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Optical Coatings for Laser Fusion Applications

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ABSTRACT

Lasers for fusion experiments use thin-film dielectric coatings for reflecting, antireflecting and polarizing surface elements. Coatings are most important to the Nd:glass laser application. The most important requirements of these coatings are accuracy of the average value of reflectance and transmission, uniformity of amplitude and phase front of the reflected or transmitted light, and laser damage threshold. Damage resistance strongly affects the laser's design and performance. The success of advanced lasers for future experiments and for reactor applications requires significant developments in damage resistant coatings for ultraviolet laser radiation.

Optical Coatings for Laser Fusion Applications

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1. Introduction

Experiments in inertial confinement fusion are being conducted at laboratories throughout the world. The goal of these programs is to heat and compress a mixture of deuterium and tritium atoms to one-hundred-million degrees Centigrade and one-thousand times liquid density. At such high temperature and density, thermonuclear burning of the atomic fuel mixture occurs with subsequent release of energy. The success of inertial confinement fusion rests on our ability to deliver sufficient energy and power to the fuel in a properly shaped pulse. Meaningful experiments now require delivering 10-100 kJ of energy at power levels of 10-100 TW, and the energy and power required for eventual reactor applications may be ten times greater.

The methods currently receiving greatest attention for delivering such enormous energy and power to a submillimeter gas-filled target are lasers and particle beams of electrons, light ions, or heavy ions. Of these potential sources, lasers are the most well-developed and widely applied for fusion experiments. The lasers currently used are (1) carbon dioxide with a wavelength of 10.6 μm, (2) atomic iodine at 1.32 μm, and

(3) glass doped with neodymium ions at 1.06 μm. Recently, several laboratories have begun fusion experiments using the second, third and fourth harmonic frequencies of Nd:glass laser radiation with wavelengths of 0.53 μm, 0.35 μm, and 0.27 μm.[1] In addition, effort to develop the 0.25-μm wavelength KrF laser for fusion studies has recently been accelerated.

Thin film coatings are used in all these laser systems. The importance of coatings to overall performance of the system varies greatly; having presently the greatest impact on Nd:glass lasers. For example, "Shiva", the 20 beam laser at Lawrence Livermore Laboratory, has 2500 optical elements, of which 2000 are coated with dielectric thin films.

A review of the optical coating applications for each fusion laser system is given in Section 2. Laser design issues related to coatings are presented in Section 3. Section 4 discusses the importance of laser-induced damage to coatings and the status of damage experiments. Promising areas for future development are reviewed in Section 5.

2. Coatings in Fusion Lasers

Thin-film coatings have three optical applications in fusion lasers: (1) high-reflection (HR) coatings for mirror surfaces, (2) anti-reflection (AR) coatings on the surfaces of lenses and windows, and (3) polarizing beamsplitters used to control the direction of beam propagation. Designs for these multilayer coatings have been presented elsewhere.[2]

2.1 CO_2 Laser

The largest operating CO_2 laser for fusion studies is the eight beam "Helios" at the Los Alamos Scientific Laboratory. Each 40-cm-aperture beam of Helios can generate more than 1000 J in pulsewidths less than 1 ns; giving the total laser an output capability greater than 8 kJ at 8 TW. The 72-beam "Antares" now under construction at LASL, is expected to produce 100 kJ at 100 TW when completed.

The following coatings are used in CO_2 lasers:

- Anti-reflection - NaF on NaCl substrates for target chamber and amplifier windows, ZnS single layer or ZnS/ThF_4 multilayer on Ge substrates for output coupler and modelocker.
- High-reflection - ZnS/ThF_4 on aluminum coated copper.
- Polarizer - ZnS/ThF_4 or a Au grid, both deposited on ZnSe substrates.

The most important coating is the NaF AR coating on NaCl target chamber and amplifier windows. This coating has a threshold fluence (energy per unit area in the laser pulse) for laser induced damage of 6 J/cm^2 for 1-ns, 10.6-μm pulses, which equals the bare-surface threshold fluence of optically polished NaCl and substantially exceeds the typical operating fluence of 1 J/cm^2. The ZnS/ThF_4 polarizer has 1-ns damage thresholds of 2 J/cm^2 and 9 J/cm^2 for 10.6-μm light with p- and s-polarization respectively.[3]

2.2 Iodine Laser

The largest iodine laser for fusion studies is the single beam Asterix III at the Max Planck Institute in Garching, West Germany. This laser has produced 300-J, 250-ps, 1.2-TW pulses from a 17-cm diameter aperture[4] with a fluence loading of 2 J/cm^2 on the output amplifier window and focusing optics. Multilayer AR, HR and polarizing coatings of SiO_2/TiO_2 are used. Coating applications in the iodine laser are similar to those in the Nd:glass laser. However, amplifier staging of Asterix III was not optimized to take full advantage of coating damage resistance. Consequently coatings do not currently limit its performance.

