FOREWORD

The Proceedings contain the papers presented at the Twenty-First Symposium on Optical Materials for High-Power Lasers held at the National Institute of Standards and Technology in Boulder, Colorado, on November 1-3, 1989. The Symposium was sponsored jointly by the National Institute of Standards and Technology, the American Society for Testing Materials, the International Society for Optical Engineering, the Defense Advanced Research Project Agency, and the Department of Energy. The Symposium was attended by approximately 200 scientists from the United States, Canada, the United Kingdom, Japan, France, and the Federal Republic of Germany. It was divided into sessions devoted to the following topics: Materials and Measurements, Mirrors and Surfaces, Thin Films, and, finally, Fundamental Mechanisms. The Symposium Co-Chairmen were Harold E. Bennett of the Naval Weapons Center, Arthur H. Guenther of the Los Alamos National Laboratory, Lloyd L. Chase of the Lawrence Livermore National Laboratory, Brian E. Newnam of the Los Alamos National Laboratory, and M. J. Soileau of the University of Central Florida. They also served as editors of the proceedings.

The editors assume full responsibility for the summary, conclusions, and recommendations contained in the report, and for the summaries of discussion found at the end of each paper. The manuscripts of the papers presented at the Symposium have been prepared by the designated authors, and questions pertaining to their content should be addressed to those authors. 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-Second Annual Symposium on this topic will be held in Boulder, Colorado, October 24-26, 1990. A concerted effort will be made to ensure closer liaison between the practitioners of high-peak power and high-average power.

The principal topics to be considered as contributed papers in 1990 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, and to see a continuing transfer of information from research activities to industrial practice. New sources at shorter wavelengths 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 diamond-turned optics and thin-film areas. It has been our intention to pause and reflect on progress over the past twenty years to the Symposium on Optical Materials for High Power Lasers. It will be our pleasure to present the last (Thin Film, the Second Decade) in a comprehensive array of tutorial lectures by distinguished workers in the field of laser induced damage in optical materials.

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

H. E. Bennett, A. H. Guenther, L. L. Chase,
B. E. Newnam, and M. J. Soileau,
Co-Chairmen

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CONTENTS

Thin Films

FUNDAMENTAL MECHANISMS

WELCOME FOR 21st BOULDER DAMAGE SYMPOSIUM

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It is my pleasure and duty to call this year's meeting to order. I was abroad when the final program was put together by my co-chairs and did not learn of this honor until a couple of weeks ago. I had no time to prepare until this weekend, so this will be a bit rough and without the benefit of elegantly prepared slides.

I don't mean to take a stab at my co-chairs, but I must admit that as I began my preparation I couldn't remember a single thing about previous opening remarks by my esteemed colleagues! Did I miss something? Surely these distinguished leaders of national laboratories must have said something profound and prophetic! So I spent part of the day Saturday reviewing the past utterances which have launched this meeting.

It is true that the memory is the second thing to go, because as I read the opening remarks for the past 20 meetings, I found many, profound statements--a few of which are listed below:

This is a quote from the next speaker from 1972:

"It is a pleasure to be here this afternoon."
Martin Stickley, 1972.

"Whatever turns you off." (Alex's definition of damage)
Alex Glass, 1974

"A name which invokes images of people cracking rocks."
Alex Glass, 1976. (In response to Martin Stickley's call for a more positive sounding name for the conference.)

"Our onion unfortunately, exists in Hilbert Space." (Alex borrowing from an ancient philosopher's description that learning is like peeling an onion--each layer exposes another.)

"Who cares?" (Alex on why study damage?)
Alex Glass, 1976.

"It is my annual hope that each year's symposium will be the last." (Alex the failed prophet.)
Alex Glass, 1978.

"The key...is terawatts per megabuck.
Alex Glass, 1978.

"Power Optics." (A supplier of megabucks at the time in comparing laser optics to electronics.)
Harry Winsor, 1978.

"Aside from a gain medium, lasers require mirrors." (Insightful words from the great visionary.)
Harry Winsor, 1978.

"Progress has been made, but I am confident that in 10 years we will celebrate the 20th and Art and Alex will still be running it!" "...we owe a debt to these 2 young men." (Note the term young.)
Martin Stickley, 1978.

