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Damage Resistant Optics for a Mega-Joule Solid-State Laser

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ABSTRACT

Research on Inertial Confinement Fusion (ICF) has progressed rapidly in the past several years. As a consequence, LLNL is developing plans to upgrade the current 120 kJ solid state (Nd^{+3}-phosphate glass) Nova laser to a 1.5 to 2 megajoule system with the goal of achieving fusion ignition. The design of the planned Nova Upgrade is briefly discussed.

Because of recent improvements in the damage resistance of optical materials it is now technically and economically feasible to build a megajoule-class solid state laser. Specifically, the damage threshold of Nd^{+3}-doped phosphate laser glass, multilayer dielectric coatings, and non-linear optical crystals (e.g., KDP) have been dramatically improved. These materials now meet the fluence requirements for a 1.5-2 MJ Nd^{3+}-glass laser operating at 1054 and 351 nm and at a pulse length of 3 ns. The recent improvements in damage thresholds are reviewed; threshold data at both 1064 and 355 nm and the measured pulse length scaling are presented.

1. INTRODUCTION

The key requirement for establishing the scientific feasibility of Inertial Confinement Fusion is the demonstration of fuel (DT) ignition and burn propagation. This should be possible using about 1.5 to 2.0 MJ of laser energy at a wavelength of 0.35 µm or less. To meet this goal, LLNL is planning to upgrade the existing Nd-glass Nova laser from 40-70 kJ (1-2.5 ns) to 1.5-2 MJ (3-5 ns).[1]

One of the keys to the successful design and operation of this laser is the availability of optical materials with high laser damage resistance. In this paper we compile results from damage tests at 1064 and 355 nm on the key optical materials used in this laser design. The measured damage thresholds meet or exceed the requirements of 18 J/cm^2 (1054 nm) and 12 J/cm^2 (351 nm) at 3 ns.

In addition, the results are summarized in a set of simple empirically-derived relationships that describe the damage threshold pulse-length scaling. These relationships are valuable in laser system design since pulse length is often a key design parameter.

2. NOVA UPGRADE SYSTEM DESIGN

The proposed Nova Upgrade is an 18-beamline Nd:glass laser whose output at 1054 nm is frequency converted to the third harmonic (3ω at 351 nm).[1] The architecture of one beamline is shown schematically in Fig. 1. In brief, each beamline consists of a compact multipass design with the optical components segmented into 4 x 4 arrays. Thus, each beamline is composed of 16 "beamlets" that are each optically independent and able to be individually pointed.

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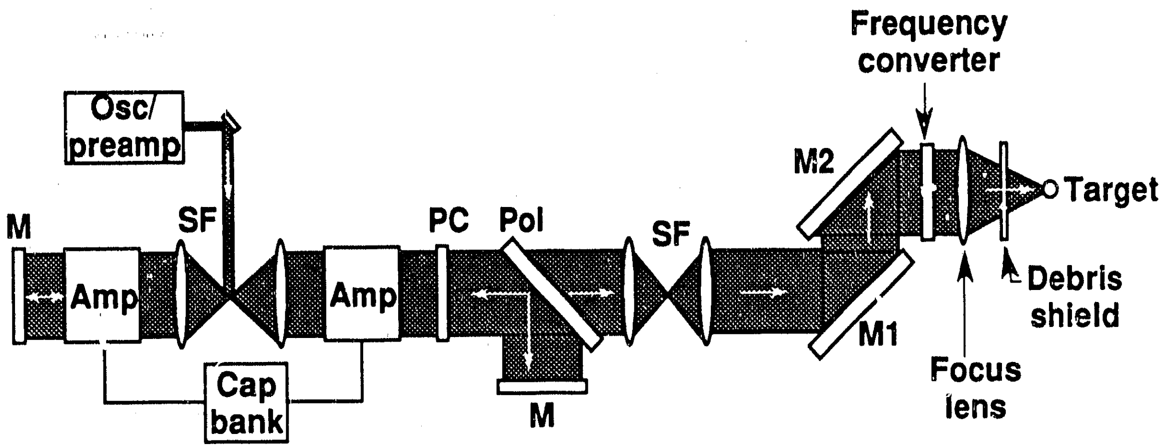

Fig. 1. Schematic representation of one beamline of the 18-beamline Nova Upgrade design. The optical resonator formed by the two end mirrors (M) contain the Nd:glass amplifiers (Amp) spatial filter (SF) and optical switch. The optical switch is comprised of a Pockels (PC) cell and polarizer (Pol). M1 and M2 are transport mirrors.