2.3 Nd:Glass Laser

The 20 beam Shiva at Lawrence Livermore Laboratory is the world's largest operational Nd:glass laser. Each 20-cm-aperture beam can produce 750-J, 1-ns pulses. The full laser generated a record power of 27 TW at shorter pulse width. Nova, scheduled for operation in 1983, will produce 100 kJ at 100 TW power in 1-ns pulses from 10 beams, each of 74-cm aperture. Multilayer SiO_2/TiO_2 coatings for AR, HR, beamsplitter and polarizing applications are used throughout the lasers. In contrast to the CO_2 and iodine lasers, whose power and energy are limited in current designs by gain saturation, the Nd:glass laser's performance is limited by laser-induced damage to these coated surfaces.

2.4 KrF Laser

A KrF fusion laser module is being developed to produce 10 kJ in 10-ns pulses giving a 1-TW output power at peak fluence loading of 5 J/cm^2. Because UV transparent coating materials damage at fluences of 1 J/cm^2, improving the damage threshold of thin-film AR and HR coatings is a key element in successful development of the KrF laser.

3. Design Requirements

The central importance of thin-film coatings in high energy, Nd:glass lasers is made clear by the diagram of an amplifier chain shown in Fig. 1. Thin-film coatings for mirrors, beamsplitters, polarizers and AR surfaces control pulse formation and propagation in the low energy stage where initial amplification occurs. Beamsplitting mirrors then divide the pulse and reflect portions into each beam line of the main amplifier stage, which is composed of the three elements (1) disk amplifiers to multiply the pulse energy, (2) spatial filters to remove high intensity "hot spots" from the beam, caused by the intensity-dependent refractive index of glass, and (3) isolation stages, consisting of Faraday rotators between crossed, thin-film polarizers, to allow light to pass only in the forward direction, toward the target. As the pulse energy increases, its diameter and the aperture of these elements are expanded to maintain constant fluence loading. Turning mirrors reflect the high energy pulse to the evacuated target chamber, where it passes through a window, low f-number lens, and a thin glass plate, which shields the lens from damage by target debris.

Except for the amplifier disks, all optical surfaces are coated with dielectric thin films. There are AR coatings on spatial-filter lenses, Faraday-rotator glass, target-chamber windows, focus lenses and debris shields. Other surfaces have polarizing or HR coatings deposited on BK-7 glass substrates. Reflecting and antireflecting coatings also are used on elements in the beam diagnostic packages.

The most important requirements of optical coatings for fusion laser applications are:

- Uniformity
- Accuracy
- Damage threshold .

"Accuracy" represents the average value of reflectance and transmittance over the coated surface area, while "uniformity" refers to local variations from the average. Uniformity is normally more important than accuracy because, while small variations from the average can be compensated by adjusting amplifier gain, lack of uniformity usually results from variations in layer thickness and causes a wavefront error in the beam in addition to the amplitude variation. Wavefront errors affect beam propagation and focusing onto the target. The wavefront error of transmitting and reflecting elements which can be allowed is one-tenth wave for HeNe laser light (632.8-nm wavelength). A summary of the design specifications for the reflectance R of coatings used on Shiva is given in Table 1.

Table 1

Reflectance Specifications for Shiva Coatings

Coating	Accuracy	Uniformity
Mirror	R ≥ 99%	± 0.2%
Beamsplitter	R ≤ 90% (± 1.5%)	± 0.1%
Polarizer	$R^*_s \geq$ 98.5%	± 0.2%
	$R^*_p \leq$ 3.0%	± 0.3%
Antireflector	R ≤ 0.2%	---

*R_s, R_p are reflectance for light with s or p polarization.

Maximum apertures of coated elements for Nova will be 80 cm for AR coatings, 72 cm for polarizers and 109 cm for HR coatings. Polarizers and beamsplitters present the greatest production difficulties because of their large number of layers (typical designs have 20-30 quarter-wave-thick layers) and sensitivity of the coating's performance to errors in layer thickness. Consideration must also be given to methods for handling and supporting in the coating chamber, substrate blanks weighing as much as 800 lb.

