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Laser Induced Damage
in Optical Materials:
1978



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Laser Induced Damage In Optical Materials: 1978

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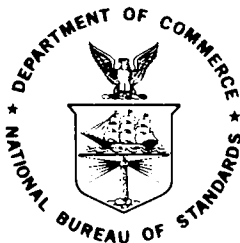
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Foreword

The Proceedings contain the papers presented at the Tenth Annual Symposium on Optical Materials for High Power Lasers held at the National Bureau of Standards in Boulder, Colorado, on September 12-14, 1978. The Symposium was jointly sponsored by the National Bureau of Standards, the American Society for Testing and Materials, the Office of Naval Research, the Defense Advanced Research Projects Agency, and the Department of Energy. The Symposium was attended by about 175 scientists from the United States, the United Kingdom, France, Canada, Japan, West Germany, and the Soviet Union. It was divided into sessions devoted to the following topics: the Measurement of Absorption Characteristics, Bulk Material Properties, Mirrors and Surfaces, Thin Film Damage, Coating Materials and Design, and Breakdown Phenomena. The Symposium Co-chairpersons were Dr. Alexander J. Glass of the Lawrence Livermore Laboratory and Dr. Arthur H. Guenther of the Air Force Weapons Laboratory, who also served as editors of this report.

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 Eleventh Annual Symposium on this topic will be held in Boulder, Colorado, from October 30 to 31, 1979. A concerted effort is being made to ensure closer liaison between the practitioners of high peak power and the high average power community.

The principal topics to be considered as contributed papers in 1979 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 damage problems is anticipated. Fabrication and test procedures will continue to advance, particularly in the micro-machined optics and thin film areas.

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

A. H. Guenther and A. J. Glass
Co-chairpersons

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Certain commercial equipment, instruments, or materials are identified in this publication in order to adequately specify the experimental procedure. In no case does such identification imply recommendation or endorsement by the National Bureau of Standards, nor does it imply that the material or equipment identified is necessarily the best available for the purpose.

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Laser Induced Damage in Optical Materials

Tenth ASTM Symposium

September 12-14, 1978

The Tenth Annual Symposium on Optical Materials for High Power Lasers (Boulder Damage Symposium) was held at the National Bureau of Standards in Boulder, Colorado, from 12-14 September 1978. The Symposium was held under the auspices of ASTM Committee F-1, Subcommittee on Laser Standards, with the joint sponsorship of NBS, the Defense Advanced Research Project Agency, the Department of Energy, and the Office of Naval Research. About 175 scientists attended the Symposium, including representatives of the United Kingdom, France, Canada, Japan, West Germany, and the Soviet Union. The Symposium was divided into sessions concerning the Measurement of Absorption Characteristics, Bulk Material Properties, Mirrors and Surfaces, Thin Film Damage, Coating Materials and Design, and Breakdown Phenomena. 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 use 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 also discussed. In commemoration of the tenth symposium in this series, a number of comprehensive review papers were presented to assess the state of the art in various facets of laser induced damage in optical materials. Alexander J. Glass of Lawrence Livermore Laboratory and Arthur H. Guenther of the Air Force Weapons Laboratory were co-chairpersons of the Symposium. The Eleventh Annual Symposium is scheduled for 30-31 October 1979 at the National Bureau of Standards, Boulder, Colorado.

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

1. Introduction

The Tenth Annual Symposium on Optical Materials for High Power Lasers (Boulder Damage Symposium) was held, as in previous years, at the National Bureau of Standards in Boulder, Colorado, from 12 to 14 September 1978. The Symposium was held under the auspices of the ASTM Committee F-1, Subcommittee on Laser Standards, with the joint sponsorship of NBS, the Defense Advanced Research Projects Agency, the Department of Energy, and the Office of Naval Research. Working sessions of the Committee F-1 Subcommittee on Lasers were held on Monday 11 September. About 175 scientists attended the Symposium, including representatives of the United Kingdom, France, Canada, Japan, West Germany, and the Soviet Union. The Symposium was divided into sessions concerning the Measurement of Absorption Characteristics, Bulk Material Properties, Mirrors and Surfaces, Thin Film Damage, Coating Materials and Design, and Breakdown Phenomena. As in previous years, several poster sessions were held. The general consensus of those presenting poster papers and those viewing them was highly favorable. In all, over fifty technical presentations were made. Alexander J. Glass of Lawrence Livermore Laboratory and Arthur H. Guenther of the Air Force Weapons Laboratory were co-chairpersons of the Symposium. At this, our Tenth Annual Symposium, we paused to reflect upon the past ten years' activities in laser induced damage to optical materials. We enlisted the services of fourteen distinguished speakers who are acknowledged to be the principal contributors in the many facets of the laser damage field. They summarized and quantified as well as possible the state of the art and the state of the understanding in their specialized areas. These review or tutorial lectures are being assembled and published as a separate volume on the subject of laser induced damage in optical materials. In addition, round-table discussions were held on those specific subjects in which there is still some question as to the correctness of our understanding to give the participants an opportunity to make recommendations for future research. The purpose of these symposia is to exchange information about optical materials for high power lasers. The authors will welcome comments and criticism from all interested readers relevant to this purpose and particularly relative to our plans for the Eleventh Annual Symposium, scheduled for 30-31 October 1979, at the National Bureau of Standards, Boulder, Colorado.

2. Principal Conclusions

Advances in the field of laser materials are incremental rather than revolutionary. Each year's progress represents a small step forward from the preceding year's position. The advances are also sporadic, unfortunately. New problems or new approaches are often identified in one year's symposium, only to be ignored in succeeding years, possibly to resurface a few years later, or not at all. One reason for this is the reluctance of investigators to report on those methods which failed. We hear only of the new approaches which have succeeded. Because of the incremental nature of advances in this field, the results reported in this summary must be viewed in the context of ten years of laser damage research; thus the significance of many of these results will not be clear for several years to come.

In the realm of operative damage phenomena, thin film damage remains the least well understood. This is to be expected, considering the complexity of the problem and the number of variables required

to characterize fully a thin film system. Most of the advances to date have been empirical, and even for film systems that usually exhibit high damage thresholds, control of the process variables is uncertain. Thus, a coating which performs excellently in one production run may well exhibit a lower threshold on the next run. The identification of the critical process variables has not been made.

There is abundant evidence that damage in thin films is not intrinsic, but arises from defects, impurities, or absorbed materials. The question is, to what degree can multilayer dielectric films be made free of these defects and impurities. The morphology of the film--its grain size, porosity, and crystalline orientation--all depend on a multiplicity of process variables, including deposition method, background pressure, substrate temperature, rate of deposition, and many others.

It is not surprising then that attempts to find simple solutions to thin film damage have not yielded consistent results. Techniques like barrier layer deposition work sometimes, but not always. At pulse durations of several ns and beyond, damage seems to be thermal, originating at highly localized sites. The identity and origin of these sites are still unclear. One does not expect this picture to improve greatly in the near future.

Regarding surface damage, the picture is substantially clearer. Chemical contamination remains the single greatest concern to surface damage. The contaminant can be H₂O, hydroxyl ions, or polishing residue. Surface roughness plays a role in determining the damage threshold, more so at long pulse durations, although the reason for the observed dependence remains open to conjecture. Regarding surface damage, the number of process variables is significantly smaller than for thin films, so the connection between process control and material performance should be much more straightforward.

Thermally induced bulk damage is an area in which great progress has been made. Note that "damage," in this context, includes distortion, birefringence, and other thermal mechanisms, in addition to catastrophic failure. By the sufficient reduction of impurity absorption, bulk absorptions can be reduced below 10^{-4}cm^{-1} for specific materials such as SiO₂ and the alkali halides. The intrinsic limit due to multiphonon absorption can be reached at infrared frequencies, and the relevant phonon assignments identified. Thus, both empirical improvement and basic understanding have been achieved for this particular scenario.

The case is quite the opposite for bulk breakdown. There is no consensus regarding the relative role of the several mechanisms which can contribute to dielectric breakdown. These include multiphoton absorption, impurity absorption, electron avalanche, and others. Attempts to link first-principle models to observed damage thresholds are probably futile, given the complexity of the intervening phenomena. Experiments are beginning to be reported in which precursors to damage, like photoconductivity or photocapacitance, are observed. These seem to promise improved correlation with theoretical models.

It is, however, safe to say that dielectric breakdown in bulk materials is not a critical problem for any application currently under investigation. It is important to understand the process and to understand electron behavior in dielectrics, because both surface damage and thin film damage are often accompanied by plasma formation, and so involve related, if not identical, phenomena. However, bulk dielectric breakdown is not on the "critical path" for system development.

Scaling laws provide a general guide to the behavior of damage thresholds as experimental conditions--such as pulse duration, spot size, or surface roughness--are changed. Departures from expected scaling often indicate the onset of some new phenomenon, or the introduction of extrinsic factors. Thus, the $t^{1/2}$ dependence, which is widely observed to apply to surface damage, is often found to describe thin film damage only at very short pulse durations. For pulses larger than a few hundred psec, extrinsic factors may enter, which can result in a departure from the simple scaling law.

The simple scaling relationships which have been reported are empirical and lack full theoretical justification. Nevertheless, they provide a useful guide for exploratory damage results to new conditions and provide a test of consistency for measured threshold values.

Whatever its origin, catastrophic laser damage is a statistical phenomenon, like any other mode of material failure. Failure does not depend on the average properties of the material, but on the strength of the weakest point. The "damage threshold" reported by experimentalists is a statistical concept, representing the intuitive dividing line between power densities at which failure is likely to occur and those at which failure is unlikely. This year, the Weibull statistics, which are widely employed to model failure of electrical components, were applied to laser damage data with gratifying results. Note that this analysis does not presuppose a particular physical model for damage, although the data can be examined, using this analysis, to see if the results are consistent with a particular model. The general approach to laser damage as a generic failure mode appears very promising.