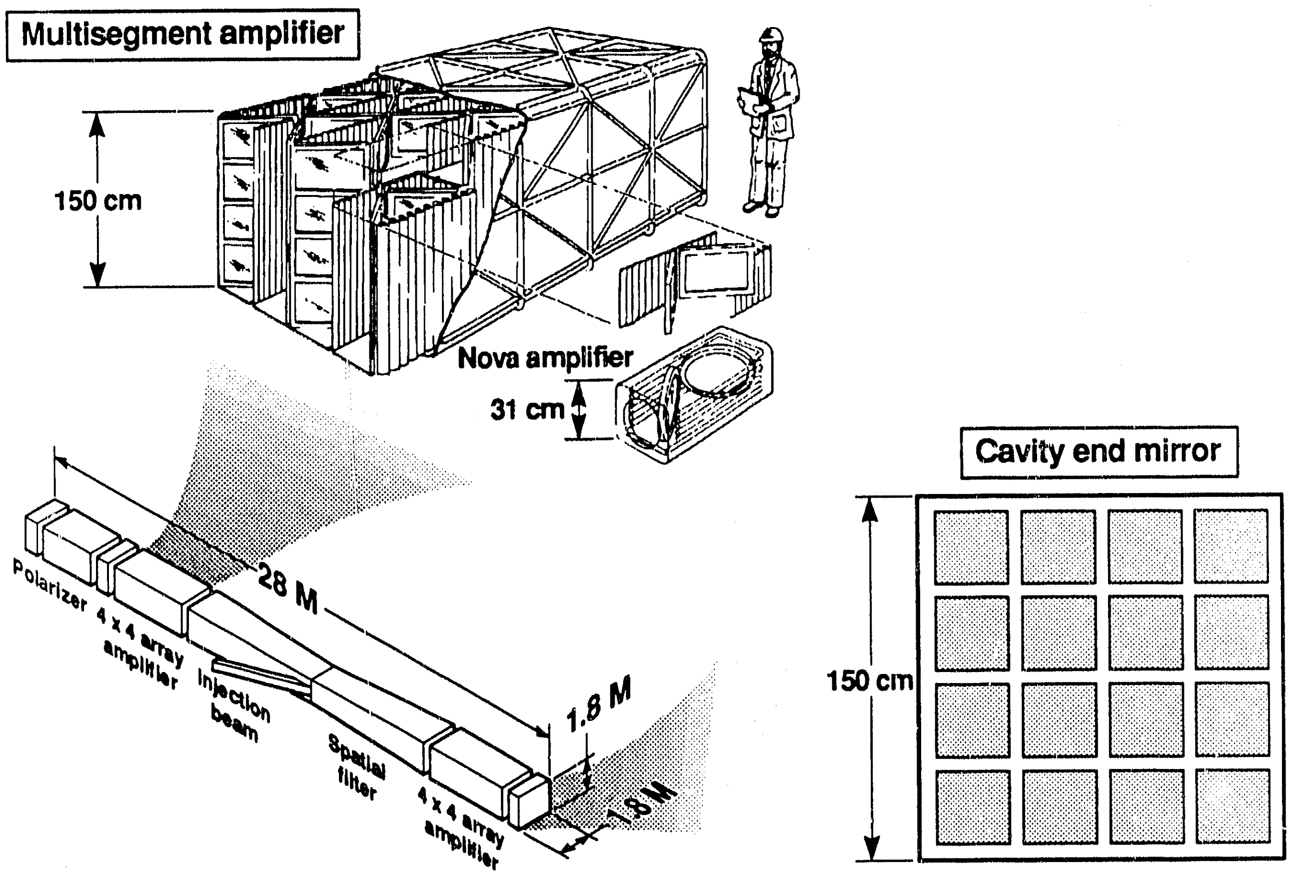

Fig. 2. Each optical component in the beamline of the Nova Upgrade is segmented into a 4 x 4 array as schematically shown here for an amplifier and resonator end mirror. The resonator is about 30 m long. Note that the multisegmented amplifier is essentially a stacked-array of the current Nova 31.5-cm amplifiers.

The optical components have been segmented to reduce both the size and cost of this system. This is shown in Fig. 2 where the multi-segmented amplifier and cavity end mirrors are shown in schematic form; the current Nova 31.5-cm amplifier is also shown for comparison. Note that individual aperture sizes for the Nova Upgrade are nearly identical to that of the current 31.5-cm amplifiers. However, the Upgrade design efficiently stacks these into large arrays.

Each beamline contains two amplifiers mounted in a resonator cavity and separated by a correspondingly segmented spatial filter. The spatial filter is also an optical relay. Each resonator cavity also contains an optical switch consisting of a 4 x 4 segmented Pockels cell and multilayer thin film polarizer (Fig. 1).

During operation, an input pulse is injected into the resonator cavity using a small mirror located near the spatial filter focus. The injected pulse first travels toward the "rear" of the cavity (i.e. the end opposite the optical switch) and reflects off the end mirror and then makes three full passes through the resonator cavity. At the time of the initial pulse injection into the cavity, sufficient voltage is applied to the Pockels cell to rotate the polarization by 90°. The combination of polarizer and cavity end mirror confines the pulse to the resonator until the Pockels cell is turned off (on the final pass).

The output from the resonator cavity is transported to the frequency conversion array using a spatial filter and series of multilayer dielectric mirrors. The third harmonic output from the conversion array is then focused onto the target. An intervening debris shield is used to prevent target debris from collecting on the final focusing optics (Fig. 1).

