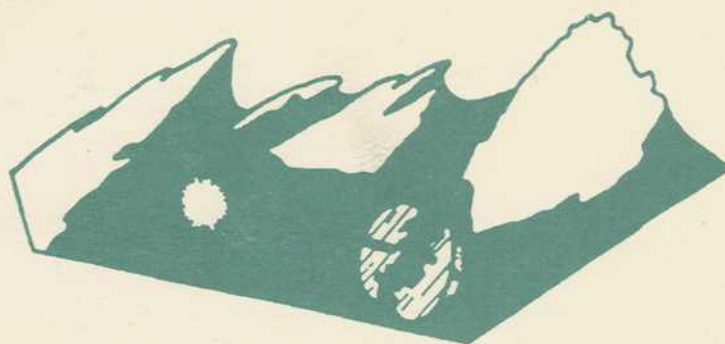


ASTM
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22nd ANNUAL BOULDER DAMAGE SYMPOSIUM
Proceedings



LASER-INDUCED DAMAGE IN OPTICAL MATERIALS: 1990

24-26 OCTOBER 1990
BOULDER, COLORADO

Editors

Harold E. Bennett
Lloyd L. Chase
Arthur H. Guenther
Brian E. Newnam
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FOREWORD

These proceedings contain the papers presented at the Twenty-Second Symposium on Optical Materials for High-Power Lasers, held at the National Institute of Standards and Technology in Boulder, Colorado, on 24–26 October 1990. The symposium was jointly sponsored by the National Institute of Standards and Technology, the American Society for Testing and Materials, the Center for Research in Electro-Optics and Lasers at the University of Central Florida, Lawrence Livermore National Laboratory, Los Alamos National Laboratory, SPIE—The International Society for Optical Engineering, and the Weapons Laboratory (USAF). The symposium was attended by 150 scientists from the United States and many foreign countries, including France, Germany, Israel, Japan, Sweden, the UK, and the USSR. It was divided into sessions devoted to the following topics: Materials and Measurements, Surfaces and Mirrors, Thin Films, and finally, Fundamental Mechanisms. Dr. Harold E. Bennett of the Naval Weapons Center, Dr. Lloyd Chase of the Lawrence Livermore National Laboratory, Dr. Arthur H. Guenther and Dr. Brian Newnam of the Los Alamos National Laboratory, and Dr. M. J. Soileau of the University of Central Florida chaired the symposium and served as editors of this report.

The editors assume full responsibility for the summary article, which contains an overview of the symposium. The manuscripts of the papers presented at the symposium have been prepared by their authors, and questions pertaining to their content should be addressed to them. The interested reader is referred to the bibliography at the end of the summary article for general references to the literature of laser damage studies. The Twenty-Third Annual Symposium on this topic will be held in Boulder, Colorado, on 23–25 October 1991. A concerted effort will be made to ensure closer liaison between the high-peak-power and the high-average-power communities.

The principal topics to be considered as contributed papers in 1991 do not differ drastically from those enumerated above. We expect to hear more about improved scaling relations as a function of pulse duration, area, and wavelength down to the x-ray region, and to see a continuing transfer of information from research activities to industrial practice. New sources at shorter wavelengths

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continue to be developed, and a corresponding shift in emphasis to short-wavelength and repetitively pulsed damage problems is anticipated. Fabrication and test procedures will continue to be developed, particularly in the thin film areas. New materials, diamond and diamondlike, for example, and the implication of thermal conductivity on damage modeling will undoubtedly be emphasized.

The purpose of these symposia is to exchange information about optical materials for high-power lasers. The editors welcome comments and criticism from all interested readers relevant to this purpose and particularly relative to our plans for the Twenty-Third Annual Symposium.