The capability to measure, localize, and identify the dominant source of failure has been greatly advanced in recent years. This year, we heard of greatly increased sensitivity in the measurement of weak absorptions in optical materials. Bulk absorptions of less than 10^{-5}cm^{-1} have been measured calorimetrically, both on long bar samples of KCl and coated samples of fused silica. Surface absorptions as low as 10^{-6} have also been measured.

Using techniques like long bar calorimetry, the scanning adiabatic film calorimeter and photoacoustic spectroscopy, the contributions of absorption in bulk materials at the surface, at thin film interfaces, or in thin film layers can be separated. This enables one to say where, if not why, the damaging absorption is occurring. Present indications are that surface absorption at the surface-film interface is a common source of absorption-induced damage.

As the pulse length varies, the dominant mechanism changes. Multithreshold analysis allows one to determine which damage process dominates as the pulse length is varied. Again, the root cause of the damage is not identified, but rather the consequence.

Scattering, as a sensitive indicator of damage, has been investigated for some time. This year, a quantitative, sensitive scattering technique was discussed, which should provide a useful addition to the arsenal of sensitive measurement techniques.

Several advances were reported in the realm of materials preparation and fabrication. One such advance is in the isostatic forging of optical elements. The forging of LiF optics, reported this year, is of great interest for short wavelength optics, since very few materials other than LiF are available for high power use at 250 nm or shorter wavelengths. Similarly, forged optics made from other alkali halides and CaF₂ will find use in systems operating in both the uv and IR. At present, forged optics show higher scattering losses than the original crystalline material, but the approach is very promising.

Metal mirrors continue to be attractive, especially where diamond-turning can be used in the fabrication. Molybdenum is a substrate material of considerable interest. As interest shifts to the uv the problem of dielectric coatings for metal mirrors commands increasing attention. The compatibility of coating and substrate will add another dimension to the already complicated problem of mirror design.

Short wavelength systems are beginning to yield data on component damage; and, as expected, laser damage is a limiting factor for uv systems. Two-photon absorption is seen to play a role in damage in both coatings and bulk material, and techniques have been advanced to measure nonlinear absorption. Nonlinear absorption coefficients have only been measured in a few materials, perhaps a dozen in all. The purity of these materials and the sensitivity of the two-photon absorption at various wavelengths to the presence of impurities have not been determined. Clearly, a substantial amount of research is required to bring the state of uv optics up to the required level.

As a consequence of a decade of damage studies, system designers are aware of the limitations imposed on system performance at high power levels, by laser damage. This heightened consciousness of damage problems within the community will undoubtedly spur the improvement of uv optics for high power systems. Additionally, at all wavelengths, techniques for damage avoidance provide a way around the limitations of materials. The term "damage avoidance" refers to methods whereby the total power from an aperture can be increased, while keeping the peak power below the damage-imposed limit. These include spatial filtering, optical relaying, plasma filtering, and phase conjugation. Other techniques undoubtedly remain to be discovered.

Fiber optics and semiconductor lasers seem out of place at a symposium on high power optics, but the power densities achieved in these devices can be high. Because of the commercial importance of these devices, it is important that the optical materials community be aware of the specific problems encountered in their use. This year, in a paper presented on damage in optical fibers, the speaker concluded that surface damage at the edge of the core was the decisive failure mode. Considering the remarkable purity of the core material in low-loss fibers, this is to be expected. This surface damage in fibers thus may be a problem strongly similar to other surface damage phenomena, and knowledge gleaned in the high power laser field may be applicable to its solution.

It is becoming clear that the materials of choice, from the infrared to the ultraviolet, are the light fluorides and oxides, along with NaCl and KCl. Other materials are under development, especially for use as high index coating materials; but, wherever possible, it seems preferable to use fluoride or fluorite crystalline materials: sapphire, and oxide and fluoride glasses. Except for sapphire, these are all low index materials, which have been developed for optical use over a long period of time. Purified starting materials are available for these materials, and they are chemically stable, which reduces surface contamination.

Given the base of materials identified above, the situation for new optical materials is comparable to that of laser materials in the 60's. At that time, ruby had been refined and developed to the point where it was the standard material for crystalline lasers. There was widespread interest in finding a better material, one with a lower threshold and with comparable, if not better, optical and mechanical properties. Literally hundreds of other crystalline hosts were examined, in small samples, with a "shotgun" approach. It was not until Bell Laboratories undertook the systematic development of YAG that a replacement for ruby was obtained.

The lesson to be learned is twofold. One must identify what characteristics are desirable for a material, and pursue development of those which offer significant promise of exceeding the performance of what is already available. Choices must be made, and a long process of development undertaken, involving purification of starting materials, optimization of the manufacturing process, and development of fabrication and finishing techniques. If these choices are made from materials which provide a reasonable promise of the same or better chemical, mechanical, and optical properties than those materials already available and if a real commitment is made to their development, significant advances will be made.

3. Summary of Papers

The subject matter of the Tenth Symposium broadly consists of six topics, and these proceedings are organized accordingly. The topics are as follows: (1) Measurement of Absorption Characteristics, (2) Bulk Material Properties, (3) Mirrors and Surfaces, (4) Thin Film Damage, (5) Coating Material and Design, and (6) Breakdown Phenomena. In this section, a concise summary of each paper is provided. Closely related papers are discussed together, wherever possible. The interested reader is referred to the complete manuscript of the papers for detail; our intention here is to provide the reader with an overview of the Symposium, and to identify the topics of discussion and the authors of the papers. Each topic is introduced with a brief statement of the underlying problems and the status of understanding within that area of interest.

3.1 Measurement of Absorption Characteristics

Without question, the optical property of ultimate concern in any high average power laser system is absorption. This property, whether present within the bulk of an optical window or at the surface of coated or reflecting elements, can lead to unacceptable thermally induced damage. Thus, it is not surprising that several papers heard at this year's meeting dealt with the measurement and identification of absorption. The papers ranged from a theoretical analysis of rate calorimetry to the comparison of several novel techniques such as total reflection and photoacoustic spectroscopy, with standard calorimetric procedures. Several authors dealt with the particularly pernicious problem of surface absorption in thin films and its separation from bulk absorption. One paper addressed the growing concern for two-photon absorption as interest moves to shorter wavelengths.

A general method for analyzing window characteristics by rate calorimetry, which includes coating absorption, was the subject of a presentation by N. C. Fernelius and G. T. Johnston of the University of Dayton Research Institute. Previous treatments of this procedure were extended to include samples with dissimilar levels of absorption on their faces. The method requires the measurement of temperature rise and reflected power in both orientations to three significant figures. Unfortunately, it is difficult to make reflected power measurements at the levels encountered with AR coated windows to better than two significant figures at the present time. Many other investigators are resorting to long bar substrates or variable thickness coatings to overcome this limitation. However, these approaches require the preparation of special samples to allow one to separate the surface and bulk absorption contributions to the total window absorption.

The increased development of high power, ultraviolet lasers is stimulating the search for and characterization of optical materials, for use both as window materials and as coating components. One promising candidate for use as a low index film material from the uv to the ir is NaF. When assessing a material's utility as a film component, it is necessary to test it in thin film form. To this end, D. L. Burdick of the Naval Weapons Center, employing the powerful technique of Attenuated Total Reflection Spectroscopy, has studied the absorption coefficient of 0.56- μm thick NaF films on ZnSe substrates from the visible to $\sim 3 \mu\text{m}$. The spectrum revealed a strong water band at 2.95 μm of very high absorption relative to the substrate. An estimate of the thickness of an adsorbed water layer of 7Å was given. The contribution of scattering to absorption was also investigated in this report. It was observed that coated portions of the test plate tended to scatter less than the uncoated portion at any given wavelength. The scattering difference was about 16 percent of the normal-incidence value observed for the uncoated surface.

With increased emphasis on short wavelength lasers, there is developing a growing interest in techniques for measuring multi-photon absorption coefficients. M. Bass, E. Van Stryland, and A. Stewart of the University of Southern California reported on a calorimetric method for measuring two-photon absorption. In their experiments, a repetitively pulsed, Q-switched Nd:YAG laser was used to illuminate samples of CdSe and CdTe at 1.06 μm . The sample was isolated in a vacuum chamber, and its temperature measured with a thermocouple. The temperature rise was measured as a function of the incident intensity.

The resulting curves were analyzed assuming that there were both an incident wave and a reflected wave in the sample. Thus, the reflection at the back surface was taken into account. Some deviation from the theoretical prediction was observed, which was ascribed to the presence of free carriers generated in the absorption process (either linear or nonlinear).

This approach to measuring two-photon absorption looks very promising, especially when combined with more sensitive methods of detection, such as photoacoustic spectroscopy. This research also shows

the importance of carrying out a careful and exact analysis of reflected wave effects in optical samples, especially in the presence of nonlinear interactions.

The level of specific absorption is extremely important in assessing the suitability of an optical material for use as a laser window over a given spectral range. H. Vora, M. C. Ohmer, and T. G. Stoebe of the Air Force Materials Laboratory have made a comparison of the bulk and surface absorption in both NaCl and KCl over the spectral range from 9.2 to 10.8 μm using the long bar technique. The measured bulk absorption in the best RAP-grown NaCl was apparently intrinsic at $9 \times 10^{-4} \text{cm}^{-1}$ at 10.6 μm and $1.4 \times 10^{-4} \text{cm}^{-1}$ at 9.2 μm . By comparison, the best KCl showed bulk absorption of 9×10^{-5} at 10.6 μm and $4 \times 10^{-5} \text{cm}^{-1}$ at 9.2 μm . These values are probably limited by the presence of some residual ClO_3 or ClO_4 impurities.