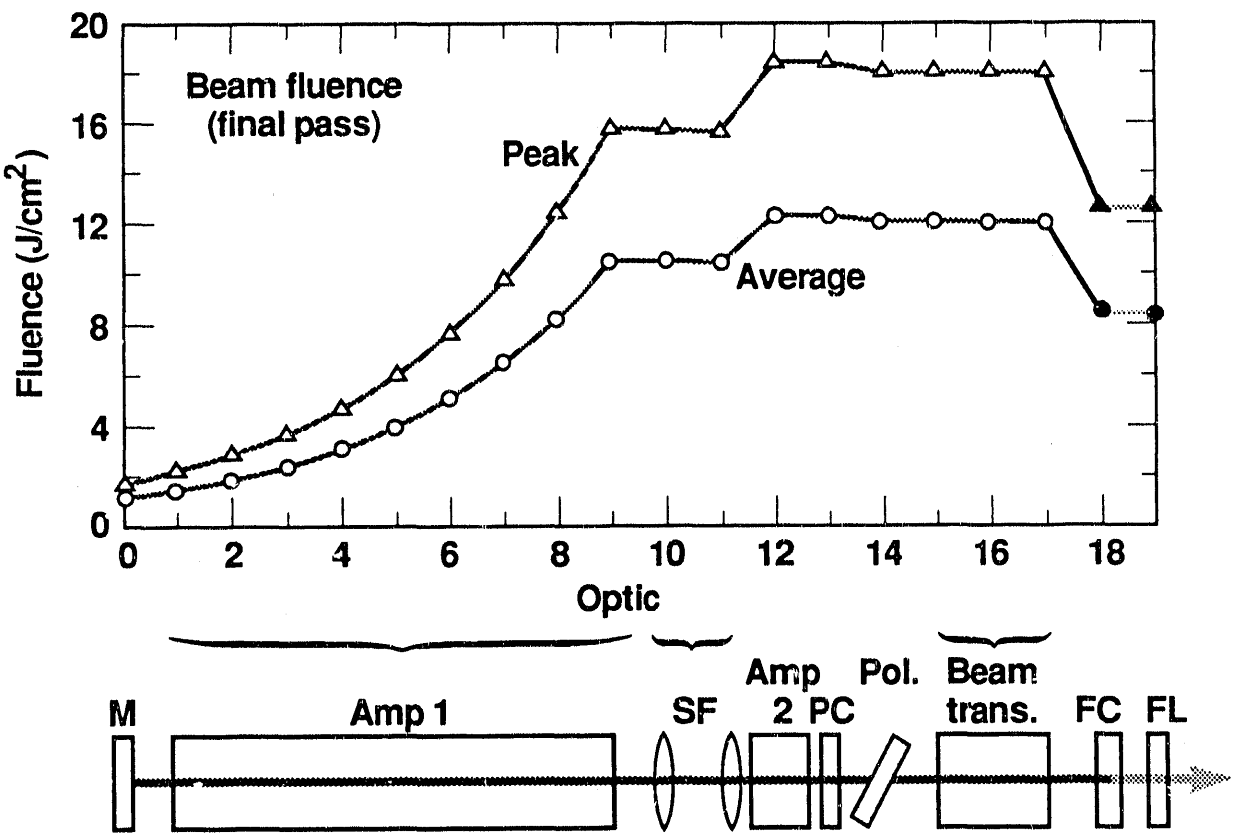

Fig. 3. Calculated fluence at various optic locations during the final pass through the resonator and subsequent beam propagation to the target. The open symbols represent 1.05 μm fluences and the solid symbols 0.35 μm fluences.

3. DAMAGE THRESHOLD REQUIREMENTS

Figure 3 shows the calculated laser fluence (at each optical component) during the final pass through resonator and transport to the target. The open symbols denote the fluence at 1.05 μm (3 ns) whereas the solid symbols are for 0.35 μm fluence. At the start of the final pass, the beam reflects off the end mirror (M1) at a peak fluence of about 2 J/cm^2. As the beam passes through the nine laser disks (abscissa labels 1 to 9) in the first amplifier (Amp1) the peak fluence increases to a value of about 16 J/cm^2. The fluence remains nearly constant as the beam passes through the > 99% transmissive 1-to-1- magnification spatial filter (SF) into Amplifier 2 (Amp2). The final amplifier boosts the output fluence to the maximum value of almost 18 J/cm^2. There is some slight drop in 1.05 μm fluence due to transmission losses through the deuterated KDP in the Pockels cell. Assuming Nova-like beam transport optics (i.e., > 99% transmission) the fluence remains nearly 18 J/cm^2 until frequency conversion. Assuming 70% conversion efficiency (as demonstrated using the present Nova laser) the peak 3ω output is about 12-13 J/cm^2 (3 ns).

The results in Fig. 3 were calculated using computer codes written to model the laser performance and validated by comparison with data from the present Nova system. The performance parameters that are modeled include, among others, the energy storage and extraction, beam propagation and frequency conversion.

To account for the spatial intensity variation in the laser beam we show both the peak and average fluence in Fig. 3. Based on both code calculations and data from Nova, the peak-to-average beam modulation is roughly 1.5-to-1. This corresponds to a damage threshold requirement of about 18 J/cm^2 at 1.05 μm and 12 J/cm^2 at 0.35 μm (3 ns).

4. DAMAGE THRESHOLDS OF IMPROVED OPTICAL MATERIAL

The 1.5-2 MJ solid-state laser shown in Fig. 1 requires optical materials having high damage thresholds; these include:

(at 1054 nm)
- bulk laser glass (free of Pt-inclusions)
- bare, polished surfaces
- bulk KDP and KD*P
- multi-layer dielectric coatings (polarizers and high reflectors)
- anti-reflection (AR) coatings

(at 351 nm)
- bulk KDP
- polished surfaces
- AR coatings

In many cases, these optical materials must have substantially higher damage thresholds than those available when the present Nova laser system was built (1980-1985). As a result, we have spent significant effort on improving most, if not all, of these materials. In the sections that follow we discuss the results from damage tests on these improved materials. The damage results are summarized in a set of "engineering" pulse-length-scaling relationships that are used in the design calculations of the megajoule laser.