Harold E. Bennett
Naval Weapons Center

Lloyd L. Chase
Lawrence Livermore National Laboratory

Arthur H. Guenther
Brian E. Newnam
Los Alamos National Laboratory

M. J. Soileau
CREOL/University of Central Florida

SYMPOSIUM WELCOME

Harold E. Bennett
U.S. Naval Weapons Center
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On behalf of my cochairs Art Guenther, Brian Newnam, M. J. Soileau, and Lloyd Chase, I welcome you to the Symposium on Optical Materials for High-Power Lasers, more affectionately known as the Boulder Damage Symposium. For 22 years, this conference has been a meeting ground for the academic community and scientists and engineers working in industry and government. It has always had an academic flavor, and virtually all of the fundamental advances in the field of laser damage to optical materials and components were first reported here. It has always had an applications bias, with strong representation from laser optics manufacturers and materials companies. However, it has never been a platform for sales pitches. As some of you may recall, last year an author from outside the community presented a paper in which he described his product, refused to say what its scientific basis was or how it worked to improve optical components, and stated that if we wanted to improve our laser optics we would have to buy his product. The audience responded with a series of questions and comments that could best be described as acidic. Shortly afterward, I was talking to a new participant from another manufacturing company and asked him about his reaction to this talk. His response was "I certainly wouldn't want what happened to him to happen to me."

This is the premier international meeting on laser damage in optics. I noted this year that on the program we welcome papers from authors in the newly united Germany, the USSR, Japan, France, China, and the United Kingdom. We also have participants from Sweden and Israel. I know how hard it is for some of the participants from outside the United States to come to this conference in Boulder. The fact that they make this effort speaks volumes about the usefulness and timeliness of the work presented here. We welcome you.

Let me suggest to all of our participants that they refrain from talking about technical subjects that may be classified. This is not a classified conference, and questions on topics that are classified in one of the participating countries can only be an embarrassment to all concerned. There are plenty of subjects relating to high-power laser components that are unclassified and that involve intriguing scientific questions to be explored. Those are the subjects on which we should concentrate here.

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As in past years, the cochairs have broken up the subject material of the symposium into four parts: Materials and Measurements, Surfaces and Mirrors, Thin Films, and Fundamental Mechanisms. It has been said that we always save the best until last, and historically the Fundamental Mechanism session has produced some of the most significant advances in our understanding of the subject of laser damage. However, there are what promise to be excellent papers in all four sessions, and who can blame us if we schedule the program so that almost no one leaves until the last paper is given.

I suppose the most remarkable thing about this year's symposium is that we are all here in Boulder again and that it is being given as usual. As many of you know, there was a problem about continuing this conference as a result of some bureaucratic decisions made in Washington concerning all conferences run by the National Institute of Science and Technology (NIST), better known to us old-timers by the now archaic name of the National Bureau of Standards. The Boulder labs are part of this Institute. These decisions, which, I might add, the local management had no choice but to carry out, made it difficult for us to hold the symposium as we had in the past. As often happens, private enterprise and the free market concept came to the rescue. It is possible to rent the Boulder facilities and contract for its personnel, providing that the subject matter relates to the NIST mission, which this one does. We therefore received the superb support of NIST employees such as Delma Oberbeck and her colleagues in making local arrangements, printing and distributing the program, and in managing the auditorium facilities; Aaron Saunders is still our NIST Coordinator, Susie Rivera and others still help us, and the main difference that you will see is that the money for the meeting is being handled by Diana Bryan from the Center for Research in Electro-Optics and Lasers (CREOL) at the University of Central Florida rather than by NIST personnel.

There is another major difference in the way that this symposium is now handled: instead of the proceedings being published by the Government Printing Office, they are now published by SPIE as a symposium proceedings. As many of you know, the International Society for Optical Engineering, or SPIE, is the largest of the nonprofit optical organizations headquartered in the United States. As of June 30, 1990, it had over 11,000 members, most of them in the United States. However, 21% of them live outside the United States and 36% of the elected governors of the organization are non-US citizens, so it is truly an international optics organization. There are Chapters in Poland, Hungary, the USSR, Taiwan, Japan, and Australia, as well. SPIE is at present the major publisher of technical meeting proceedings in the optics field. The number of proceedings they print has increased dramatically over the last 10 years to nearly 200 per year, and in 1989 they sold about 79,000 copies. The proceedings are published in a timely fashion and they are well done. We now have an agreement with them to publish the proceedings of the Boulder Damage Conference.

Under the terms of agreement with SPIE, we cochairs will continue to manage the Boulder Conference for you as we have done in the past. However, the onerous task of getting authors to send in their papers in a timely manner, compiling the front matter, and publishing the volumes will be done by the SPIE staff. Each conference attendee will receive a copy of the proceedings as part of his registration fee. The proceedings will also be sold by SPIE through their standard mailing lists, which include many libraries. The proceedings will therefore become much more accessible to the scientific community than they have been in the past. You should check with your library to see that they order a copy of the proceedings from SPIE.