A variety of samples of NaCl and KCl from various sources were evaluated together with an investigation of the efficacy of different cleaning and etching procedures to reduce surface absorption. This study has led to a proposed new multiphonon limit for the intrinsic absorption in NaCl, lower than Deutsch's reported value of $1.17 \times 10^{-3} \text{cm}^{-1}$.

As optical component quality improves, it becomes increasingly imperative that diagnostic instrumentation for the characterization of these elements keeps pace. No where is this more necessary than in the measurement of the absorption in thin films and at interfaces. Thus, it was quite appropriate that T. H. Allen, J. H. Apfel, and C. K. Carniglia of the Optical Coating Laboratory reported on the construction and testing of a 1.06- μm laser absorption calorimeter for thin film coatings. This instrument is quite suitable for routine measurements of coatings deposited on thin discs. Samples, irradiated by a 6 W cw Nd:YAG laser, were usually 2.54 cm in diameter and ranged in thickness between 0.02 and 0.13 cm. The temperature of the coated disc is compared to a similar uncoated element using thermistors, arranged in an AC Wheatstone Bridge, in direct contact with each disc. An ambient pressure of 100 torr is maintained in the sample chamber to reduce thermal variations. The precision of the calorimeter was determined over an absorbance range of 9×10^{-6} to 3.8×10^{-4} and was found to be essentially constant at 2×10^{-6} . Sensitivity for a 0.04-cm thick substrate was $3.8 \times 10^5 \mu\text{v/watt}$. Tests on uncoated fused silica discs with thicknesses from 0.04 to 0.13 cm show a surface absorbance of 6×10^{-6} and a bulk value of $5 \times 10^{-5}/\text{cm}$.

A very elegant technique for isolating the contributions due to interface, bulk, and substrate absorptions in single-layer films was described by P. Temple, D. Decker, T. Donovan, and J. Bethke of the Michelson Laboratory. They prepared samples in the form of a wedge of coating material deposited on a substrate, leaving part of the substrate uncoated. The absorption of this sample was then measured, using the scanning adiabatic calorimeter the authors described in the 1977 Symposium Proceedings. The sample was scanned with a 0.5 W laser, in a spot 500 μm in diameter. A plot of energy absorbed versus film thickness was then generated. The intercept of this plot, corresponding to zero thickness, was generally different from the absorption value obtained on the uncoated portion of the sample. The difference was assumed to represent the sum of the contributions from both the outer and inner interfaces.

The slope of the absorption plot yields the bulk absorption coefficient. By measuring the absorption at the $\lambda/2$ and $\lambda/4$ thicknesses, and taking into account the difference in field configurations, the authors can extract the relative contributions of the air-film and the film-substrate interfaces. Data are presented for NaF and As_2Se_3 films on CaF_2 substrates, measured at 2.87 μm and 2.72 μm . The former wavelength lies within a water band, while the latter does not. For the NaF film, bulk absorption due to water was detected, while for the As_2Se_3 film, the principal effect was due to water absorption at the film-substrate interface.

Photoacoustic spectroscopy (PAS) is a technique for measuring weak absorptions that dates back to Lord Rayleigh and the spectrophone, but is enjoying a revival in current physics. N. Fernelius and D. Walsh of the University of Dayton Research Institute applied this method to the measurement of the absorption spectra of several thin films and bare samples, including samples coated using the discrete graded-index method described in the paper by Moravec and Skogman (see below). PAS provides information concerning the spectral absorbance of the sample and can discriminate between bulk and surface absorption by the variation in the phase of the signal with chopping frequency. It is thus a valuable method for the analysis of optical samples.

In this work, it was found that thin film materials showed different absorption spectra from the same materials in bulk, due either to different crystal forms or to impurities in the coating. The theory of Rosencwaig and Gersho for the chopping frequency dependence of the PAS signal was verified. The PAS method should find wide applicability for investigations of optical materials.

3.2 Bulk Material Properties

Absorption characteristics, discussed in the preceding section, represent only one of the many parameters of interest for the optical materials used in laser systems. Other optical, thermal, and mechanical properties of laser materials are also of importance in determining system performance. At high power, stress-optical and thermo-optical properties can be of great significance for laser window materials, lens materials, substrates, and, in glass lasers, the laser medium itself.

For many years, the National Bureau of Standards has carried out a program of measurement and computation of the optical properties of materials suitable for use in various laser systems. The evaluation of stress-induced birefringence is an important consideration in the mechanical design and thermal performance of high-power laser systems. These changes in refractive index can lead to significant wavefront distortion in actual operation. This year, R. M. Waxler, A. Feldman, and D. Horowitz reported extensive measurements of the piezo-optical coefficients of a wide variety of increasingly important optical materials, including four neodymium phosphate and fluoro-phosphate laser glasses, as well as CaF_2 , BaF_2 , and SrF_2 . Polarimetric and interferometric techniques were employed at the HeNe wavelengths of 0.6328 μm , 1.15 μm , and 3.39 μm . The laser glasses obviously were not measured at 3.39 μm .

Another aspect of the optical materials characterization program at the National Bureau of Standards concerns the measurement of refractive index and dispersion in transparent window materials. M. J. Dodge, of the above organization, reported on the refractive index of fusion cast SrF_2 at 20°C over the spectral range 0.2138 μm to 11.475 μm . SrF_2 and other alkaline earth fluorides, BaF_2 and CaF_2 , are candidates for the 2- μm to 6- μm range because of their low index of refraction and dn/dT values as well as their good mechanical stability. These factors, along with others, play an important role in determining optical distortion.

Using a minimum deviation method, 53 data points were fitted to a three-term Sellmeier dispersion equation of the form:

$$n^2 - 1 = \sum_j [A_j \lambda_j^2 (\lambda^2 - \lambda_j^2)^{-1}].$$

The resulting constants for SrF_2 were as follows:

$$\begin{array}{ll} A_1 = 0.67805894 & \lambda_1 = 0.05628989 \\ A_2 = 0.37140533 & \lambda_2 = 0.10801027 \\ A_3 = 3.3465284 & \lambda_3 = 39.906666 \end{array}$$

Similar results are presented for BaF_2 and CaF_2 , as well.

Wide band-gap materials, especially monovalent and divalent fluorides and chlorides, are of great interest as materials for use in windows and lenses, over the entire range of wavelengths from 10.6 μm to 250 nm. Single-crystal materials can be fabricated in large sizes, but these materials exhibit poorer mechanical properties than polycrystalline material. A technique for combining the optical homogeneity and chemical purity of single-crystal materials with the mechanical strength of polycrystalline materials is isostatic forging. Several authors contributed to a status report on this promising fabrication technique.

Addressing the need for improved optical materials with both good ultraviolet transparency and low linear and nonlinear refractive indices, J. F. Ready, H. Vora, R. A. Skogman, K. M. Leung, and E. Bernal G. reported on the development of LiF windows by isostatic forging of single crystal starting material. While the mechanical properties of yield strength and fracture energy were seen to improve, it was found that the ultraviolet transmission of the final product was not appreciably degraded. This is an important observation, since LiF has the widest band gap of any known optical material and can now be made into relatively large, strong, high quality optical elements. The forgings are usually made along the $\langle 100 \rangle$ axis at a strain rate of 5×10^{-3} /min under a 2000 ps isostatic helium constraint with temperatures ranging from 300° to 600°C. Resultant grain sizes are in the 10- to 40- μm range. Long-term stability appears to be acceptable. However, whereas the index inhomogeneity of the single crystal starting material was in the range of 4.4 to 8.8×10^{-6} over 2.5 cm diameter samples, the forged materials exhibited Δn values of 17.4 to 22.3×10^{-6} .

In a continuing development of forged optics, R. H. Anderson of the Honeywell Corporation and J. M. Bennett of the Naval Weapons Center have investigated the optical properties of plano-plano and plano-concave KC \times optical elements isostatically forged at 4000 psi between optically polished dies. In this study, the elements were prepared in a two-step forging process. The KC \times was forged between teflon sheets first, and then water polished, prior to final forging, between fused quartz or pyrex dies at 200 to 275°C under a helium atmosphere. The optical figure, homogeneity, internal strain, scattering, and surface character of these two-step samples were compared with both single-crystal and one-step, press-forged KC \times samples. It was readily apparent that the two-step process produced a superior element in terms of surface figure, homogeneity, surface roughness, and scattering. The water polishing greatly reduced the occurrence of grain boundaries and thus surface scatter. While the surface topography (roughness) of the die was not replicated exactly, the forged surface compared favorably with state-of-the-art, mechanically polished samples and exhibited lower scatter values.

In a somewhat related paper, R. H. Anderson, R. A. Skogman, and J. F. Ready of the Honeywell Corporation and J. M. Bennett of the Naval Weapons Center presented results of an initial investigation

of the forging of CaF₂. However, in this case, the isostatic forging resulted in considerable veiling (cloudiness) in the polycrystalline CaF₂ windows. Microscopic evaluation suggests that the veiling may result from microvoids formed by the aggregation of vacancies produced by dislocation intersections during plastic deformation, which also results in measurable internal stress. The CaF₂ samples were forged at 750° to 800°C in a helium atmosphere at a pressure of 14.82 MN/m². Single crystals having <111>, <100>, <112>, and <113> orientation were deformed approximately 60 percent to ensure a uniform grain size of less than 15 μm. Obviously, much more work needs to be accomplished to assess fully the suitability of isostatic forging for materials such as CaF₂, particularly if their intended use is at shorter wavelengths where scattering is of major concern as a loss mechanism.