All damage thresholds reported here have been measured using methods and systems previously described.[2] The vast majority of the measurements have been made using the same or nearly identical damage-test systems. In brief, the damage tests are carried out using the output from a commercial Nd:YAG laser directed through an attenuator and long focal-length lens (2-3 m) onto the test sample. The attenuator is used to vary the test fluence. The sample is located in a near-field region where the beam diameter is generally at least 1 mm in diameter (1/e^2). The test sample is examined both before and after laser irradiation using 100x Nomarski microscopy; we define damage as any observed change in the sample under these viewing conditions. The beam profile and energy are recorded using a calorimeter and video camera as described in reference 2. The fluence profile of the beam is then calculated using a commercially available software package.

4.1 Bulk laser glass

One of the major damage problems experienced during activation of the present Nova laser system (and an on-going problem for many years) was damage due to platinum inclusions in the laser glass.[3,4] These inclusions originate from the crucibles used to melt the glass. Although the inclusions are microscopic in size (typically 5-10 μm), upon laser irradiation at high fluences they produce fractures in the laser glass that can grow to as much as several millimeters in size. Damage measurements by Gonzales and Milam[5] on Pt-inclusions in phosphate laser glass showed that the damage threshold scales with pulse length as

$$D_t = 2.2\,\tau^{0.3}$$

where D_t is the damage threshold (J/cm^2) and τ is the pulselength (ns). Model calculations of inclusion damage agree well with the experimental results.[6] This damage threshold (at 3 ns) is shown in Fig. 4 relative to the design fluence in the phosphate laser glass disks for the 1.5-2 MJ Nova Upgrade laser. The fluence is for normal incidence and has been corrected for the fact that laser disks sit at Brewster's angle. Notice that for the current laser design nearly 60% of the laser disks see fluences above the Pt-inclusion damage threshold. Therefore the laser glass must be essentially free of platinum inclusions.

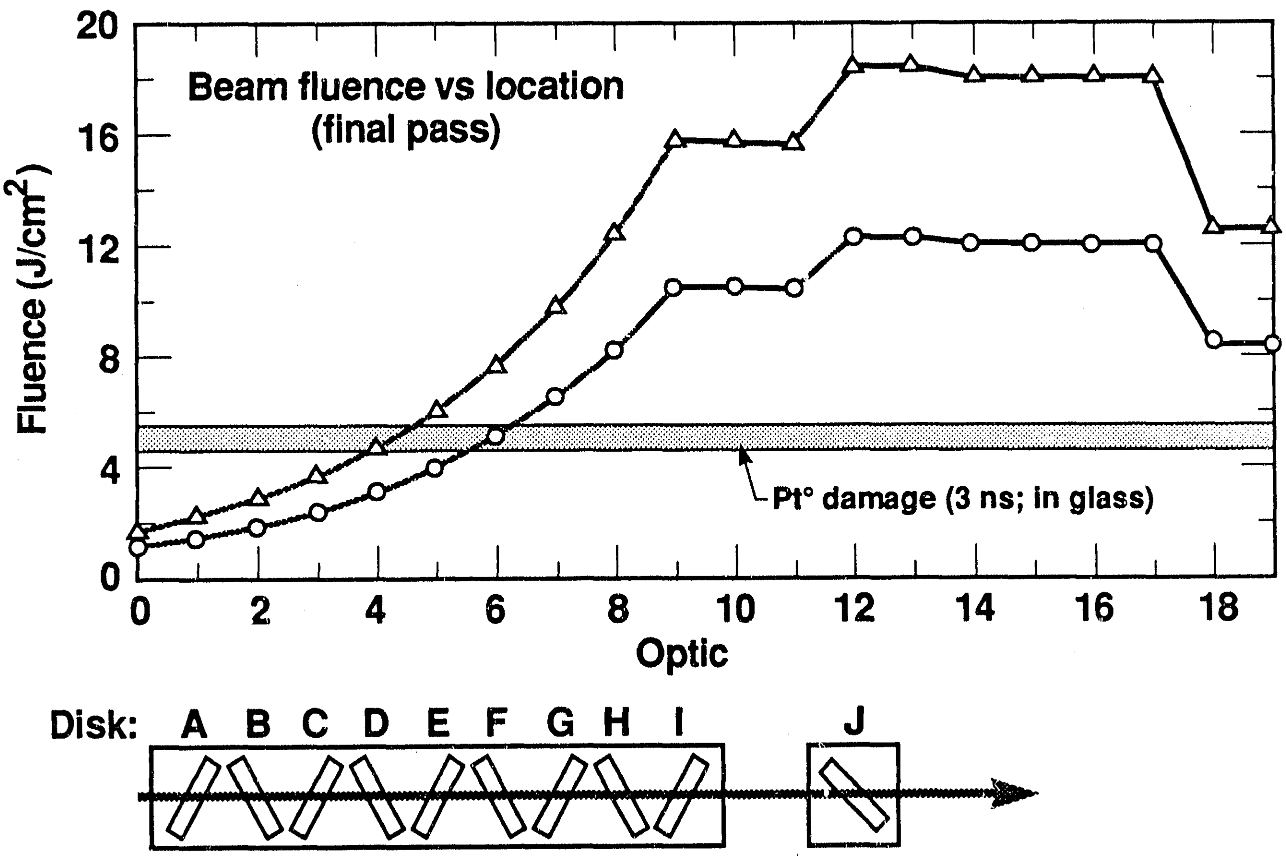

Fig. 4. Calculated fluence at 1.054 μm (3 ns) through the various Nd:phosphate glass laser disks versus location in the Nova Upgrade beam path. The shaded band represents the limiting fluence for damage due to platinum inclusions.