The two complaints we as cochairs have most frequently heard about this meeting are that the proceedings are slow in being published and that proceedings from former years are almost unobtainable. The agreement with SPIE should solve both of these problems without materially affecting the way in which the conference itself is run. The manuscripts for this meeting are due December 15, 1990. A major difference which those few of you that have been getting your manuscripts in months late will see relative to this meeting is that you will be contacted soon after the paper deadline by some very persistent editors who will keep calling you until you get your manuscript completed. *Vivre la difference!*

SPIE is also considering making back issues of the proceedings available, probably on microfiche, for the scientific community. Most of you probably received questionnaires this fall about the interest in these back issues. Some 40% of you returned these questionnaires, which the SPIE staff thinks is phenomenal; a few percent return on a questionnaire is normal. Nearly all of you would like to see the back issues made available. However, it appears that the estimated \$200 to \$300 cost for all back issues in book form is too high for most of you. Since the back issues of the proceedings contain much material not published elsewhere, they represent a trove of data on laser-damage-related phenomena. If reprinting them is too expensive, microfiche may be the answer. We are also discussing the possibility of providing them on computer cassettes. Another goal we have is to develop a cumulative index to all of the proceedings. We plan to include in it the review articles on the field that we heard in celebration of the 20th anniversary of this meeting, but which have not yet been published; we have talked with SPIE about publishing this cumulative index. Your input on all these questions would be appreciated.

Let me take this opportunity to thank the professional and financial sponsors of this conference. It started because of the need felt by a subcommittee of the American Society for Testing Materials (ASTM), and they are still our technical

(continued)

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sponsor. In addition, we would like to thank the Center for Research in Electro-Optics and Lasers at the University of Central Florida and the National Institute of Standards and Technology here in Boulder for their interest in the symposium, and for their support in making it possible for the symposium to continue. We also thank SPIE, The International Society for Optical Engineering, for their interest in the symposium and their financial support. Major financial support came from our sponsors, the Defense Advanced Research Projects Agency, Lawrence Livermore National Laboratory, Los Alamos National Laboratory, and the Weapons Laboratory (USAF). The scientific community is indebted to them for helping to make this conference happen.

SUMMARY OF MEETING

**Laser-Induced Damage in Optical Materials
Twenty-Second ASTM Symposium
24-26 October 1990**

The Twenty-Second Annual Symposium on Optical Materials for High-Power Lasers (Boulder Damage Symposium) was held at the National Institute of Standards and Technology in Boulder, Colorado, 24-26 October 1990. The symposium was held under the auspices of the ASTM Committee F-1, Subcommittee on Laser Standards, with the joint sponsorship of the American Society for Testing and Materials, Center for Research in Electro-Optics and Lasers at the University of Central Florida, Lawrence Livermore National Laboratory, Los Alamos National Laboratory, NIST, SPIE, and the Weapons Laboratory (USAF). Approximately 150 scientists attended the symposium, including representatives from the United States, France, Germany, Israel, Japan, Sweden, the United Kingdom, and the USSR. The symposium was divided into sessions concerning Materials and Measurements, Surfaces and Mirrors, Thin Films, and Fundamental Mechanisms. As in previous years, the emphasis of the papers presented at the symposium was directed toward new frontiers and new developments. Particular emphasis was given to materials for high-power apparatus. The wavelength range of prime interest was from 1.06 μm to the UV region. Highlights included surface characterization, thin film/substrate boundaries, and advances in fundamental laser-matter threshold interactions and mechanisms. Harold E. Bennett of the Naval Weapons Center, Lloyd L. Chase of the Lawrence Livermore National Laboratory, Arthur H. Guenther and Brian E. Newnam of the Los Alamos National Laboratory, and M. J. Soileau of the University of Central Florida were cochairs of the symposium. The Twenty-Third Annual Symposium is scheduled for 23-25 October 1991, at the National Institute of Standards and Technology, Boulder, Colorado.

Key Words: laser damage; laser interaction; optical components; optical fabrication; optical materials and properties; thin film coating.