In choosing a window material for a high power cw laser, both the power level at which failure occurs and the nature of the damage process are of interest. J. Detrio and R. Petty of the University of Dayton Research Institute conducted an investigation of thermally induced failure in SrF₂ and CaF₂ windows, using the multi-kilowatt DF laser at the Army Chemical Laser Facility. Polycrystalline samples of Raytheon, fusion-cast SrF₂ were irradiated at power levels up to 8.4 kw on a spot size of 0.3 cm² area. Failure inevitably occurred at power densities greater than 22 kw/cm². All samples were AR-coated at 3.8 μm.

Failure was noncatastrophic and was ascribed to compressive loading in the center of the irradiated area and consequent strain. Plastic deformation was seen to occur in the form of slip along the (100) plane. At the point of failure, the compressive stress was estimated to be 15 Kpsi, and the peak temperature 980°C.

A feature of this investigation was the observation of the sample before, during, and after irradiation using interferometry and a polariscope simultaneously. Comparison of the polariscope patterns with those observed in oriented single crystal specimens of CaF₂ made it possible to identify the crystalline orientation of the polycrystalline samples.

Thermal damage in bulk materials which are used in the region of transparency arises from multiphonon absorption and residual impurities. The latter effect can be reduced by controlling the purity of the raw material, and preventing contamination in the manufacturing process. The chemical vapor deposition process is one means of maintaining the purity of bulk materials during fabrication. However, even in the purest materials, multiphonon absorption must be measured, to obtain the limit of transparency.

As an indication of our progress in achieving an understanding of the properties of one particular material, C. Klein, B. diBenedetto, R. Donadio, T. Kahone, and J. Pappis of the Raytheon Company reported a detailed listing of phonon assignments leading to an excellent prediction of experimental lattice absorption for CVD (chemical vapor deposition) ZnS, a potential window material for use at 2.7 and 3.8 μm. Through an analysis of spectrophotometric data at wavelengths to 25 μm, it was concluded that multiphonon processes dominate the absorptive spectrum at frequencies below 1000 cm⁻¹. As an adjunct to this study, the absorption coefficient was measured for CVD ZnS at laser wavelengths in μm of 2.7 (HF), 3.8 (DF), 5.25 (CO), 9.27 (CO₂), and 10.6 (CO₂). The absorption coefficients in cm⁻¹ being $(7.2 \pm 0.5) \times 10^{-3}$, $(2.3 \pm 0.5) \times 10^{-2}$, $(4.5 \pm 1.1) \times 10^{-2}$, $(7.9 \pm 1.3) \times 10^{-2}$, and $(2.4 \pm 0.1) \times 10^{-1}$, respectively. Additional data relating to the utility of CVD ZnS as a window material for infrared imaging applications were also presented.

In the laser fusion program, emphasis is being placed on the construction of very large facilities. CO₂ and Nd glass lasers operating at 100 kJ or more are under construction. The capital cost of these facilities is very large, and the output obtained must be maximized by careful optimization of all components of the systems. Two papers were presented relevant to the choice and development of materials for large, Nd glass lasers.

In an effort to reduce the nonlinear index coefficient of laser glasses, the Lawrence Livermore Laboratory, working with the major laser glass manufacturers, has undertaken the development of fluorophosphate and fluoroberyllate laser glass compositions. S. Stokowski, D. Milam, and M. Weber reported on the status of the damage properties of these fluoride-based laser glasses. Damage measurements were made in both fluorophosphate and fluoroberyllate glasses at 1.06 μm, using pulse durations from 0.1 nsec to 1 nsec. Both bulk and surface damage were observed.

FK-51 is a fluorophosphate composition which has been commercially available for some time. It exhibits a surface damage threshold close to that of BK-7 or fused silica, i.e., 20-25 J/cm² at one nsec. Bulk thresholds are greater than 20 J/cm² in FK-51. Newer compositions, both fluorophosphate and fluoroberyllate, show surface damage at values of 12-16 J/cm², and bulk damage thresholds in excess of 25 J/cm². The glass manufacturers are still developing the melting process for these glasses, so further improvements are expected. The newer glasses are still observed to contain bubbles and crystallites, which may be the locus of damage. Development of polishing techniques for these glasses is still under way.

Thus, although low index laser glasses are still in the state of development, preliminary results indicate that surface and bulk damage thresholds comparable to those achieved in borosilicate glasses should be attainable.

Optical liquids find a variety of uses in glass laser systems operated at moderate or high repetition rates: as coolants, for index matching, and as electrodes. The physical properties of these liquids are of great importance to the laser system designer. A series of measurements in the physical and optical properties of a number of liquids of interest has been carried out by J. Rinefield, S. Jacobs, D. Brown, J. Abate, O. Lewis, and H. Applebaum of the University of Rochester.

A variety of index matching and coolant liquids was examined. The properties measured were refractive index, dispersion, optical absorption, dn/dT , density, thermal conductivity, and viscosity. An estimate of the electronic portion of the nonlinear index coefficient, n_2 , was obtained from the measured values of the index and dispersion. Values of these optical and physical parameters are tabulated for twelve liquids. In general, where comparisons exist with tabulated values, the agreement is satisfactory. Among the liquids examined, H_2O exhibits an attractive combination of properties for a coolant: high thermal conductivity, low dn/dT , low viscosity, and low n_2 .

3.3 Mirrors and Surfaces

In most situations, optical surfaces, whether they be on reflecting or transmissive elements, are the bridge between the laser system and the real world and as such are often subjected to hostile environmental conditions. In the hierarchy of damage sensitivity, surfaces fall midway between bulk materials and coatings, and become the critical element in systems forced to use uncoated elements. Thus, there is considerable import associated with raising the damage threshold of uncoated surfaces. One obvious solution, at least for reflecting components, is to use diamond-turned metal mirrors. Papers were presented not only on the physical and optical properties of micro-machined elements but also on the correlation between optical and metallurgical properties.

It seems that the subjects of surface roughness and its influence on damage resistance are still with us. A paper was presented concerning the pulse duration dependence of damage on surfaces of varying roughness. In addition, for the first time, a paper on damage to optical fibers with both nsec and msec pulses was given. We are sure that both of these subjects will be favorite topics for many years to come.

Many diamond-turned metal surfaces are adequate for 10.6 μm applications, but significant improvement is necessary in their quality if they are to be used at shorter wavelengths without additional polishing. D. Decker and D. Grandjean of the Michelson Laboratory reported on their progress in establishing a high precision diamond-turning mechanism. The machine differs from conventional diamond-turning devices in that all components are mounted on a black granite surface plate, isolated from the environment through air suspension. The planar layout minimizes the effects of vertical temperature gradients, and provides a convenient work surface with great flexibility of configuration.

The machine is operational with open-loop control. Surfaces show rms roughness of 10\AA (OFHC copper), with slope errors a factor of 2 less than those observed on optics diamond-turned on the Battelle or Y-12 machines. The addition of closed-loop, interferometric controls of slide position is expected to increase the machine precision even further. A contour figure accuracy of 100 \AA peak-to-valley over a 0.4-m diameter is expected, when the full servo system is implemented. The authors discuss the design of the machine and the relative roles of tool and machine errors in determining the surface character, and show surface profiles and statistics for pieces turned on this machine as well as for those turned on the Battelle and Y-12 machines.

Molybdenum is a mirror element of potentially great utility because of its good heat conductivity, low thermal expansion, stiffness, and relatively high damage threshold. Unfortunately, it is difficult to fabricate with low-scatter surfaces. In a rather comprehensive study of Mo mirrors, an extensive optical and metallurgical characterization was accomplished by S. M. Wong of Rockwell International, G. Krauss of the Colorado School of Mines, and J. M. Bennett of the Naval Weapons Center. The study attempted to correlate metallurgical process variables and resulting microstructure and surface finish of several samples from different sources. It was determined that there is a close correlation between grain and subgrain structure in the material and structure appearing on polished surfaces, resulting evidently from variations in hardness. As might be expected, little correlation was seen on ground surfaces. Inhomogeneity of the Mo is sufficient to produce measurable variations in surface finish within a given lot, particularly when inhomogeneities are associated with dispersion hardening agents such as Ti or Zr. Guidelines for the selection of optimum raw Mo stock for use as mirror substrates are given.

It is well established that at long pulse durations (~ 40 ns), there is a strong correlation between surface damage threshold and surface smoothness. At pulse durations of a few ns or less, however, this correlation is not consistently observed, especially as the surface roughness is reduced below 40 \AA . It is important to know what the influence of surface roughness on damage threshold is, since this information can influence the procedure used for polishing optical surfaces and the surface quality required for laser components.

D. Milam of the Lawrence Livermore Laboratory investigated the pulse duration dependence of 1.06- μm surface damage on three BK-7 samples and one fused silica sample, with different surface roughnesses. Among the BK-7 samples, one was conventionally polished, grade A material, one was PH-3 material, carefully ground with alumina grits of descending size, and finally polished with commercial CeO_3 , and the third had one bowl-feed polished surface. The fused silica sample was conventionally polished.

In general, entrance surface thresholds were observed to be higher than exit surface thresholds, but not as high as predicted from simple Fresnel theory. Cleaning raised the threshold on the conventionally polished BK-7 surface, but not on the others, indicating they were fairly clean initially. The expected scaling with pulse duration (\sqrt{T}) was generally observed. No correspondence between surface smoothness and damage threshold was observed in this range of pulse durations, indicating that other factors are dominant. The damage threshold observed at the entrance surfaces were typically 20-25 J/cm^2 in one ns.

Both from the value observed and from the adherence to the root-T scaling law, it appears that the surface damage seen in these experiments may be considered "intrinsic," or at least not dominated by absorbing impurities on the surface. The implication of the research is that super-polished surfaces (roughness $\sim 10 \text{ \AA}$) offer no advantages over conventionally polished surfaces for pulse durations of a few nsec, as long as the surfaces are carefully cleaned. It is not obvious why the sensitivities to surface roughness for very smooth surfaces should be so much greater at longer pulse durations.