To this point I've spared you the profound utterance of my current co-chairs such as:

"Welcome to the Tenth Anniversary Damage Symposium." (Art Guenther gave this greeting at the 11th meeting.)
Art Guenther, 1979.

Then there were profound things said regarding the international participation.

"...countries represented include the British Isles, Canada, England, France, Japan, Scotland, and West Germany:"
Brian Newnam, 1980.

"International contributors...have come a long way..."
Hal Bennett, 1985.

It should be clear to all how difficult it is for me since these guys have used up all the good stuff! Further review of these openings presented me with a good outline for my remarks. I will follow the trail blazed by my predecessors:

Outline

1. Welcome participants.

2. Acknowledge sponsorship of NIST, ASTM, and others.

3. Count the papers for this year's meeting and comment on the statistical distribution.

4. Observe that thin films are a major problem.

5. Profound and prophetic statement about the future of the meeting.

I do welcome you to the 20th Anniversary Boulder Damage Symposium. Those of you who are still asleep or partially hung over, may be confused by the fact that last year was our 20th Anniversary celebration. The resolution of this dilemma is the fact that last year was the 20th meeting and this is the 20th Anniversary (but the 21st meeting). One might say that this meeting is old enough to drink - but you will also note that there is no wine and cheese this year. This situation has resulted from rulings by NIST accountants. In fact, the accountants have made it difficult for us to conduct business as usual, so you can expect further changes next year.

We do want to thank NIST and the ASTM for their continued sponsorship and all the helpful folks at Boulder who make the meeting run smoothly.

There are about 70 papers this year with contributions from 6 countries, in addition to the U.S. The talks from abroad constitute 27% of the papers, about the same percentage as from Livermore and Los Alamos. About an equal number of papers come from U.S. aerospace companies (15%) and U.S. universities (16%). About 9% are from DoD labs and the remaining 8% from various other sources.

Our next speaker (Martin Stickley) has suggested on a number of occasions that the name of the conference be changed to something more positive. I want to finish this presentation by noting that there are many positive things being done with phenomena studied by participants in these meetings. Here is a list of a few:

"Spin Offs" of LID Phenomena

1. Laser marking, cutting and drilling of materials.

2. Laser medicine
   a. laser scalpel
   b. laser-induced breakdown for eye treatments and plaque removal.

3. Laser disc storage - the first application of LID to consumer products.

4. Photorefractive information storage, processing, and phase conjugation interconnects.

5. Nonlinear refraction and nonlinear absorption for limiters, switches, and optoelectronic computing.

6. Electro-absorptive switches using UHV manufactured quantum well devices (SEED's).

So I issue a challenge to us all to keep the name Damage Symposium, but continue to seek positive applications of the phenomena we study. A wise professor once told me that phenomena are neither good or bad--they exist and it's up to us to find ways to make good things using phenomena given by nature.

Before I left Orlando, I looked into by crystal ball for a glimpse of future laser damage or optical materials problems--here is my short list:

Future Topics for Optical Materials Research

1. Thin films for all applications. Two talks viewing 20 years of thin film work.

2. New laser host and nonlinear optical materials for compact, efficient, tunable and solid state lasers for many old and many new applications.

3. X-ray optics for lasers (remember Harry Winsor said that lasers have mirrors...), and optics for x-ray microscopy and x-ray lithography.

4. Materials for x-ray lithography.

I'm sure that these and other topics will keep optical materials people busy for some time--the only question is where will the funding come from? DoD funding will surely decline as peace is breaking out all over. DOE funding usually finds its way to the national labs--but not much finds its way out. DARPA, under Martin Stickley's leadership, provided much of the spark that lead to modern day materials and much of the research reported at this conference. Materials research tends to be too long-term for present day funding. We need to all do our part in ensuring continued research support for the foundation of the technology food chain--materials research.

Since we don't have an official wine and cheese gathering, I hereby propose that we forgo small gatherings of old friends for dinner, etc. and meet instead at the Dark Horse for an informal, pay as you go, social hour.