(continued)

1. Introduction

The Twenty-Second Annual Symposium on Optical Materials for High-Power Lasers (Boulder Damage Symposium) was held, as in previous years, at the National Institute of Standards and Technology in Boulder, Colorado, 24-26 October 1990. The symposium was held under the auspices of the ASTM Committee F1, Subcommittee on Laser Standards, with the joint sponsorship of the American Society for Testing and Materials, Center for Research in Electro-Optics and Lasers at the University of Central Florida, Lawrence Livermore National Laboratory, Los Alamos National Laboratory, NIST, SPIE, and the Weapons Laboratory (USAF). Approximately 150 scientists attended the symposium, including representatives from the United States, France, Germany, Israel, Japan, Sweden, the United Kingdom, and the USSR. The symposium was divided into sessions concerning Materials and Measurements, Surfaces and Mirrors, Thin Films, and finally, Fundamental Mechanisms. In all, approximately 60 technical presentations were made. Harold E. Bennett of the Naval Weapons Center, Lloyd L. Chase of the Lawrence Livermore National Laboratory, Arthur H. Guenther and Brian E. Newnam of the Los Alamos National Laboratory, and M. J. Soileau of the University of Central Florida were co-chairs of the symposium. Aaron A. Sanders of the National Institute of Standards and Technology acted as Conference Coordinator.

The purpose of these symposia is to exchange information about optical materials for high-power lasers. The authors welcome comments and criticism from all interested readers relevant to this purpose and particularly relative to our plans for the Twenty-Third Annual Symposium, scheduled for 23-25 October 1991 at the National Institute of Standards and Technology, Boulder, Colorado.

2. Overview

The 22nd Boulder Damage Symposium contained approximately 60 presented papers, and over 150 participants. These numbers are reduced from our averages of ~70 papers and ~200 participants, due primarily to inadequate notice as well as the downturn in research and development funding. We expect to increase both the number of presentations and attendees this coming year. There were numerous contributions in the categories that we have historically applied to this meeting: Materials and Measurements, Surfaces and Mirrors, Thin Films, and Fundamental Mechanisms. Our objective in this section is to give the reader a sense of the emphasis and general concerns of this year's symposium. Although we do not review all of the excellent work presented, some highlights are touched upon briefly.

Materials and Measurements

The conference this year contained a good mix of material and measurement or instrumentation presentations. An example of the continuing improvement of laser materials addressed at our first symposium was a report on platinum inclusions in laser glass. This subject is of increased importance as optical elements continue to grow in size and volume primarily in laser fusion applications. Inclusions have been reduced from ~ 20 parts/mm square down to ~ 0.07 parts/mm square, a most significant improvement that will benefit the entire optical materials community.

Two vastly different classes of materials were also highlighted: first, optical fibers for the transmission of high-energy or high-power pulses, and second, diamond. The fiber work was driven by their use to detonate explosives. Greater energy or power handling capability increases detonation reliability and timing. As might be expected, critical failure modes at the entrance and exit facets were identified and discussed. Several unique procedures were developed to reduce failure at these sites.

A comprehensive talk on diamond technology was well received, not only because of the interest in this material, but because of the fundamental and tutorial nature of the presentation to a variety of applications. It was pointed out that diamond is not a cure-all in many scenarios, primarily as a result of the induced stress resulting from CVD deposition at high temperatures on some windows. The lattice match between diamond or silicon substrates may suggest their use as improved reflectors in the extreme ultraviolet over bare silicon.

Two diagnostic papers stood out at this meeting, the first related to the increased accuracy needed in refractive index measurement by the microelectronics industry. The NIST is being requested to measure refractive index to 10^{-6} to 10^{-7} accuracy for calibration or control in microlithography. Previously the demonstrated capability was only 10^{-5} . Obviously, as the microelectronics industry proceeds to finer features, tolerances on the optics employed become more severe.

Finally, a paper detailing the capabilities of photothermal deflection as a technique to determine precatastrophic damage onset was exhibited to be a most powerful procedure, especially as applied to thin films. Its application should grow, especially as one attempts to unravel the mechanism of conditioning of which more will be heard later.