A welcome addition to this year's Symposium was the report of M. J. Landry of Sandia Laboratories on the subject of laser induced damage to fiber optics including both single and multiple fibers. To our knowledge, this is the first time this subject has been treated at our Symposium and is an indication of both the breadth of the meeting and the coming importance of fiber optics as power transmitting optical elements. In this study, fibers of five manufacturers were subjected to 1.06- μm , 30-nsec pulsed laser exposures as well as unpolarized free-running exposures of a spiked nature for $\sim 100\text{-}\mu\text{s}$ duration. The highest surface damage levels for single and multiple fibers exposed to the Q-switched pulse were 48.2 and 31.6 J/cm^2 , respectively. In the case of long duration exposures, single laser exposure levels of 4.66 kJ/cm^2 were the highest achieved. Multifiber bundles initially exhibited damage in the cladding or matrix material. A decrease in the fiber coupling efficiency (ratio of output to input energy) was attributed solely to surface damage. Damage to gamma-irradiated fibers exposed to $\sim 10^6$ rad(Si) from a Co^{60} source were also reported. In general little effect was noted on coupling efficiency or damage level due to the irradiation. This result is to be expected since most of the interaction took place at the entrance surface, and thus the remainder of the fiber played little role in these experiments.

3.4 Thin Film Damage

Even though optical materials in thin film form remain the most damage sensitive component of high power laser systems, our efforts to improve their performance are largely empirical, based primarily on parametric studies and go/no go testing of commercially supplied elements, frequently with a short-gain approach characterized by new candidate materials, designs, etc. This situation is made manifest by the exigences of program deadlines and the need for rapid system maintenance. What is needed is a broad-based, fundamental program founded upon the growing wealth of parametric studies and some good sound science and materials engineering. This will be discussed further in the recommendations.

This year's thin film session was again generally a mix of parametric studies and an assessment of the state of the art in coating technology. The first paper was concerned with the current trend to shorter wavelengths (266 nm and 353 nm). Immediately following papers dealt with multithreshold analysis of coating damage at 2.7 μm and 3.8 μm and the role that adsorbed water layers play at the former wavelength.

Continuing their series of short wavelength studies of optical damage in thin film coatings, B. Newman and D. Gill of the Los Alamos Scientific Laboratory measured the damage threshold of fourteen different thin film materials at both 355 nm and 266 nm. The incident light was generated by doubling and tripling the frequency output of an Nd:YAG laser, Q-switched to produce a pulse of 35-ns duration. The 355-nm pulse width was 27 ns, and the 266-nm pulse width was 22 ns.

The film materials were deposited as quarter-wave layers on fused silica substrates, and, in some cases, as binary multilayer dielectric coatings designed for high reflectance. Damage thresholds were obtained as a function of wavelength, coating design, and, in cases where picosecond damage data had previously been taken, pulse duration. Both fluoride and oxide materials were tested.

The single-layer coating with the highest threshold was NaF, the material with the greatest band gap, which exhibited a threshold of 11 J/cm^2 at 355 nm. Fogging of the film due to exposure to a humid atmosphere apparently had no effect on the damage threshold. Of the multilayer reflectors, the NaF/ Al_2O_3 film showed the highest thresholds: 3.6 J/cm^2 at 266 nm and 12 J/cm^2 at 355 nm. Al_2O_3 in a single layer showed a lower threshold, presumably because damage was occurring at the coating-substrate interface in the latter case. The wavelength dependence observed was consistent with the linear absorption increase at short wavelengths, for several oxide materials, although the

evidence was not entirely conclusive. Two-photon absorption did not seem to be playing a major role in damage at 20 ns, whereas it was significant for 20-ps pulses. The damage threshold was found to increase with pulse duration more slowly than $t^{1/2}$. This would be expected if the damage were mediated by absorbing impurities. Other scaling laws were also investigated.

This work, providing as it does a broad survey of materials and parameters under well-characterized test conditions, is very valuable in developing a picture of the relevant factors for short wavelength damage in thin films. It also provides a practical guide as to what materials appear most promising.

Pulsed laser damage in NaF, SiO_x , Al_2O_3 , ZnS, As_2S_3 , and Si coatings at 2.7 and 3.8 μm was evaluated via a multithreshold analysis by J. O. Porteus, T. M. Donovan, J. L. Jernigan, and W. N. Faith of the Naval Weapons Center. This type of evaluation is most appropriate at the intermediate pulse length of 100 nsec employed in this study to allow for a greater delineation of damage mechanisms between thermal failure and dielectric breakdown. This type of analysis aids in understanding the role of impurities such as water, which absorbs at one of the two wavelengths employed.

After discussing in some detail the deposition conditions and substrate characteristics, the authors described the experimental variables and multithreshold diagnostic instrumentation including ion and light emission, the onset of delamination, cracking, flow, erosion, or perforation as well as other selective, as opposed to uniform, damage criteria. When appropriate correction factors were applied to convert from incident to internal energy/area values, NaF and Al_2O_3 were seen best at both the DF and HF wavelengths with SiO_x also useful at 3.8 μm . ZnS, As_2S_3 and Si, all higher index materials and SiO_x at 2.7 μm were markedly lower in damage resistance.

Continuing their work on multithreshold damage to films of As_2S_3 , As_2Se_3 , and NaF, T. M. Donovan, J. O. Porteus, J. L. Jernigan, and E. J. Ashley of the Naval Weapons Center extended their measurements this year to 2.8 μm and 3.8 μm from those reported last year at 10.6 μm . Two principal damage processes were identified. The first is a "uniform" mode associated with the amorphous chalcogenide matrix while the second is a more "selective" phenomena associated with micron-sized crystalline defects. Each type of damage is easily discernable by inspection of the damage morphology of the irradiated area. It was noted that single-layer film (N on I) conditioning led to an improvement in damage resistance, most probably through gently removing by desorption any adsorbed water layer, which would absorb at 2.7 μm . However, for multilayers of As_2Se_3 and NaF, (N on I) conditioning led to enhanced crystallite growth, which resulted in a decrease in damage thresholds.

Important results of this study indicated that As_2S_3 first damages at a fluence (areal energy density) of $\sim 50 \text{ J/cm}^2$ while NaF, with a 30 times higher absorption, damaged at $\sim 400 \text{ J/cm}^2$. Thus, absorption alone does not determine the damage sensitivity. For comparison purposes, multilayer films of alternate As_2Se_3 and NaF layers in an enhanced reflection design on polished Mo exhibited a higher threshold than Au-coated, diamond-turned Cu mirrors.

The remaining papers in this session dealt with three diverse areas of coatings, which have been with us a long time. They are a morphological investigation of damage in barrier layers, which emerged last year as a potential means of increasing the damage threshold of antireflection coatings; a significant improvement in the utility of scattering as a quantifiable indication of the onset of damage; and finally, an in-depth analysis of the statistics of absorptive laser damage and its usefulness for identifying the appropriate damage mechanism and as an engineering design tool.

The relatively low damage threshold of antireflection (AR) coatings makes it a limiting factor in the design and achievement of high-power laser systems. Last year the utility of barrier layer coatings to enhance the damage resistance of AR coatings by as much as 50 percent was revealed. C. K. Carniglia and J. H. Apfel of Optical Coating Laboratory, Inc., G. B. Carrier of the Corning Glass Works, and D. Milam of the Lawrence Livermore Laboratory have continued to investigate the role barrier layers play on the damage sensitivity of 1.064- μm AR coatings. The basic coating employed was a standard four-layer silica/titania design on BK-7 glass substrates. Samples were prepared with and without half-wave silica barrier layers. Detailed morphological investigation employing transmission electron microscopy revealed that damage sites were characterized by a 1- μm nuclei which could lead to 3- μm craters. The titania layer seems to fracture while the silica layers appear to melt or tear with evidence of heating in the substrate. The results of this study seem to indicate that damage originates at the interface between the coating and the substrate and may arise as a result of thermal expansion of the material at, or close to, this boundary, most probably resulting from polishing or cleaning residue rather than from absorption in the bulk of the materials themselves.

For many years people have felt that scattering should be both a good indicator of surface or film quality and a useful diagnostic technique to indicate the onset of damage. Unfortunately, to date, proposed laser scattering techniques, while sensitive, have been rather subjective. To increase the utility of scattering procedures and to place them on a quantifiable basis, T. W. Walker and A. H. Guenther of the Air Force Weapons Laboratory and P. E. Nielsen of the Air Force Institute of

Technology reported on new optical techniques for the determination of pulsed, laser-induced damage in thin films. Briefly, this scheme incorporates two fast photo-diodes. The first diode records a reference signal directly proportional to the intensity of the incident laser pulse, as well as a signal due to that fraction of the incident pulse nearly ($\sim 50^\circ$) back scattered from the target, and a probe signal generated from the incident pulse but delayed up to 55 nsec after the incident exposure of the test film. The delayed probe pulse is reflected from the exposure site into the photo-diode. By appropriate use of delay cables, all three signals can be displayed on a high time resolution transient digitizer. A second photo-diode records the transmitted incident laser pulse through the film and substrate.

By this technique, the relative amplitudes of the signals are compared first at an energy below the damage threshold, second at the damage threshold, and finally at an energy comparable to the first laser exposure by another exposure on the same site. The ratioing of the incident, delayed probe and back scattered signal affords a positive indication of change which can be arrived at by an objective evaluation of the signal amplitudes. The changes in the signal ratios offer, as well, a potential insight into the changes experienced by the thin film-substrate system upon irradiation by pulsed laser radiation. The use of the variable delay probe combined with re-exposure after damage indicates when modification of the film structure takes place and whether or not it is permanent. Films of MgF_2 , ThF_4 , and ZrO_2 were tested at $0.53 \mu m$ with 18-nsec pulses. Interestingly, this technique has indicated damage in films without the observance of either a visible spark or a modification of the transmitted laser pulse. This technique should gain wide acceptance, since it now places sensitive scattering techniques on an objective, but relative, quantitative basis.