"Damage threshold" is the fluence which begins to cause irreversible physical change in the coating. We detect the onset of damage by examining the surface with a Nomarski microscope, typically at 100X magnification. Photographs of each site are taken before and after irradiation. Comparing these photographs allows detection of micron-size damaged spots in the millimeter-diameter irradiated areas. Nd:glass lasers are designed to operate at fluence levels just below the damage threshold. The greatest possible damage resistance of coatings is therefore required to minimize the laser system's aperture and thus its cost. To achieve this design goal requires extreme care in preparing and cleaning substrate surfaces, eliminating spatter and other coating defects, and maintaining correct stoichiometry on a microscopic scale.

It is also important that coating properties remain constant as the coatings age. Of particular concern are possible spectral shifts of polarizers and changes in damage fluence. In one test, for example, damage thresholds of three identical SiO_2/TiO_2 HR coatings were measured soon after coating and again after storage for one year in a normal laboratory environment. The threshold of two of these coatings decreased by one-half after aging, but were restored to the original value by baking at 275^{o}C for 4 hours. Threshold of the third sample was not changed by aging or improved by baking.

Optical elements of lasers normally are handled with great care in environments in which dust, humidity and temperature are controlled, so physical durability, abrasion resistance and adherence are less important than in other applications.

4. *Laser Damage to Coatings*

Because laser-induced damage to coatings is very important in the design and performance of Nd:glass fusion lasers, we have devoted great effort to understanding the causes of laser damage and to developing materials and deposition processes which improve damage thresholds.[5]

Laser damage results from absorption of light in the coating. Temperature in the small absorbing volume increases, leading to thermal-stress fracture or melting. The major sources of absorption in transparent dielectrics are (1) direct absorption by particulates, chemical impurities, local deviations in stoichiometry and physical defects, and (2) absorbing plasma generated by electron-avalanche ionization. Importance of plasma absorption is greatest for pulses of subnanosecond duration. Direct absorption dominates the damage process for nanosecond-and-longer pulse widths, which is the regime of greatest interest for laser fusion experiments.

Laser calorimetry[6] has been recently developed which allows measurement of linear absorptions as small as 1 part in 10^5. The absorption coefficients measured for thin films typically lie in the range $1\text{-}10^3$ cm^{-1}. For comparison, the absorption coefficient of optical glass is 10^{-4} - 10^{-3} cm^{-1}, and we estimate coefficients in the interface region between film and substrate to be 10^2 - 10^4

cm^{-1}. These absorption coefficients are values averaged over the volume of the coating through which the calorimeter laser beam passes. We expect the absorption at localized impurity sites to be greater by one or more orders of magnitude.

4.1 AR Coatings

AR coatings on the input lenses of spatial-filters are the most vulnerable to damage of all coatings in the laser system. These coatings receive the greatest fluence loading (up to 8 J/cm^2 for 1 ns pulses in current Nd:glass laser designs) and in addition AR coatings have lower damage thresholds than other coatings. The function of an AR coating is, of course, to conduct the incident electromagnetic fields to and through the substrate interface. High absorption in the interface region compared to the substrate and remainder of the coating is the primary cause of the low damage thresholds measured for AR coatings. The interface of polarizer coatings also is exposed to the field of p-polarized light, but fluence loading is less on these coatings than on AR coatings because the laser beam is incident on them at Brewster's angle.

The evolution of damage morphology for an AR coating, which is shown by the electron-beam microscope photographs in Fig. 2,[7] gives further evidence that AR damage begins at the substrate interface. The individual damage sites, shown in each 3-μm wide area photographed, are randomly distributed over the 2-mm diameter area which is irradiated by the laser. The sites shown in Fig. 2a-d were progressively closer to the center of the irradiated area, where fluence loading was greatest. These photographs indicate that damage is produced by melting below the surface and spalling off of material above. This coating was a 0.4 μm thick four layer SiO_2/TiO_2 design. The silica layers are amorphous and the titania layers have a crystalline, columnar structure. It appears that a small, very hot spot is generated at approximately the glass substrate interface with the first TiO_2 layer. The intense heat melts the glass and generates considerable pressure, causing the coating layers to fracture. The fracture propagates up and outward through the amorphous silica layers and normal to the surface through the TiO_2 layers, along the crystalline columns. The TiO_2 layers thus appear as the two white bands in the photograph, Fig. 2d. When the fracture reaches the surface, the sudden release of pressure ejects molten glass from the center of the crater, where it quickly solidifies.