Surfaces and Mirrors

Real advances, mostly evolutionary, continue to be made in this area. Just as one needs to reduce inclusions as optical elements increase, so does one have to

strengthen larger surfaces. It was reported that ion exchange treatment of laser glass surfaces can now be scaled to slab dimensions of several tens of centimeters, yielding breaking strengths twice as large as unstrengthened glass.

A highlight of this area was a presentation on the effectiveness of ion milling of fused silica for window fabrication as a function of an extensive matrix of polishing parameters. Although the results of these investigations are not complete, it was found that ion beam milling substantially decreases scattering levels with a concurrent increase in the damage threshold by a factor of four. The use of internal reflection spectroscopy was incorporated and compared to Nomarsky microscopy when probing for subsurface strains and absorption.

Thin Films

Thin films continue to receive the most attention at the conference, primarily because of the diversity of thin film applications and because they have lower damage thresholds than the bulk and surfaces. Historically there have been three approaches to increasing damage resistance of thin films: materials, design, and deposition, to which this year we must add conditioning.

A clear advancement were some impressive results on Rugate filters by a group from the United Kingdom, which discussed improvements not only in damage resistance, but reflection as a result of improved designs. This work, together with some reported in the United States, pointed to the efficacy of ion-assisted or microwave-plasma-assisted coating. One of the most impressive revelations was that they are currently able to choose which two reflection peaks they desire within broad limits and then take the Fourier transform of the two peak shapes and predict from that the coating design of the Rugate filter to produce the desired results. There is great promise in the flexibility of this approach, now that controllable deposition facilities are at hand. Regarding related work, it should be noted that ion beam deposition of fluoride coatings in a reactive atmosphere is being pursued in an attempt to obtain vacuum ultraviolet optics at 193 nanometers. Some difficulties are being evidenced in the in-situ diagnostics for microwave plasma CVD coating at high temperature.

Without question, from a real-world, system, or procedural standpoint, the results on improved operating levels achievable by low-level conditioning of $\text{HfO}_2\text{-SiO}_2$ multilayers (usually through a ramping of the intensity) is most noteworthy. Permanent improvements in damage thresholds of two or three seem routine, especially for thin-film-coated elements. This improvement has allowed for scale-up of fusion lasers from multikilojoule to the megajoule level. It was clear from the papers presented that the causes of this conditioning phenomenon are not well understood.

The fusion community presses ahead on all fronts of optical technology to produce demonstrated improvements with increased damage thresholds of coated optics, by sol gel application, conditioning, to enhanced KDP damage thresholds resulting from filtering and ultraviolet irradiation during crystal growth as advanced by the Japanese. Sol gels are also being improved by the use of a Teflon perfluorinated compound that is more resistant to environmental degradation.

Fundamental Mechanisms

Customarily, the meeting concludes with a session on fundamental mechanisms (covering the interaction of intense laser light with matter) and system-related presentations to determine if we have transferred our understanding to the laboratory floor. As usual, results were mixed. Advances in practice this year outpaced improved understanding. Although conditioning effects (both negative and positive) have been observed for a long time, no one has employed beneficial conditioning procedures on a routine basis until now. Our understanding is not keeping pace. We don't know from first principles why they're better, although almost anyone you ask in the community has a pat answer. Unfortunately, we haven't even determined improvements in absorption levels (if present) associated with conditioning. We fully hope we'll have some answers next year.

Several historical and frequently addressed topics emerged anew this year. It was demonstrated that one could achieve a closed form for the onset of damage threshold analysis (a la Foltyn and Porteus), reducing the number of parameters to two and making the analysis more tractable and comfortable.

The parametrics of damage scaling was also revisited and the speaker's enthusiasm for this subject was an appropriate conclusion to the meeting. There were some heated interchanges concerning the selection of data and the scaling relative to understanding interaction mechanisms from gases to liquids to solids including surfaces and thin films.

On the other hand, nonlinear refraction and dispersion in solids appears to be in good shape, analytically as well as experimentally. In addition, some new insight on the response of optical solids to high intensities was reported, and how that interaction might in a fundamental way effect damage was reported.

Our understanding of materials properties, and optical damage thresholds, continues to improve each year. Most improvements are first presented and documented in these proceedings. There is no question but that the symposium creates progress, generates beneficial interactions, and represents a unique collection of informed practitioners.