It has long been suspected that an appropriate statistical treatment of pulsed laser damage experiments would afford an insight into the physical mechanism of damage and thus allow one to choose between competing theories. To this end, A. B. Budgor and K. F. Luria-Budgor of Lawrence Livermore Laboratory have performed a statistical analysis of absorptive laser damage in dielectric thin films using data supplied by D. Milam of the same organization. They applied a Weibull distribution, which is normally employed to describe both time-to-failure of electrical components and the DC breakdown of insulating materials. The Weibull distribution arises from the theory of extreme values. In this study, the time-to-damage and intensity-to-damage statistics were treated for thin films of ZrO_2 , SiO_2 , and Al_2O_3 . In all cases, correlation greater than 90 percent was achieved. Excluding "over-simplified" statistical theories such as the lucky electron model, it was concluded, based on the pulse length dependence of breakdown and an experimentally nonobserved >2 multiphoton absorption, that the avalanche mechanism is the most likely initiator of the plasma requisite for lattice melting. It was pointed out that statistical confidence bands for material survivability as a function of laser intensity and pulse length can now be constructed, leading to a practical utility of Weibull distributions as engineering design and diagnostic tools.

3.5 Coating Materials and Design

Since thin film coatings remain the Achilles heel of high power laser systems, there is continuing interest in improving their performance. New coating materials continue to be investigated, often in connection with a particular wavelength, or a specialized application. It is well established that not only the coating material but also the design and details of deposition influence the characteristics and performance of a thin film coating.

Among the materials investigated for use as the low-index component of coating systems, fluorides are the most common, since they usually exhibit wide band gaps, and correspondingly low absorption in bulk form.

R. C. Pastor, J. A. Harrington, L. E. Gorre, and R. K. Chew of the Hughes Research Laboratories prepared and evaluated six compounds as candidates for 3.8- μm and 9.3- μm dielectric coatings. They were the rare earth fluorides LaF_3 , PrF_3 , CeF_3 ; the tri-halides of Bi, BiF_3 , and BiI_3 ; and the binary salt $KGaF_4$. Using a purification procedure involving RAP (Reactive Atmosphere Process), an intrinsic absorption coefficient of $< 0.1 \text{ cm}^{-1}$ was sought. Unfortunately, the bulk absorption of the rare earth fluorides ranged between 0.6 and 0.9 cm^{-1} .

Optical transmission studies of single crystals of the rare earth fluorides indicated that only LaF_3 does not exhibit absorption bands in the 3- to 10- μm region. Both CeF_3 and PrF_3 exhibit absorption between 3.5 and 6 μm due to low lying Stark levels. While it was not possible to grow large enough single crystals of BiF_3 or $KGaF_4$ to permit accurate measurements, these materials appeared to have low absorption at 9.2 μm and 3.8 μm . BiI_3 looked the most attractive, due to its featureless spectra between 2.5 and 20 μm .

For a rather specific application, P. Baumeister of Aerojet-General and G. P. Arnold and D. F. Edwards of Los Alamos Scientific Laboratory investigated the deposition and damage thresholds of single-layer PbF_2 films employed as antireflection coatings for a CdSe OPO (optical parametric oscillator) pumped at 2.8 μm with 120-nsec pulses. Reported damage thresholds were as follows: uncoated CdSe, 68.5 MW/cm^2 ; $\lambda/4$ PbF_2 on CdSe, 50.6 MW/cm^2 ; $\lambda/1$ $PbF_2/\lambda/8$ ZnS, 50 MW/cm^2 (ZnS, used as an adhesive layer, exhibited no detrimental effects on the damage threshold); commercial PbF_2 coatings on CdSe, 6 MW/cm^2 ; and finally $\lambda/4$ PbF_2 on Ge at 3 μm , 22 MW/cm^2 . Explicit and

complete details as to selection of starting materials, polishing, and deposition conditions are given. The presence of PbOH in the starting material or hydrolyzed from PbF₂ leads to the production of metallic Pb upon heating, resulting in inferior films.

Thin film coatings are recognized to be the most easily damaged optical elements in a high power laser system. Damage occurs in regions of high electric field and at film-substrate interfaces, where impurities aggregate. Recently, strong interest has developed in ways to eliminate conventional antireflection coatings. One such way is by use of graded-index coatings. In graded-index coatings, two materials are co-deposited on the surface simultaneously, with varying rates, so that the refractive index varies continuously in the desired fashion during the deposition. The control of the graded-index coating process is often difficult. An alternative means to achieve the same end has been proposed by T. Moravec and R. Skogman of the Honeywell Corporate Material Sciences Center. They constructed discrete graded-index films, by alternatively depositing layers of high index material (TlI, $n = 2.4$ at $10.6 \mu\text{m}$) and low index material (PbF₂, $n = 1.63$ at $10.6 \mu\text{m}$) on KCl substrates. The thickness of each pair of layers was determined to give a certain value of the average refractive index at that layer. By building up a coating from as many as 50 to 100 layers, a discrete approximation to a continually varying index can be constructed. Individual layers as thin as 100 \AA were employed.

TlI normally grows in an orthorhombic crystal. On KCl, two crystalline orientations develop in TlI, resulting in optical scattering in the film. By growing only thin layers, the TlI is kept in a cubic crystalline form and scattering is reduced. Discrete graded-index films are also free from birefringence, further evidence of cubic crystal structure.

The discrete film method provides a very flexible means of constructing graded-index films. Discrete graded-index films exhibited absorption values similar to those seen in conventional films of the same material. Damage tests have not yet been done, so comparisons with conventional, multilayer films and continuous graded-index films are not available.

The standing-wave pattern formed in a multilayer, dielectric coating creates local maxima and minima of electric field within the coating. The placement of these extrema is an important factor in determining the peak performance of the coating. Thus, the analysis of coating performance is a valuable tool in evaluation of coating designs for high power use.

Although exact calculations of thin film performance are possible using large computers, it is often useful to be able to carry out approximate evaluations of thin film reflectance, transmission, and absorption, using analytic expressions. H. E. Bennett and D. K. Burge of the Michelson Laboratory discussed the general method of obtaining simple analytic expressions for evaluating weakly absorbing, antireflection or high-reflectance coatings. In this age of programmable pocket calculators, the utility of the expressions will be immediately apparent.

In order to employ these expressions, one must know the volume absorption coefficient of the coating materials as deposited, the substrate absorption, and the absorptance at each interface. The indices of all materials must be known. For metal substrates, the effect of surface roughness can be included. All of these parameters can, in principle, be determined experimentally. Their measurement has been discussed in several papers presented at the Symposium this year and in past years. Additionally, these analytic formulae can be used to estimate the effect of absorption, in the volume of the coating materials or at interfaces, on the performance of thin film coatings. In this mode, they provide a useful tool for coating design analysis and for determination of coating specifications.

The analysis of the reflectivity and absorption of a complex dielectric multilayer film, as a function of frequency, generally requires a significant computational effort. M. Sparks and M. Flannery of Xonics, Inc., showed that simple analytical approximations can be obtained in the case of a quarter-wave stack, a design commonly used for high-reflectance mirrors. The authors showed that, to a good approximation, the phase shift can be represented by a linear function of $\omega - \omega_c$, where ω_c is the center frequency for the stack (zero phase shift), and that the absorption can be represented by a quadratic function of $(\omega - \omega_c)$, plus a substrate contribution. The coefficients of the quadratic form can be obtained from analyzing the infinite, quarter-wave stack, and depend only on the absorption constants and refractive indices of the low and high index coating materials.

By varying the operating frequency with respect to ω_c , the field maxima can be shifted into either the high or low index media. Thus, depending on which of these is more susceptible to damage, the coating should be designed to operate off the center frequency, to minimize the field in the more vulnerable material.

Herbert B. Rosenstock of the Naval Research Laboratory reviewed the situation relative to electric fields produced at or near surfaces and in coated elements. He pointed out quite correctly that the use of a coated element at other than design wavelength can either increase or decrease the total electric field depending on the optical constants, thicknesses and specific film design, as well as the wavelength. He also pointed out that it may be useful to coat the exit surface of a transmission element to reduce the field at that point, but that it may introduce a weakness due to increased absorption in the film or at the film/substrate boundary.

3.6 Breakdown Phenomena

The phenomenon of the bulk failure of a transparent dielectric, in the presence of an intense light wave, associated with the formation of a luminous plasma, may be the oldest, and least well understood of the various effects observed under the heading "laser damage." A number of theoretical models have been advanced, each usually stressing one or another aspect of what is ultimately a very complicated process. Indeed, it may not be prudent or even possible to model the breakdown process completely.

Among the competing effects are multiphoton ionization, direct excitation from impurity levels or defect sites, avalanche ionization, thermal ionization of highly absorbing impurities, and phonon-assisted processes. At present, research is directed toward identifying the relative importance of each of these competing effects, as a function of pulse duration, wavelength of illumination, and experimental conditions. It is safe to say that, as yet, no wholly satisfactory model has been developed for dielectric breakdown.

A very preliminary account was given of an attempt to simulate, numerically, the propagation of light through a damage site in a transparent dielectric. P. Kelly and D. Ritchie of the National Research Council and P. Braunlich and A. Schmid of Washington State University are in the process of adapting a "particle-in-a-cell" (PIC) code, originated by D. Henderson of the Los Alamos Scientific Laboratory, to model light propagation in the dielectric in the presence of polarons. The generation of the polarons is assumed to proceed via a four-photon process for NaCl, the material initially studied.