Working jointly with Schott Glass Technologies, Inc. and Hoya Optics, Inc. we have successfully developed a method to produce phosphate laser glass that is nearly free of Pt-inclusions.[7] The process is unique to phosphate glasses and is largely attributable to the solubility of platinum in phosphate-based glass compositions. By melting the glass under highly oxidizing conditions it is possible to enhance the rate of Pt dissolution and thereby dissolve Pt-inclusions that are present in the glass. In addition, we have developed other methods that substantially reduce the introduction of Pt-inclusions into the glass in the first place.[7] The dissolved (ionic) Pt absorbs in the UV thus does not interfere either with the optical pumping or the 1.05 µm transmission of the laser glass.

Using this new glass melting technology, all of the laser disks on the current Nova system have been replaced. Results from 100% damage testing of the laser glass disks showed that the Pt-inclusion density has been reduced approximately 1000-fold from roughly 100/liter in the original Nova glass to about 0.07/liter in the new glass. Approximately 60% of the 7-liter laser glass disks had no platinum inclusions (Fig. 5). After 2-3 years of full-power operation we have seen no evidence of Pt inclusion damage on the present Nova laser. Based on these improvements in the laser glass we anticipate no Pt-inclusion damage problem for the Nova Upgrade.

With the elimination of the Pt-inclusion problem, the laser disks damage threshold is now limited by the surface damage threshold. This is discussed in the next section.

4.2 Bare, polished surfaces

In general, bare surfaces of optical dielectric materials have lower damage thresholds than the corresponding bulk phase, provided inclusions and other damaging defects have been eliminated. Consequently, a major concern in the design and construction of any high-peak-power laser is the damage threshold for the various finished surfaces. In addition, most bare substrate surfaces are coated, the major exception being the laser glass that is mounted at Brewster's angle in the amplifiers (we discuss coatings in a later section).

Last year we reported[8] damage thresholds for a number of bare polished glass surfaces. These data represent an accumulation of measurements carried out at LLNL over the past ten years.[8-11] The glasses that were

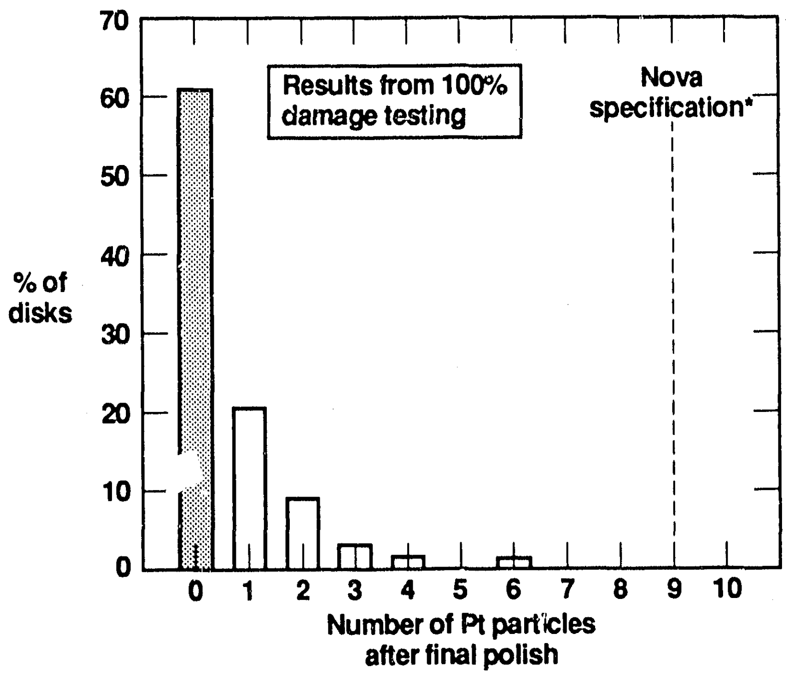

Fig. 5. Percent of the 300 Nova phosphate glass disks having a given number of Pt-inclusions. These results are based on 100% damage testing. Each disk contains about 7 liters of glass. All the disks exceed the current Nova production specification of less than 9 inclusions per disk.

tested have approximately the same refractive index and thus it is valid to compare damage-test results between the various glass types (Fig. 6). In general, various glass surfaces tested at the same pulse length appear to have approximately the same damage threshold. Moreover the pulse length scaling ($\tau^{0.4}$) is also approximately the same. The glass compositions include silicates (BK-7, ULE, CVD, fused silica), phosphates (LG-750), and fluorophosphates. To a first approximation there is little if any effect of composition.