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4. References

- [1] Glass, A. J., and A. H. Guenther, Eds., *Damage in Laser Glass*, ASTM Spec. Tech. Pub. 469, ASTM, Philadelphia, PA (1969).
- [2] Glass, A. J., and A. H. Guenther, Eds., *Damage in Laser Materials*, Nat. Bur. Stand. (U.S.) Spec. Publ. 341 (1970).
- [3] Bloembergen, N., *Fundamentals of Damage in Laser Glass*, National Materials Advisory Board Publ. NMAB-271, National Academy of Sciences (1970).
- [4] Glass, A. J., and A. H. Guenther, Eds., *Damage in Laser Materials: 1971*, Nat. Bur. Stand. (U.S.) Spec. Publ. 356 (1971).
- [5] Bloembergen, N., *High-Power Infrared Laser Windows*, National Materials Advisory Board Publ. NMAB-356 (1971).
- [6] Glass, A. J., and A. H. Guenther, Eds., *Laser-Induced Damage in Optical Materials: 1972*, Nat. Bur. Stand. (U.S.) Spec. Publ. 372 (1972).
- [7] Glass, A. J., and A. H. Guenther, Eds., *Laser-Induced Damage in Optical Materials: 1973*, Nat. Bur. Stand. (U.S.) Spec. Publ. 387 (1973).
- [8] Glass, A. J., and A. H. Guenther, Eds., *Laser-Induced Damage in Optical Materials: A Conference Report*, Appl. Opt 13 (1):74-88 (1974).
- [9] Glass, A. J., and A. H. Guenther, Eds., *Laser-Induced Damage in Optical Materials: 1974*, Nat. Bur. Stand. (U.S.) Spec. Publ. 414 (1974).
- [10] Glass, A. J., and A. H. Guenther, Eds., *Laser-Induced Damage in Optical Materials: 6th ASTM Symposium*, Appl. Opt. 14 (3):698-715 (1975).
- [11] Glass, A. J., and A. H. Guenther, Eds., *Laser-Induced Damage in Optical Materials: 1975*, Nat. Bur. Stand. (U.S.) Spec. Publ. 435 (1975).
- [12] Glass, A. J., and A. H. Guenther, Eds., *Laser-Induced Damage in Optical Materials: 7th ASTM Symposium*, Appl. Opt 15 (6):1510-1529 (1976).
- [13] Glass, A. J., and A. H. Guenther, Eds., *Laser-Induced Damage in Optical Materials: 1976*, Nat. Bur. Stand. (U.S.) Spec. Publ. 462 (1976).