Our attempts to improve damage thresholds of AR coatings have emphasized substrate and coating materials and substrate surface preparation. One experiment examined the effect of the method of substrate polishing on damage threshold. A set of fused silica substrates was polished, by conventional fresh-feed process, to optical quality with a measured roughness of ~20 A rms. Other fused silica substrates were polished by bowl-feed process. In the bowl-feed process, the slurry is recirculated during polishing. As the abrasive particles break down, the surface is polished with successively finer particles, resulting in very smooth surfaces (≤ 5 Å rms).[8] Fig. 3 shows a comparison of 1-ns, 1.064-μm pulse damage thresholds of SiO_2/TiO_2 AR coatings deposited on these substrates. The median damage threshold increased from 5 J/cm^2 on the conventional surfaces to 8 J/cm^2 on the bowl-feed surfaces. Two possible reasons for the higher thresholds of films on bowl-feed surfaces are (1) the smoother surface has lower residual particulate contamination after cleaning and (2) the surface may have a different chemical composition and react differently with the coating.

In another experiment, we found that SiO_2/TiO_2 AR coatings deposited on fused silica and those deposited on the standard optical glass, BK-7 had equal damage thresholds. However, a half-wave-thick silica "undercoat" layer deposited on either of the two substrate materials beneath the AR coating increased the coating's median damage threshold by 30%.

We measured damage thresholds of AR coatings made of many different materials, all deposited by electron-beam evaporation. Among oxide coatings we tested SiO_2 in combination with each of the higher-index materials: TiO_2, Ta_2O_5, ZrO_2 and Al_2O_3. We also examined the fluoride coatings MgF_2, NaF, Na_3AlF_6, MgF_2/ThF_4, MgF_2/PbF_2, ZnS/ThF_4 and MgF_2 with an Al_2O_3 overcoat. All coatings were deposited according to standard commercial practice by Optical Coating Laboratory, Inc. (OCLI), Lambda Airtron or Perkin-Elmer. The single-layer coatings were half-wave optical thickness for 1.06 μm-light and the multilayer combinations were two- or four-layer AR designs for 1.06 μm-light. None of these single or multilayer coatings had damage thresholds consistently better than the 5 J/cm^2 median threshold of the standard, four-layer SiO_2/TiO_2 AR coating produced by OCLI, although a few SiO_2/Ta_2O_5 AR coatings had damage thresholds of 8-12 J/cm^2.

We then systemmatically studied the influence of the major deposition variables: temperature, rate and oxygen pressure on damage thresholds of SiO_2/TiO_2 and SiO_2/Ta_2O_5 AR coatings. OCLI prepared matrix arrays of the AR coatings at temperatures between 175°C and 350°C, oxygen pressure between 0.7×10^{-4} Torr and 2.0×10^{-4} Torr and at two deposition rates, 1.5 A/s and 5 Å/s. Initial measurements indicate that coatings deposited at the lowest temperatures have the highest damage thresholds. Oxygen pressure and deposition rate did not significantly affect damage thresholds.

Absorption and net stress were also measured for each AR film in the deposition matrix. The fraction of the incident beam absorbed by the coatings ranged from 2×10^{-5} to 2×10^{-2}. Net stress ranged from 25 to 62 kpsi, with all films being in compression. Damage thresholds did not correlate with net stress. Thresholds decreased with increasing absorption when the coating absorption was 3×10^{-3}; but thresholds and absorption were uncorrelated for films of lower absorptivity.

Another experiment, done in collaboration with Hoya Corporation tested the dependence of damage threshold on coating adhesion. Half-wave thick coatings of the oxides SiO_2, Al_2O_3, ZrO_2, Ta_2O_5 and TiO_2, and the fluorides MgF_2, ThF_4, LaF_3, and CeF_3 were deposited on four different glass substrates: LSG-91H silicate, LHG-8 phosphate, alkaline rich P-1 phosphate and LHG-10 fluorophosphate. Film adhesion was evaluated by the "scratch test", developed by Heavens.[9] A diamond stylus with 30-μm tip diameter was drawn across the surface at 1mm/s, with an increasing load applied until the coating was removed.

The weight required to scratch the test coatings varied from 10 to 150 grams. We found no consistent relation between damage threshold and adhesion for these coatings.

We believe the observed lack of correlation of damage threshold with absorption, stress or adhesion arises from the fact that these are macroscopic, average properties, and that damage depends instead on microscopic, localized properties, such as absorption by particulates, physical defects and chemical impurities.