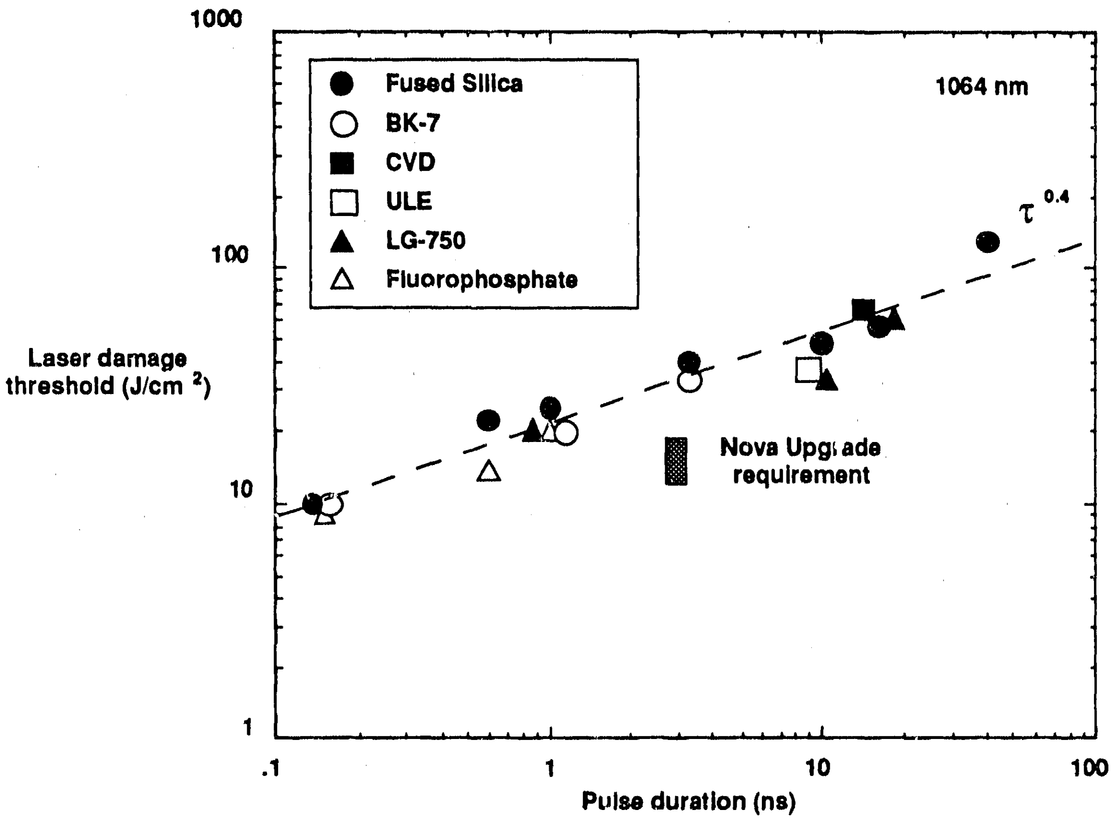

Fig. 6. Damage thresholds at 1064 nm vs. pulse length for bare polished surfaces of various glass types. BK-7, CVD and ULE are silicate glasses, and LG-750 a commercial phosphate laser glass. The cross-hatched region shows the Nova Upgrade threshold requirement at 3 ns.

The shaded region in Fig. 6 shows the threshold requirement for the Nova Upgrade; it is clear that the current glass finishing technology is adequate to meet this requirement.

Fused silica is used for all the transmissive optics of the Nova Upgrade design (aside from the laser disks and KDP). This primarily includes lenses, windows, polarizer substrates, and debris shields. Figure 7 summarizes the damage threshold measurements on polished, bare, fused silica at both 355 and 1064 nm for a range of pulse lengths. The 355-nm thresholds are about a factor of 2-3 lower than that at 1064 nm based on the data set shown here. The 351-nm data represent an average of more than 5 tests at each pulse length with a range of about ± 15 to 20%.

The fused silica was polished using the standard but proprietary "super polish" techniques employed by such companies as, for example, Eastman Kodak Co. and Zygo Corporation. Based on the results in Fig. 7, the "super polished" fused silica surfaces meet both the 1ω and 3ω damage threshold requirements for the Nova Upgrade laser.