Such a computation is necessarily limited by the extent of the physics phenomena which can be included. In reality, the nonlinear optics of the medium, as well as the generation of polarons, must be included; and impurity effects will have to be modeled. The applicability of the PIC method to a strongly convergent focus, especially in the presence of self-focusing, is also open to question.

There has been extensive discussion in the laser damage literature of the relative roles of impact and multiphoton ionization in determining the bulk damage threshold of transparent dielectrics. B. G. Gorshkov, A. S. Epifanov and A. A. Manenkov of the Lebedev Physical Institute in Moscow presented a theoretical analysis of the relative dependence of these two phenomena on optical frequency and laser pulse duration. The dependence of multiphoton ionization on frequency is simply given by the ratio of the ionization potential to the photon energy, for all pulse lengths of interest. For avalanche (impact) ionization, the authors conclude that two different dependencies on photon energy can be observed. In the subnanosecond region, the breakdown field is always expected to show a monotonic increase with frequency, while for pulses several nanoseconds wide, if the photon energy approaches the gap energy, the breakdown field can show an oscillatory dependence on photon energy. Consequently, as the pulse width is varied at fixed frequency, in some cases, the two processes can compete over a wide range of pulse durations.

In a short presentation, S. Brawer and W. Smith of the Lawrence Livermore Laboratory offered a conjecture regarding the modeling of bulk damage in transparent dielectrics. They proposed that electrons near the bottom of the conduction band can be considered as lying in localized states. Transitions between these states are assumed to be dipole allowed. When a conduction electron acquires an energy equal to the band gap in the material, it can excite a valence electron to the bottom of the conduction band by an Auger process. In this way, a population of conduction electrons is built up. Electron energy loss occurs via collisions with the lattice (phonon emission). This process heats the lattice and leads to damage. Avalanche may or may not accompany damage.

The new aspect of the theory is that it assumes localized states in the conduction band and does not require an avalanche for damage to occur. Only preliminary conclusions have been drawn from the theory, and detailed predictions will await further calculation.

A series of investigations of laser induced damage in semiconductor materials was reported by Yu. K. Danileiko, A. A. Manenkov, and A. V. Sidorin of the Lebedev Institute of Moscow. Using three laser probes, a 10.6- μm , CO₂ laser with a 60-ns pulse width, a 2.76- μm , Er:CaF₂ laser with a 90-ns pulse width, and an Er:YAG laser operating at 2.94 μm with a 100-ns pulse width, they measured the dc and microwave photoconductivity induced in Si, Ge, and GaAs. In Ge, no damage was observed, although significant photoconductivity was measured. At the shorter wavelengths, the photoconductivity was attributed to two-photon absorption, with a measured two-photon absorption coefficient of 7.5×10^{-2} cm/MW. At 10.6 μm , the mechanism giving rise to the photoconductivity was unclear. Neither avalanche ionization nor thermal effects could account for the observed dependence of carrier concentration on incident intensity. The absence of damage was attributed to self-defocusing of the incident light by the free carriers generated in the focal region. However, damage was observed in GaAs and Si. The observed damage levels were poorly correlated with measured bulk absorption coefficients. This was probably due to absorbing defects in the material. Defect type of morphology was observed in all cases of damage.

Scaling laws have been useful guides in damage studies, providing estimates of system performance over a range of operating parameters. Additionally, departure from the expected scaling is often evidence of the influence of extrinsic factors. M. J. Soileau of the Michelson Laboratory and M. Bass and E. Van Stryland of the University of Southern California tested the bulk damage threshold of KCl and NaCl as a function of spot size and of laser frequency. Significant departures from the empirical scaling law proposed by Bettis, et al., for spot-size dependence were observed in both materials. Furthermore, the frequency dependence of the damage threshold, measured at a fixed-spot diameter, contradicted the values obtained earlier for NaCl in the infrared, yielding values more in line with those reported last year by Manenkov.

Experiments were carried out at 2.7 μm , in a 140-ns pulse, at 3.8 μm , in a 70- to 100-ns pulse, and at 10.6 μm , in a 60- to 110-ns pulse. Spot sizes varied from 20 μm to 60 μm . In general, the threshold field decreased monotonically with increasing spot size, but no consistent pattern or functional form for the dependence on spot size was evident. In several cases, the spot-size dependence was different at different frequencies.

The authors attribute the lack of a simple set of scaling relations to the effect of impurities, defects, and other extrinsic factors in the materials examined. As Manenkov pointed out in his paper this year, however, the frequency dependence of damage can be quite complicated, even for ideal materials, without invoking any impurity effects. As to the departures of the spot-size dependence from the conjecture of Bettis, et al., uncertainties in the data and the absence of a firm foundation for the scaling law make it difficult to draw any unequivocal conclusion from the result.

A careful study of the surface breakdown mechanism for infrared optical materials was presented by V. I. Kovalev and F. S. Faizullov of the Lebedev Physical Institute in Moscow. They propose as the dominant mechanism in IR material damage a two-step process, consisting first of the boiling off of adsorbed water from the surface, followed by gas breakdown in the evolved water vapor. They carried out experimental tests of five critical predictions of this model. The tests were as follows:

- a) The breakdown threshold depends on the ambient gas pressure, but not the gas species, as long as the ambient gas is transparent to the incident light.
- b) Since the electron loss in the breakdown region is limited by the depth of the evolved gas rather than the width of the illuminated area, no spot-size dependence is expected.
- c) Surface treatment to reduce surface absorption should increase the observed damage threshold.
- d) At optical frequencies, the threshold intensity should decrease with increasing wavelength as λ^{-2} .
- e) For long pulses ($> 1 \mu\text{s}$), the threshold should increase with increasing pulse rise time, due to gas-dynamic expansion of the water vapor during the breakdown process.

Good agreement was observed between the predictions of this model and the experimental results. The materials tested included NaCl, ZnSe, KRS-5, KRS-6, and Ge.

4.0 Recommendations

As a result of this year's symposium format, it is quite straightforward to cull from the invited papers and round-table discussion an objective summary of the state of the art and understanding in the general area of optical materials exposed to high power lasers. Resulting recommendations are, of necessity, less detailed and specific than normal, but rather are general in nature as appropriate for a ten-year assessment of the field.

Following the order of topics discussed in the section on principal conclusions, we single out those areas which need further attention and note why they are important, whether due to a lack of consensus, inadequate capability or just incomplete data.

The first area appropriately concerns the general subject of laser induced damage to materials, in thin film form, at their surfaces and within the bulk proper. Of interest is not only demonstrated damage resistance but also our understanding of the damage process or mechanism itself. Thin films are at present the most damage sensitive optical feature in any optimally designed system. Optical materials in this form, as compared to surfaces and bulk materials, exhibit their lowest damage resistance. This undoubtedly arises from the presence of absorbing impurities or imperfections in film structure or at interfaces.

The existing data base, correlating the effects of starting material purity (of both films and substrate) and deposition conditions with the resultant structural and optical properties of the prepared optical coating, is grossly inadequate. To obtain a true understanding of why films fail and how to improve their performance, one must follow the road religiously, from describing the selection,

character, and purity of starting materials and substrate, through the fully documented deposition process, to a comprehensive physical and structural characterization of the thin film. Following this, one must determine the film's optical properties and correlate them, if possible, with the early steps. Damage testing and careful morphological investigation to elucidate performance and failure mode can then hopefully lead, after analysis, to an assessment of why films fail and suggest material and process changes which can be recommended to the fabricator. Comprehensive and careful multithreshold analysis will be invaluable at this stage.

The lack of a sufficient capability in this area is leading laser specialists to consider seriously the elimination of coatings, accepting the resultant losses. This is really a very inefficient type of damage avoidance. Other solutions recently rediscovered involve the use of graded-index surfaces which can be achieved by ion implantation. In this case, there is really no film per se but rather a hopefully appropriate index variation from air to bulk. Certainly more work is required in this area to answer the question, "Do these structures exhibit bulk damage levels, damage levels of a reduced index material, or levels typical of thin films." In addition, achievable uniformities, index gradients, optical performance (high and low reflectivity, filtering action), and damage resistance should be determined. One should note that the index change is not only due to the concentration of ions implanted in the base structure but also to the concentration of defects produced as well. Questions on the choice of ions, their energies, rates, angles of incidence, etc., and the utility of annealing, etc., still remain to be answered.

Two years ago, a way around the sensitivity of film/substrate interfaces was proposed. The barrier layer came on the scene with a great hope for materially improving the damage resistance of antireflection coated elements. Up to 50 percent improvement in the damage threshold was reported, and the mechanism for this improvement seemed to be understood. Subsequent studies, however, indicated that improved performance was not always obtained and that the morphology observed was not always consistent with the understanding of the role of barrier layers. Further work is required to reduce the concept to practice reliably.

One last principal recommendation in the thin film area concerns the need for improvements in reflective dielectric coatings for metal mirrors, particularly in the uv. Unstable resonator systems require large aperture mirrors. Metal mirrors must be coated, to obtain a high reflectivity in the uv and to prevent unacceptable levels of thermal distortion. Also, large aperture focusing lenses for uv use will be difficult to fabricate and will be expensive, since the choice of materials is severely constrained by two-photon absorption. There is no question that, at short wavelengths, coated-mirror damage resistance levels will define system design and size. There will be a greater importance attached to scattering in thin films, as a loss mechanism, at these shorter wavelengths.

Even if one either eliminates coatings or can raise their damage resistance to levels comparable to the intermediate values typical of surfaces, there will still be several important areas which will need to be addressed. Certainly, the most important is the further development of metal mirrors and their figuring and finishing to uv required tolerances whether by diamond turning or more conventional methods. The two most important concerns are the reduction of surface absorption (equally true for window surfaces), no matter what its cause, be it plasmon excitation or just plain dirt, and concurrently cleaning, which is particularly important prior to coating. There is no question but that the future bodes well for the further development and employment of metal optics in high power applications from the ir to the uv, if further attention leads to improved surfaces. As metallic optics continues to invade the commercial field, increased attention to environmental degradation will be required to extend the utility and range of application of these components.