To determine possible effects on damage threshold of the grain size and phase composition of the crystalline TiO_2 layers, a series of half-wave thick TiO_2 coatings were prepared by Pacific Northwest Laboratories. One set of coatings had grain size of 10 nm and phase composition mixtures ranging from 100% rutile to 60% rutile/40% anatase. No systemmatic dependence of damage threshold on composition was found. However, in a set of pure rutile coatings with grain size decreasing from 63 nm diameter to an apparently amorphous coating, the damage threshold increased uniformly from 1 J/cm^2 to 9 J/cm^2.[10] A plausible qualitative explanation for this trend is that coatings with larger grain size have smaller total grain boundary volume in which to distribute absorbing impurities that tend to be concentrated in the boundary region. Thus the peak local absorption is greater and damage threshold lower for the larger grain coatings.

4.2 HR Coatings

HR coatings used in several damage experiments consisted of fifteen alternate layers of titania and silica, vacuum evaporated onto BK7-PH3 glass substrates, beginning with a titania layer. Each layer had quarter-wave optical thickness for 1.06 μm light. With assumed refractive indices of 1.45 for silica and 2.2 for titania, the theoretical reflectance of the 15 layer coating is 99.6%. While an AR coating is designed to conduct electromagnetic fields to and through the substrate interface, HR coatings repel the fields and establish a standing-wave electric field intensity which has a null at the air interface and rises to a maximum of 0.82 $\bar{E}_0^2$ at the first TiO_2/SiO_2 interface, where E_0 is the incident electric field. The field strength in the coating then decreases through the adjacent silica layer to zero at the next interface. Further into the coating, the field varies periodically but decreases rapidly in amplitude.

We believe the greatest absorption of laser light takes place in the titania layers and at interfaces. Because absorption of energy varies as the product of field strength and absorption coefficient, damage to HR coatings normally begins in the outermost titania layer or interface.[5] Designing the coating for a wavelength different from the laser allows the electric field peaks to be shifted into the titania or silica layers, with consequent reduction in reflectance.[11] If one material is more highly absorbing than the other, variations in the amount of laser energy absorbed and in the damage threshold would be expected. This principle was tested in a set of coatings deposited by OCLI, which were designed to have maximum reflectance at 1.19 μm, 1.09 μm and 0.92 μm. Damage thresholds were measured and the results compared to the calculated values of peak, average and interface field strengths for the outermost titania layer. Damage thresholds were most strongly correlated with the electric field strength at the first TiO_2/SiO_2 interface. However, this result should not be regarded as conclusive because it is possible for local defect absorption to have dominated any average field effect.

To study the effect of average absorption on HR coating damage thresholds, OCLI prepared a series of coatings at different oxygen pressures and found their absorptions to decrease monotically from 0.01 at the lowest pressure (0.5×10^{-5} Torr) to 1.4×10^{-5} at the highest pressure (3.0×10^{-4} Torr). Damage thresholds tended to increase for decreasing absorption. However, for those coatings with absorption less than 10^{-4}, all thresholds were within one standard deviation of the average 14.4 J/cm^2. Consequently, one may conclude only that absorption above 10^{-4} reduces the damage threshold.

Among our experiments with HR coatings, the most significant improvement in damage threshold resulted from depositing a silica "overcoat" on top of the standard reflector. Overcoats have been used previously on mirrors to improve their durability and abrasion resistance. Their effect on damage threshold is shown by the two histograms in Fig. 4. The median damage threshold increased from 8 J/cm^2 for nonovercoated mirrors to 15 J/cm^2 for overcoated mirrors.

The silica overcoat was 0.4μm thick (half-wave optical thickness for 1.06μm light). This layer is under compressive stress, which in addition to its amorphous structure, gives it relatively large fracture resistance. TiO_2, which is the outer layer of the standard reflector, is crystalline and deposits with tensile stress. Consequently TiO_2 is relatively weak and fractures easily. It is therefore likely that silica overcoats improve damage thresholds by preventing rupture of the more fragile TiO_2 layer.

5. Areas for future coating development

Future developments will deal with:

- Special application coatings,
- Alternate deposition technologies,
- Coatings for UV application.

Examples of special application coatings which are currently under development are:

(1) Durable coatings which can be chemically stripped without damage to the substrate surface. Use of these coatings would reduce operating costs by eliminating expensive refinishing of the optical surfaces before recoating the damaged element. Our studies of strippable AR coatings which have a cryolite layer next to the substrate have given promising results.[13]

(2) Durable coatings deposited at room temperature. Such coatings are required for temperature sensitive glass and crystals.

(3) Transparent conductive coatings with damage threshold equal to AR coatings.[14] These coatings may permit fabrication of large aperture electro-optic switches and possibly cause dramatic changes in the basic architecture of fusion lasers.