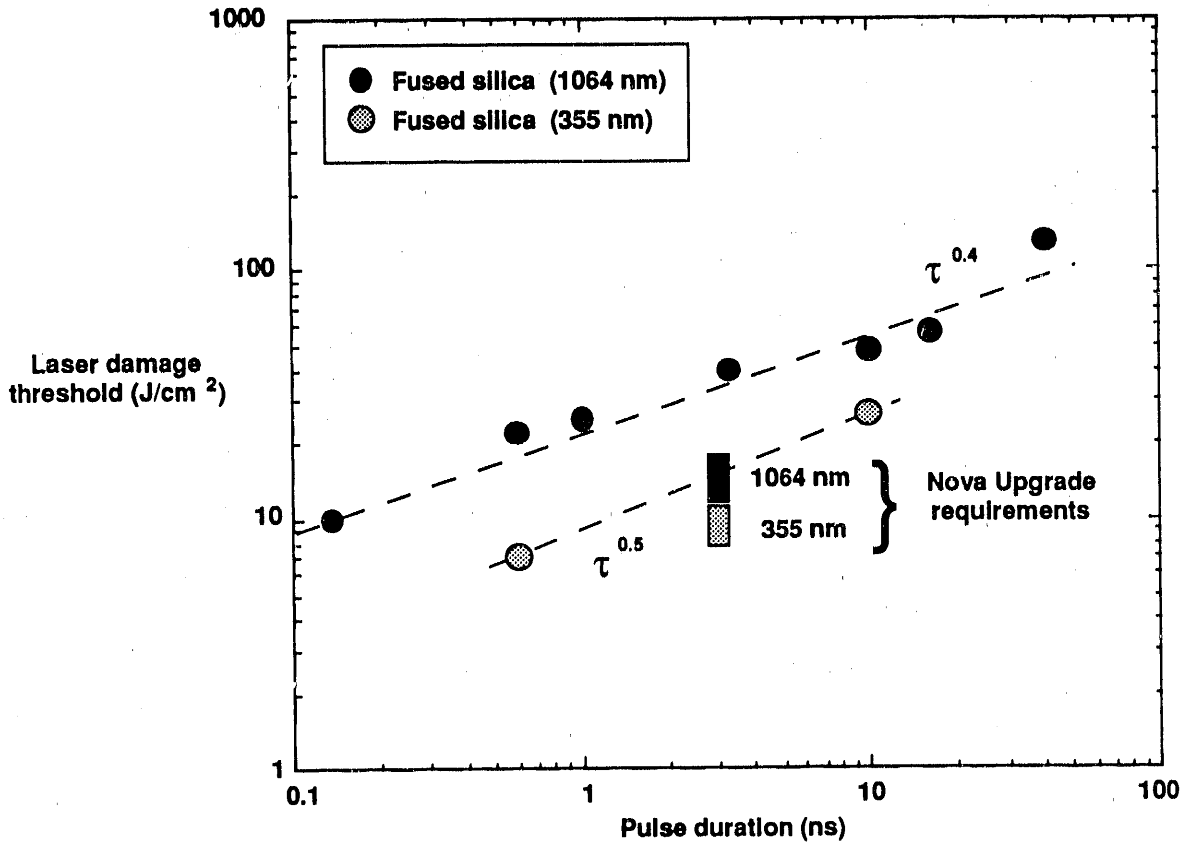

Fig. 7. Damage threshold vs. pulse length for polished fused silica surfaces at 1064 and 355 nm vs. pulse length. The dashed lines represent approximate pulse length scaling.

4.3 Anti-reflection coating

Thomas et al.,[12-14] have developed a single layer sol-gel AR coating that has a high damage threshold at both 1.06 and 0.35 µm. The sol-gel coating consists of SiO_2 particles packed in a roughly 50% porous structure giving a refractive index of 1.22-1.25. The SiO_2 particles are about 20 nm in diameter.

Results from damage tests on these coatings at both 1.06 and 0.35 µm are shown in Fig. 8. Surprisingly the damage thresholds are nearly equivalent for the two wavelengths. This may simply be due to the fact that the 1.06-µm data are from several years ago[12] and in the past few years significant improvements have been made in both the coating preparation and the deposition process. This is supported by the recent data at 1.06 µm indicated in Fig. 8 with the upward arrow. These data are from coatings recently prepared using the improved process and the samples were not able to be damaged at the fluences indicated. In addition, we use the SiO_2 sol-gel AR coatings on the present Nova system and have not seen coating damage even when the laser fluence has exceeded (by 10-15%) the damage thresholds shown in Fig. 8. The AR damage threshold requirements for the Nova Upgrade laser are shown in Fig. 8 by the shaded regions at 3 ns.

In addition to the sol-gel AR coatings we have also recently investigated AR coatings made using a fluorocarbon polymer. The damage thresholds for the fluorocarbon coatings exceeds that of the sol-gel at both 1.06 and 0.35 µm and thus is a potential replacement. This work is reported separately at this Symposium.[15]