This brings us to the last area associated specifically with the laser induced damage process: breakdown mechanisms and phenomena. It has been amply stated that there is no consensus on an analytical or phenomenological description of laser induced breakdown in dielectric materials. Thus, scaling relation studies, statistical analysis, and multithreshold investigation are necessary as benchmarks to validate and bound proposed theoretical descriptions. For example, roughness scaling may indicate whether an experimental result is indicative of intrinsic behavior or an impurity dominated extrinsic result. The same can be said for the use of statistical analysis as an indicator of probabilistic or deterministic behavior, another measure of intrinsicity or extrinsicity, similarly so for multithreshold experiments coupled with careful morphological investigations.

Unfortunately, most morphological assessments are more indicative of the secondary effects of breakdown or of a breakdown plasma interacting with the specimen than the initiation process itself. Thus there was a strong call this year for threshold interaction experiments, to quantify the phenomena of potential precursors before a catastrophic response. Scattering and conductivity, e.g., ellipsometry, were immediately suggested as candidate diagnostics of these pre-breakdown experiments as both are very sensitive indicators of change. This is an excellent area for basic research, and should be closely coupled with scaling studies to insure that mechanisms are not changing, therefore allowing one to bound the applicability of the relation.

The necessity of determining the structural and optical properties of materials, particularly thin films and surfaces, resulting from process variables was mentioned earlier. In order to accomplish this task adequately, improvements in measurement and characterization techniques are

dictated. In concert with developments in these areas, calibration and standardization methods must keep pace to take advantage of the numerous advances in instrumentation. This requirement is best met by the National Bureau of Standards which not only has prime responsibility in the standards area, but should increase its tabulation and documentation efforts as well. To accomplish this task effectively, we must all support the continuation of NBS's activities and encourage their expansion through the acquisition of the latest advances in instrumentation. The desirability and necessity of this course of action is evident to those working in the field of optical materials for high power lasers.

An especially fruitful area of endeavor is the refinement of techniques for measuring nonlinear absorption. One would like to have accurate measurements of two-photon absorption, as a function of frequency, together with a comparison of the spectral dependence of one- and two-photon absorption, as a measure of the density of states accessible by odd and even parity transitions.

In the area of materials and fabrication, there are two principal recommendations, one in each category. Based upon a careful consideration of the numerous and diverse reports presented on thin films over the years during this series of symposia and upon a realization of the almost unlimited number of potential coating materials, it seems particularly propitious to recommend a narrowing of our attention to a reduced set of candidates. We tentatively propose the oxides of aluminum and silicon as well as fluorine containing compounds such as the fluorides and higher fluorine analogues (e.g., PbF_2 , CaF_2 , CeF_3 , ThF_4 , ...). It appears that this group provides a reasonable range of refractive indices for the designer (perhaps augmented by a few selected high index materials) and is sufficiently durable and environmentally stable, due to the strength of the chemical bonds in these materials. The thin film community needs to concentrate on perfecting the deposition of these materials. This recommendation will surely meet with some opposition, for everyone has his pet material or design. However, in spite of this expected reluctance, it appears that a concentration on these materials can lead to real improvements in the damage resistance and utility of coated elements.

We are still unsure as to how the hardness of alkali halides contributes to the differences and difficulty of grinding and polishing optical elements fabricated of these materials to required tolerances and figure. Forging may be a solution to this problem. Each year, we see continued improvements in both understanding and demonstrated quality of forging technology, this year particularly evident with CaF_2 . Additional research and development are desirable in this area to more fully appreciate the capability and limitations of this technique for fabrication of optical components from crystalline dielectrics. This is an area where additional material characterization is particularly necessary.

The shibboleth of the high power laser systems designer is damage avoidance. He now looks at the overall system performance and asks himself where the critical problems are. For example, can one really expect to achieve diffraction-limited system performance in the uv. Probably not, but then again, it may be necessary. In this uv case, the limit will probably be due to damage levels, unmanageable tolerance requirements, or just plain saturation. The designer instead looks to damage avoidance techniques such as phase conjugation to achieve desired system quality. Other damage avoidance techniques will undoubtedly surface now that our attention has been acutely drawn to this concept.

Phase conjugation is only one of a growing list of new endeavors in the area of laser induced damage to optical materials. Potential solutions usually bring potential problems as well. In this case, phase conjugation devices are subjected to potentially increased damage sensitivity due to the requirement for overlapping high power beams. This is somewhat reminiscent of the different damage sensitivities of intra- and extra-cavity second harmonic generation crystals reported many years ago. In that case, while frequency conversion efficiency was improved for the intra-cavity case, the resistance to damage was much less than for low efficiency extra-cavity elements.

As has been pointed out, this year saw the first report of laser induced damage to optical fibers. It is anticipated that interest in this area will grow as applications for power transmission through fibers increase and the frequency domain of usage extends into the infrared where new materials promise extremely low transmission losses. It is also anticipated that new problems will arise in connection with the continued development of free electron lasers over a wide range of wavelengths. To this we must obviously add the continued movement to shorter wavelengths, which promises increased concern about scattering, more stringent figures and surface tolerances and nonlinear processes.

The revelation that copper optics degrades in industrial CO_2 laser environments is one indication of the important role surface chemistry plays in optical damage phenomena. Environmental stability in general, along with the problems of surface contamination in the preparation of optical elements, needs to be addressed using the analytical tools and diagnostic techniques of surface chemistry. Many diagnostic techniques, such as ATR spectroscopy, and ion, electron, and optical microprobes, are available for this area of investigation.

The laser fusion community is moving to slightly longer pulse durations, in the few to 10 nsec regime. Thus, one would expect more emphasis on thermal mechanisms, especially in thin films, most certainly if systems are repetitively pulsed. It is at these longer pulse durations, compared with the subnanosecond domain, that certain scaling relations, such as surface roughness, become more manifest.

There are two remaining recommendations, both of which we have touched upon earlier. We have matured enough in this field that there should be considerably less excuse for repeating the errors and inefficient approaches characteristic of our earlier years. Through these proceedings, we have tried to transfer information and effectively document in one series the principal efforts and thoughts on laser induced damage to optical materials.

We should now be able to advance in technology by paying careful attention to our history, our tortured and occasionally wandering travels, capitalizing on past successes, and avoiding past pitfalls. This is an appropriate time to assemble our understanding, and to tabulate the results of the past decade's program of measurement of relevant properties of materials. The former will be accomplished through publishing the invited papers given at this, the Tenth Symposium. The latter will probably be best accomplished by the National Bureau of Standards. NBS has maintained a measurements program for optical materials for several years. We should all support the assumption, by NBS, of the responsibility for assembling and cataloguing the parameters of optical materials.

The variety of factors which influence the properties and performance of optical thin films is only matched in number by the fragmented, mostly uncoordinated efforts involving thin films. Unlike the thin film activities of the electronics industry, there is no single incentive for an optical thin film application of comparable magnitude. Rather, there is large diversity of applications, no one of which can justify a comprehensive and fundamental approach to understanding and improving thin films. When this situation arises and is recognized, there is no more appropriate solution than for the problem to be addressed by a government agency or group of agencies collectively. The first alternative is difficult because the problem is so large and multifaceted that, like industry, no one agency can go it alone either. Therefore, the only recourse is a collective attack by interested parties. The group should most logically include the Office of Basic Energy Sciences of the Department of Energy, the various research arms of the Department of Defense, including the Army Research Office, the Office of Naval Research, the Air Force Office of Scientific Research, and, of course, Defense Advanced Research Projects Agency. To these we add the National Bureau of Standards of the Department of Commerce and the National Science Foundation. Industry and education must of necessity play key roles along with government. We must revitalize our depleted thin film physics capability in the academic community. Thin film optics is still largely an art. The development of centers of excellence would not only lead to improvements in understanding and performance but would more importantly establish an open and thus widely available technology base. A concentrated, coordinated, and sound program in optical thin films can lead to tremendous improvements in commerce, communication, defense and energy, as well as many other endeavors. Your support for this approach is solicited.

5. Acknowledgment

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S.I. CONVERSION UNITS

In view of present accepted practice in this technological area, U.S. customary units of measurement have been used throughout this report. It should be noted that the United States is a signatory to the General Conference on Weights and Measures which gave official status to the metric S.I. system of S.I. units in 1960. Readers interested in making use of the coherent system of S.I. units will find conversion factors in ASTM Standard Metric Practice Guide, ASTM Designation E 380-76 (available from American Society for Testing and Materials, 1916 Race Street, Philadelphia, Pennsylvania 19103). Conversion factors for units used in this paper are:

Length

- 1 in = 0.0254* meter
- 1 ft = 0.3048* meter
- 1 microinch = 2.5400* x 10⁻⁸ meter

Area

- 1 in² = 6.4516* x 10⁻⁴ meter²
- 1 ft² = 9.2903 x 10⁻² meter²

Force

- 1 lb (lbf) = 4.448 newton
- 1 kip = 4448 newton

Pressure Stress

- 1 psi = 6895 pascal
- 1 psf = 47.88 pascal

Energy

- 1 ft-lbf = 1.3558 joule

Moment

- 1 lbf-ft = 1.3558 newtonmeter

Temperature

- ToC = 5/9 (ToF - 32)

Heat

- Thermal conductivity,
- 1 cal (thermochemical) cm.s. °C = 418.40* watt/meter kelvin
- specific heat, C
- 1 cal (Thermochemical)/gm.°C = 4184.00* joule/kilogram kelvin

*Exact value

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