There are deposition technologies not ordinarily used for optical coatings that have the potential to produce damage resistant coatings. Among the possibilities are: (1) oxide coatings deposited from metal-organic solutions,[15] (2) chemical vapor deposition, (3) deposition in ultra-high vacuum, and (4) viscous liquid coatings which flow continuously over the element surface. Improvements may also come from preparing substrate surfaces in the evacuated coating chamber by such methods as: (1) surface etching with laser, electron or ion beams, (2) high temperature baking, or (3) strong UV irradiation.

Finally, the development of damage resistant coatings for UV fusion laser applications requires immediate attention. The coatings should withstand 5 J/cm^2 fluence of 0.25-μm wavelength radiation, and must survive in the corrosive, fluorine gas environment, exposed to the effects of a high-voltage electric discharge, including energetic electrons and vacuum-UV radiation. Successful coatings will probably be high-band-gap oxides and fluorides deposited with great attention to purity and cleanliness.

In conclusion, thin film coatings play a central role in the performance of Nd:glass lasers for fusion experiments. Recent, substantial improvements in coating damage thresholds were required for Nova, which will be the primary laser for fusion studies in the mid-1980's. Development of UV lasers for fusion experiments and possible reactor applications depends critically on improvements in damage resistant UV coatings.

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Figure Captions

Figure 1. Schematic diagram showing components in one beam of the Nd:glass laser Nova, under construction at LLL.

Figure 2. Morphology of damage to AR coating, photographed using electron-beam microscope.[7] Laser pulse fluence increased from (a) to (d). Width of each photographed region was 3 μm.

Figure 3. Comparison of 1-ns 1.06-μm pulse damage thresholds of SiO_2/TiO_2 AR coatings deposited on (a) conventionally polished surface and (b) bowl-feed polished surface.

Figure 4. Comparison of 1-ns, 1.06-μm pulse damage thresholds of SiO_2/TiO_2 HR coatings: (a) normal quarter-wave stack without overcoat, (b) quarter-wave stack with half-wave-thick silica overcoat.

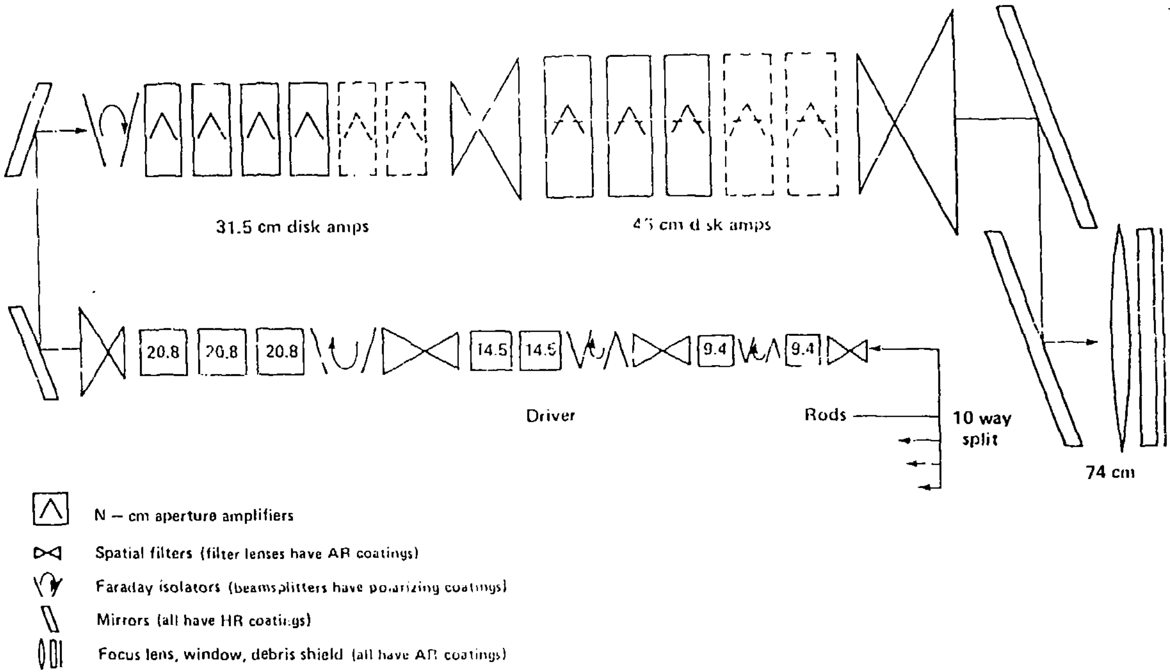

31.5 cm disk amps
20.8
20.8
20.8
14.5
14.5
9.4
9.4
Driver
Rods
10 way split
74 cm
N – cm aperture amplifiers
Spatial filters (filter lenses have AR coatings)
Faraday isolators (beamsplitters have polarizing coatings)
Mirrors (all have HR coatings)
Focus lens, window, debris shield (all have AR coatings)