Manuscript received
2-14-90

SEARCH FOR TECHNOLOGY TRANSFER IN HIGH POWER OPTICS

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In the late 60's and through the 70's, DARPA supported a broad program to develop optics for use with high power cw CO_2 lasers and new laser and nonlinear optical materials. This paper summarizes those efforts and asks anyone who knows in what defense systems these have been used to contact the author.

In the late 1960's and through the 1970's, the Materials Sciences Office (now the Defense Sciences Office) of the Defense Advanced Research Projects Agency (DARPA) funded a broad program to develop optics for high power continuous development of approaches to fabricate large area windows with high transparency (absorption of 10^{-5} per cm), optical surface preparation techniques which leave very little residual absorption, and techniques for depositing antireflection as well as reflecting coatings for transparent windows and mirrors. Some development of new laser and nonlinear optical materials was also funded. Approximately $22.9 M dollars were spent between 1967 and 1978.

The Defense Sciences Office is now searching for examples of where optical parts fabricated using these techniques and the laser and NLO materials have been used in defense systems. While defense uses are of primary importance, NASA and industrial uses are also of interest.

Technologies which may have had the best chance of being utilized include, for windows: casting of fluorides, reactive atmosphere processing of halides, forging of halides, and CdTe growth, distortion and damage studies; for surfaces and coatings: polymers and surface preparation of halides, fluorides, and selenides; for lasers: erbuim glass, and holmium and erbium in YLF; for mirrors: beryllium optics; and for laser damage: platinum removal and surface preparation of Owens-Illinois glass, and bulk and surface damage of ruby.

The tables which follow summarize the activities which were supported in each major area. Included are the specific technology developed (e.g. fluoride fusion casting), the contractor, the amount of funding provided, and at the time period where the work was done.

If the reader knows of areas where any of these technologies may have been used in defense systems (as well as for NASA and the commercial sector), please contact the author.

LASER WINDOW MATERIALS

Fluorides

● Fluoride Fusion Casting	Raytheon	166K	76-77
● Scaling of Fluoride Casting	Raytheon	790K	74-76

Halides

● Halide Superalloys for High Power Windows	Raytheon	191K	72-73
● Halide OH Removal	Hughes Res. Labs	174K	72
● Reactive Atmosphere Processing	Hughes Res. Labs	215K	76-78
● RAP of KBR	Hughes Res. Labs	244K	74-76
● Extrusion and Cross-Rolling	Honeywell	1 95K	72-73
● Forging of Alkali Halides	Honeywell	1483K	73-78
● Radiation Hardening	Oklahoma	113K	72-74
● Press Forging Halides	NRL	521K	72-75
● RAP of KBR - Characterization	NRL	80K	76

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LASER WINDOW MATERIALS

II-VI Materials

● II-VI Distortion and Damage	USC	1336K	72-77
● CVD of Cadmium Telluride	Raytheon	192K	73-75
● CVD of CdTe and GaP	Raytheon	196K	75-77
● Characterization of II-VI Materials	MIT	308K	73-76

Chalcogenides

● Oxygen-Free Chalcogenides	Catholic University	283K	72-74
● Structure-Dependent Absorption	Texas Instruments	72K	73-74

Other

● Covalent Carbon Window Materials	UCLA	114K	75-76
● Copper-Leaded CERVIT	Owens Illinois	27K	76

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LASER WINDOW MATERIALS

Measurement Techniques

● Spectroscopy of Halides	Cornell	209K	75-76
● Emissivity Facility	Block Eng.	250K	73-75
● Multiple Wavelength Calorimetry	Alabama	58K	74-76
● Chemical Laser Window Absorption	Raytheon	60K	74-75
● CO_2 Laser Window Evaluation	AVCO	279K	75-76
● Proof Testing	MIT	168K	75-76
● Mechanical Properties	MIT	320K	72-75

Theory

● Theory of Coatings and UV Materials	Xonics	1342K	72-78

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LASER COATINGS AND SURFACES

● Polymer Protective Coatings	UC Berkeley	169K	75-77
● Polymer Protective Coatings	Rockwell	149K	73-74
● Surface and Coating Technology	Hughes Res. Lab	1076K	73-76
● Window Polishing and Characterization	NWC	1696K	72-77
● Passive Characterization/HF Coatings	NWC	1042K	76-77
● Coating Stress Measurements	Perkin Elmer	200K	76-77
● Coating Growth and Stress	AFCRL	255K	73-75
● Transparent Abrasives	Raytheon	207K	73-75