LASER-INDUCED DAMAGE IN OPTICAL MATERIALS: 1990

SPIE Volume 1441

- [14] Glass, A. J., and A. H. Guenther, Eds., *Laser-Induced Damage in Optical Materials: 8th ASTM Symposium*, Appl. Opt. 16 (5):1214-1231 (1977).
- [15] Glass, A. J., and A. H. Guenther, Eds., *Laser-Induced Damage in Optical Materials: 1977*, Nat. Bur. Stand. (U.S.) Spec. Publ. 509 (1977).
- [16] Glass, A. J., and A. H. Guenther, Eds., *Laser-Induced Damage in Optical Materials: 9th ASTM Symposium*, Appl. Opt. 17 (15):2386-2411 (1978).
- [17] Glass, A. J., and A. H. Guenther, Eds., *Laser-Induced Damage in Optical Materials: 1978*, Nat. Bur. Stand. (U.S.) Spec. Publ. 541 (1978).
- [18] Glass, A. J., and A. H. Guenther, Eds., *Laser-Induced Damage in Optical Materials: 10th ASTM Symposium*, Appl. Opt. 18 (13):2212-2229 (1979).
- [19] Bennett, H. E., A. J. Glass, A. H. Guenther, and B. E. Newnam, Eds., *Laser-Induced Damage in Optical Materials: 1979*, Nat. Bur. Stand. (U.S.) Spec. Publ. 568 (1979).
- [20] Bennett, H. E., A. J. Glass, A. H. Guenther, and B. E. Newnam, Eds., *Laser-Induced Damage in Optical Materials: 11th ASTM Symposium*, Appl. Opt. 19 (14):23375-2397 (1980).
- [21] Bennett, H. E., A. J. Glass, A. H. Guenther, and B. E. Newnam, Eds., *Laser-Induced Damage in Optical Materials: 1980*, Nat. Bur. Stand. (U.S.) Spec. Publ. 620 (1981).
- [22] Bennett, H. E., A. J. Glass, A. H. Guenther, and B. E. Newnam, Eds., *Laser-Induced Damage in Optical Materials: 12th ASTM Symposium*, Appl. Opt. 20 (17):3003-3019 (1981).
- [23] Bennett, H. E., A. H. Guenther, D. Milam, and B. E. Newnam, Eds., *Laser-Induced Damage in Optical Materials: 1981*, Nat. Bur. Stand. (U.S.) Spec. Publ. 638 (1983).
- [24] Bennett, H. E., A. H. Guenther, D. Milam, and B. E. Newnam, Eds., *Laser-Induced Damage in Optical Materials: 13th ASTM Symposium*, Appl. Opt. 22 (20):3276-3296 (1983).
- [25] Bennett, H. E., A. H. Guenther, D. Milam, and B. E. Newnam, Eds., *Laser-Induced Damage in Optical Materials: 1982*, Nat. Bur. Stand. (U.S.) Spec. Publ. 669 (1984).
- [26] Bennett, H. E., A. H. Guenther, D. Milam, and B. E. Newnam, Eds., *Laser-Induced Damage in Optical Materials: 14th ASTM Symposium*, Appl. Opt. 23 (21):3782-3795 (1984).
- [27] Bennett, H. E., A. H. Guenther, D. Milam, and B. E. Newnam, Eds., *Laser-Induced Damage in Optical Materials: 1983*, Nat. Bur. Stand. (U.S.) Spec. Publ. 688 (1985).
- [28] Bennett, H. E., A. H. Guenther, D. Milam, and B. E. Newnam, Eds., *Laser-Induced Damage in Optical Materials: 15th ASTM Symposium*, Appl. Opt. 25 (2):258-275 (1986).
- [29] Bennett, H. E., A. H. Guenther, D. Milam, and B. E. Newnam, Eds., *Laser-Induced Damage in Optical Materials: 1984*, Nat. Bur. Stand. (U.S.) Spec. Publ. 272 (1986).
- [30] Bennett, H. E., A. H. Guenther, D. Milam, and B. E. Newnam, Eds., *Laser-Induced Damage in Optical Materials: 16th ASTM Symposium*, Appl. Opt. 26 (5):813-827 (1987).

(continued)

LASER-INDUCED DAMAGE IN OPTICAL MATERIALS: 1990

SPIE Volume 1441

- [31] Bennett, H. E., A. H. Guenther, D. Milam, and B. E. Newnam, Eds., *Laser-Induced Damage in Optical Materials: 1985*, Nat. Bur. Stand. (U.S.) Spec. Publ. 746 (1987).
- [32] Bennett, H. E., A. H. Guenther, D. Milam, and B. E. Newnam, Eds., *Laser-Induced Damage in Optical Materials: 1986*, NIST (U.S.) Spec. Publ. 752 (1987).
- [33] Bennett, H. E., A. H. Guenther, D. Milam, B. E. Newnam, and M. J. Soileau, Eds., *Laser-Induced Damage in Optical Materials: 1987*, NIST (U.S.) Spec. Publ. 756 (1988).
- [34] Bennett, H. E., A. H. Guenther, B. E. Newnam, and M. J. Soileau, Eds., *Laser-Induced Damage in Optical Materials: 1988*, NIST (U.S.) Spec. Publ. 775 (1989).
- [35] Bennett, H. E., L. L. Chase, A. H. Guenther, B. E. Newnam, and M. J. Soileau, Eds., *Laser-Induced Damage in Optical Materials: 1989*, NIST (U.S.) Spec. Publ. 801, ASTM STP 1117 and SPIE Vol. 1438 (1989).
- [36] Wood, R. M., *Laser Damage in Optical Materials*, 1986, Adam Hilger, Bristol (U.K.).
- [37] Wood, R. M., Ed., *Selected Papers on Laser Damage in Optical Materials*, SPIE Milestone Series Vol. MS24, 1990, Bellingham (U.S.).