Figure 1

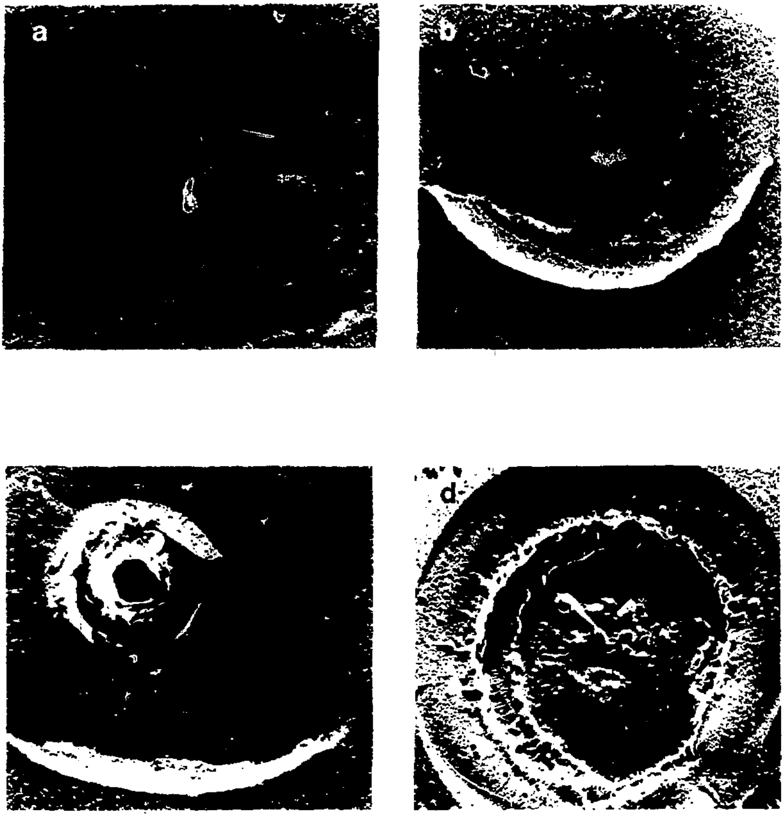


Figure 2

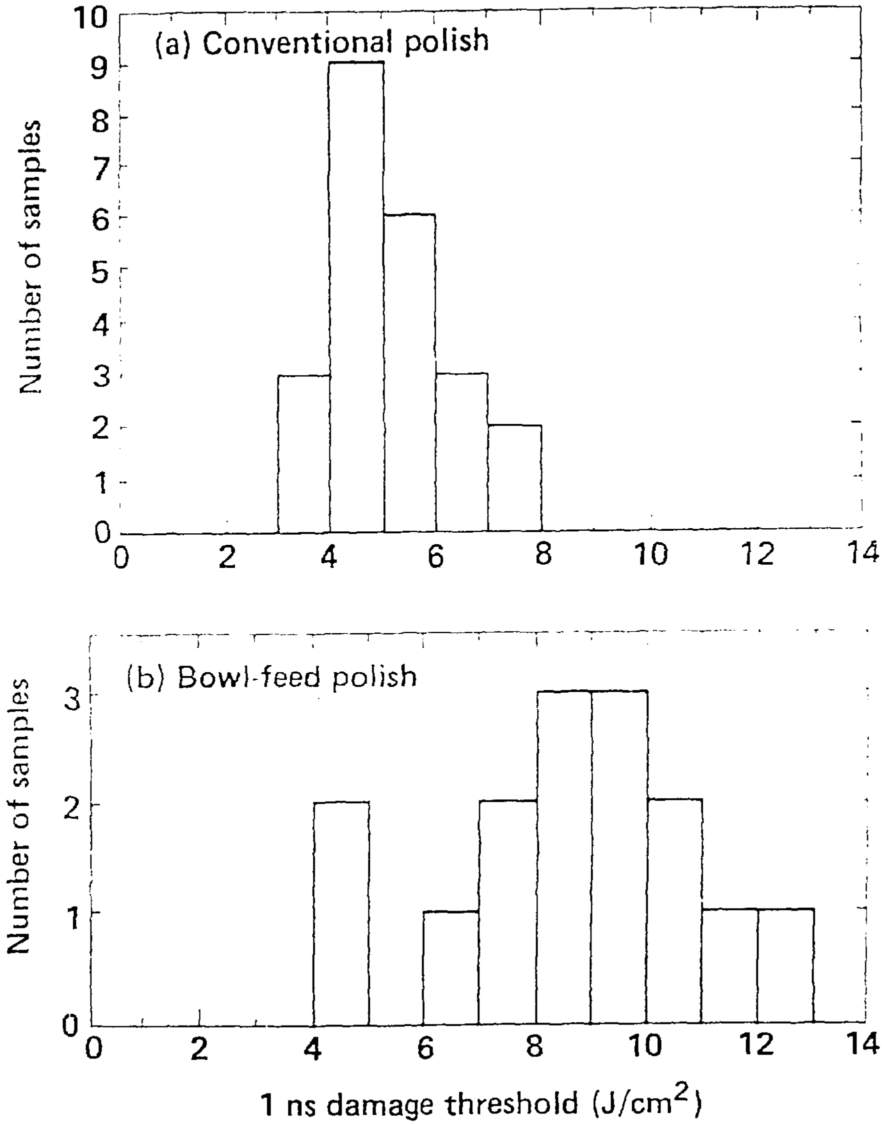
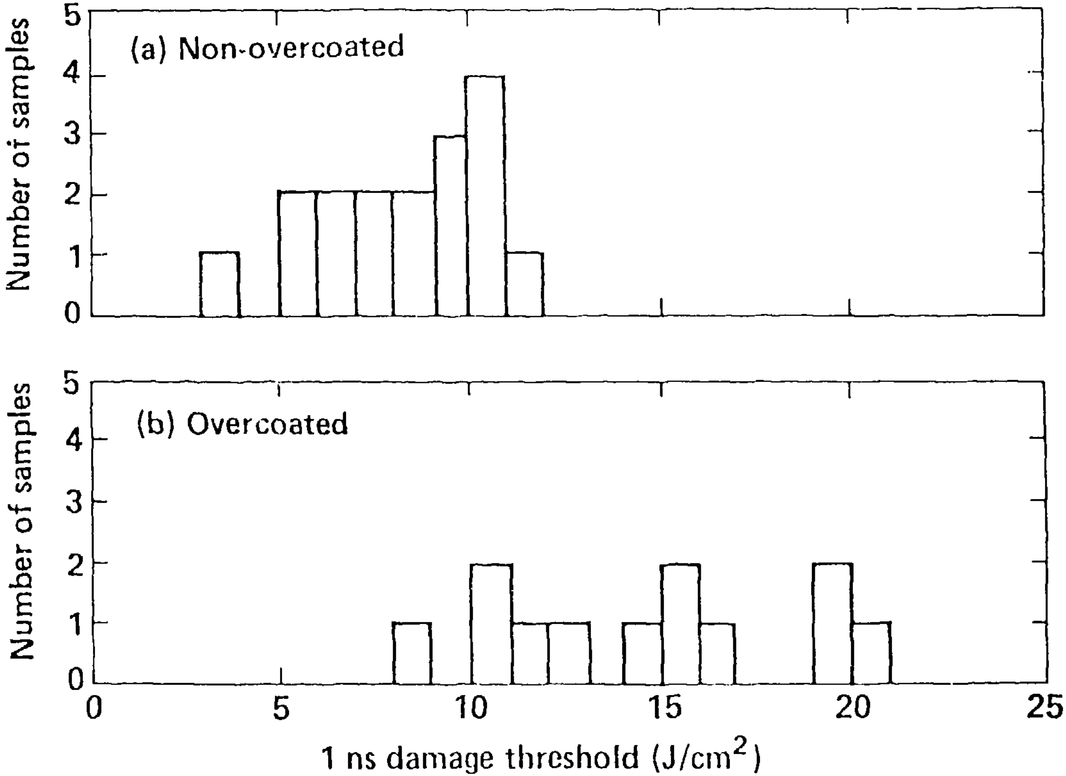

(a) Conventional polish
Number of samples
0
1
2
3
4
5
6
7
8
9
10
0
2
4
6
8
10
12
14
(b) Bowl-feed polish
Number of samples
0
1
2
3
0
2
4
6
8
10
12
14
1 ns damage threshold (J/cm2)

Figure 3



(a) Non-overcoated
Number of samples
5
4
3
2
1
0
(b) Overcoated
Number of samples
5
4
3
2
1
0
0
5
10
15
20
25
1 ns damage threshold (J/cm2)