LASER MATERIALS

● Erbium Glass	American Optical	191K	69–71
● Holmium in YLF	Sanders Associates	203K	71–73
● Near Visible Laser Materials	Sanders Associates	270K	72–75
● Ceramics for Lasers	Union Carbide	193K	1977
● Wide Linewidth Materials	Texas Instruments	225K	72–73

MIRRORS AND SURFACES

● Beryllium for Optics	Perkin Elmer	1434K	Prior to 69
● Ion Beam Optical Figuring	Kollsman	146K	Prior to 69

NONLINEAR OPTICAL MATERIALS

● Cinnabar	Tyco	190K	70–71
● Chalcopyrite	Stanford	279K	70–74
● High Damage Threshold Materials	Isomet	98K	1973
● Chalcogenides	Westinghouse	230K	72–75
● IR Laser Components	Westinghouse	201K	Before 1969
● IR Quantum Counter	Purdue		

DAMAGE TO LASER MATERIALS

Glass

● Laser Glass Damage	Owens Illinois	616K	69–71
● Glass Surface Treatment	Owens Illinois	291K	72–73

Ruby

● Bulk and Surface Damage	Hughes Res. Labs	400K	69–71

Measurement Techniques

● Laser Measurements	NBS	2369K	Prior to 69
● Laser Damage Measurements	NBS	161K	72–73

Mirrors

● RF Sputtered Metal Mirrors	Battelle NW	450K	72–73

Research

● Miscellaneous Topics	Harvard, NWC, USC, AFCRL, Raytheon, Bendix	749K	71–76

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Laser Induced Damage in Optical Materials

Twenty-First ASTM Symposium
November 1-3, 1989

The Twenty-First 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, November 1-3, 1989. The Symposium was sponsored jointly by the National Institute of Standards and Technology, the American Society for Testing and Materials, the International Society for Optical Engineering, the Defense Advanced Research Project Agency, and the Department of Energy. Approximately 200 scientists, including representatives of the United Kingdom, France, Japan, Canada, and the Federal Republic of Germany, attended the Symposium. The Symposium was divided into sessions concerning Materials and Measurements, Mirrors and Surfaces, Thin Films, and, finally, 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 the prime interest was from 10.6 μm to the uv region. Highlights included surface characterization, thin film substrate boundaries, and advances in fundamental laser-matter threshold interactions and mechanisms. The scaling of damage thresholds with pulse duration, focal area, and wavelength was discussed in detail. Harold E. Bennett of the Naval Weapons Center, Arthur H. Guenther of the Los Alamos National Laboratory, Lloyd L. Chase of the Lawrence Livermore National Laboratory, Brian E. Newnam of the Los Alamos National Laboratory, and M.J. Soileau of the University of Central Florida were co-chairmen of the Symposium. The Twenty-Second Annual Symposium is scheduled for October 24-26, 1990, 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 coatings.

1. Introduction

The Twenty-First 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, November 1-3, 1989. The Symposium was held under the auspices of the ASTM with the joint sponsorship of NIST, and the Department of Energy. Approximately 200 scientists, including representatives of the United Kingdom, France, Japan, Canada, and the Federal Republic of Germany, attended the symposium. The Symposium was divided into sessions concerning Materials and Measurements, Mirrors and Surfaces, Thin Films, and, finally, Fundamental Mechanisms. In all, approximately 70 technical presentations were made. Harold E. Bennett of the Naval Weapons Center, Arthur H. Guenther, and Brian E. Newnam of the Los Alamos National Laboratory, Lloyd L. Chase of the Lawrence Livermore National Laboratory, and M. J. Soileau of the University of Central Florida were co-chairmen of the Symposium. Aaron A. Sanders of the National Institute of Standards and Technology acts 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-second Annual Symposium, scheduled for October 24-26, 1990, at the National Institute of Standards and Technology, Boulder, Colorado.

2. Overview

The following comments by the Symposium co-chairmen represent their impression of significant advances that were discussed immediately after the close of the meeting. This is not meant to be a thorough review of the conference, but only a brief glimpse of some of the highlights.

The largest single group of papers in the Fundamental Mechanisms session dealt with the effects of high photon energies on laser-induced damage (LID) at lower photon energies. As one example, short-wavelength harmonic radiation generated within free-electron lasers can potentially reduce the LID at the fundamental lasing wavelength. Another case involved the effect of ultraviolet radiation on the damage resistance at 10.6 μm. Yet another paper dealt with the use of photoconductivity as a diagnostic to identify defects within the bandgap and to monitor the onset of LID.

One area covered at this meeting for the first time was the nonlinear properties of inorganic polymers as well as those of organic polymers. In addition, a theoretical paper described the contribution of conjugated electronic systems to the nonlinear polarizability of such materials which have potential use as photoelectronic devices.

Always of interest to theoreticians are the possible relationships of apparently different classes of materials properties. This year, one group studied the relationship between the nonlinear refractive index and two-photon absorption coefficient using a model that assumed that a Kramers-Kronig relationship exists between the two.

One paper provoked a great deal of discussion and controversy, and suggested that avalanche breakdown is not a fundamental mechanism even for intrinsically pure materials, as generally accepted. Data which they believed supported their claim that damage occurs first by multiphoton absorption followed by nonlinear free-carrier absorption and heating that then leads to damage were presented. To account for earlier observation by other experimenters, it was asserted that avalanche processes do take place after breakdown is initiated. Nevertheless, indications of avalanche before breakdown were ascribed to extrinsic processes and/or impure materials. These conclusion challenge the laser damage community to propose a set of independent experiments that can confirm or discount their proposed model.

Concerning surfaces and mirrors, perhaps one of the most encouraging developments, after many years of continuous effort, was the progress reported for the polishing of silicon carbide. SiC and Be are among the most attractive mirror materials now being considered for use in space missions. One study reported on two different techniques for producing SiC mirrors which could be finished to varying degrees of surface polish and which were stable. The most attractive technique was physical-vapor deposition finishing of SiC by ion-beam sputtering very smooth coatings with a low level of stress. The rms surface roughness on these elements was less than 0.5 nm(5 Å), and stable with time.

Another exciting development was that ultra-precise grinding of glass surfaces with diamond had attained 0.5 nm(5 Å) roughness, which is remarkable. A number of papers concentrated on mirrors for the vacuum ultraviolet, a new thrust this year. There was some concentration on production problems of working with a system with 1 m diameter mirrors subjected to very high laser fluences. Systematic errors in surface topography using noncontact interferometers were discussed. We also heard a novel suggestion for laser protection of surfaces by developing small spherical particles that would diffusely reflect incoming laser beans. The particles must have absorption levels of $\sim 10^{-5}$ to 10^{-6} cm^{-1}. If this becomes possible, then mirrors with very high reflectance of 99.999% or better could result.

In the area of thin film coatings, degradation by ultraviolet and vacuum-ultraviolet wavelengths was emphasized. One parametric study concerned degradation to ZrO_2 films caused by 25-eV synchrotron radiation. Surprisingly, after a short period, the initial damage apparently healed, possibly by the material evolving to a different crystal structure. Another paper described the much higher resistance of HfO_2 films to color-center formation caused by a 248-nm KrF laser when the usual 3% ZrO_2 impurity content was reduced to a few tenths of a percent. We also heard a report on much higher damage thresholds being attained for multilayer reflectors prepared by the sol-gel process as a result of altering the coating process to decrease the concentration of absorbing impurities.

3. Acknowledgments

The editors acknowledge the invaluable assistance of Aaron A. Sanders and the other involved staff members of the National Institute of Standards and Technology in Boulder, Colorado, for their interest, support, and untiring efforts in the professional operation of the symposium. Particular thanks to Susie Rivera of NIST for her lead in the preparation and publication of the proceedings, as well as Margalene Hartman of NIST. Thanks, also, to Pat Whited of the Air Force Weapons Laboratory and Delma Oberbeck of NIST for conference coordination.

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