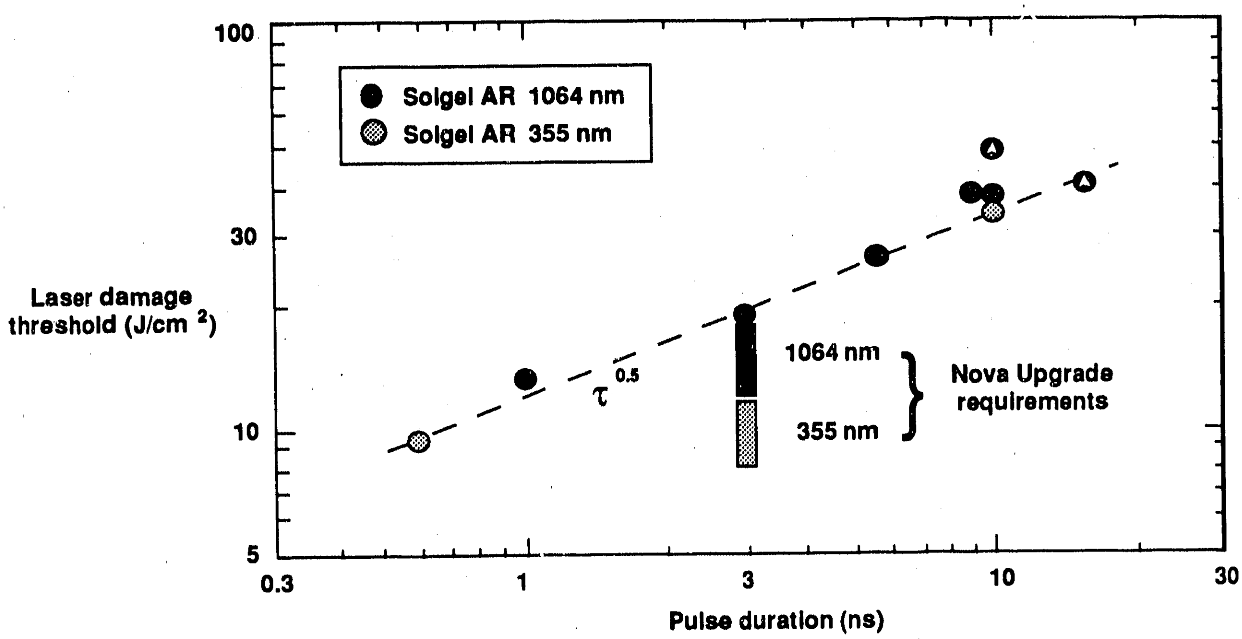

Fig. 8. Damage threshold vs. pulse length at 1.06 and 0.35 μm for single layer sol-gel AR coatings on fused silica. The shaded regions at 3 ns show the damage requirements for the Nova Upgrade laser (see Fig. 3).

4.4 Multi-layer HR and polarizer coatings

In the past, multi-layer dielectric coatings have been a weak point in most high-peak-power laser designs because of their low damage thresholds. Recent work by Kozlowski et al.[16-18] has shown that the damage threshold of multi-layer coatings can be substantially and permanently improved by first "conditioning" the films using low fluence irradiation. Conditioning has been observed in a number of optical materials, both bulk and thin films. Conditioning simply refers to the process of exposing the optic to small increments in laser fluence beginning at a fluence significantly below the single-shot damage threshold.

The work by Kozlowski et al.[16-18] has shown that HfO_2/SiO_2 multilayer films give the most consistent improvement with conditioning. These results are shown in Fig. 9 and compared with the required damage thresholds for the Nova Upgrade. In general, the conditioning produces about a 2- to 3-fold improvement in the damage threshold. It is clear that with conditioning the multilayer HR films can meet the Nova Upgrade design fluence.

Conditioning has also been observed for multi-layer dielectric film polarizers made using HfO_2/SiO_2.[8] The magnitude of the improvement (~ 0.5 to 5.0) varies much more than is observed for the case of HR coatings. The reason for the variability is not understood. Nevertheless the polarizers typically have damage thresholds for both p- and s-polarization greater than the required 18-20 J/cm^2 at 3-ns and 1064 nm.

Laser conditioning represents perhaps the greatest single practical improvement in thin-film damage thresholds in the past 10 years. Unfortunately, the mechanism for laser conditioning remains illusive. Recent work by Kozlowski et al.[18] and Schildback et al.[19] on the fundamental mechanism of conditioning are reported in these proceedings.

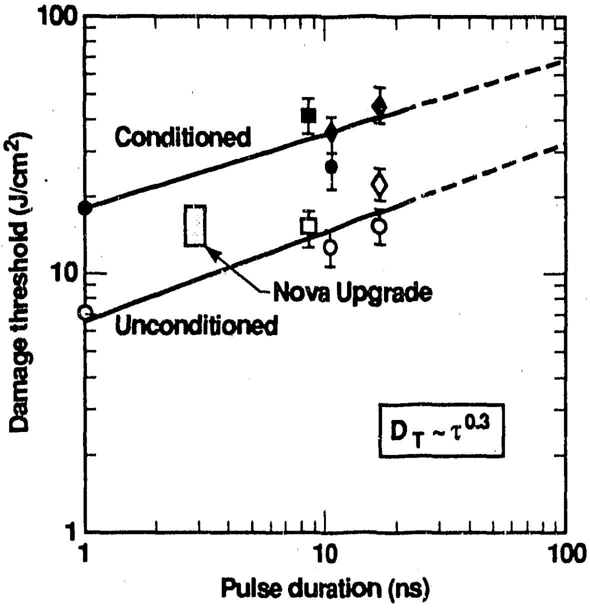

Fig. 9 Damage threshold at 1064 nm vs. pulse length for multilayer HfO2/SiO2 HR coatings. The thresholds scale with pulse length as approximately $\tau^{0.3}$. The shaded region represents the requirement for the Nova Upgrade.

4.5 Potassium Dihydrogen Phosphate (KDP)

KDP and the deuterated analogue, KD*P are the proposed materials for use in the Nova Upgrade frequency converter and Pockels cell, respectively. The Pockels cell sees only 1.06-µm radiation whereas the frequency converter must be damage resistant at 1.06, 0.53 and 0.35 µm. Although other nonlinear materials have better conversion efficiency and less angular sensitivity, KDP remains the material of choice primarily due to its relatively low cost and ease of growth to large sizes. KD*P is preferred over KDP for a Pockels cell material because of its 5- to 10-fold lower absorption loss at 1.06 µm and factor of 2 lower half-wave voltage. It has the same advantage as KDP in terms of growth to large sizes but is more costly because of the deuteration process.

The damage data presented in this section are for KDP only. This is because highly deuterated material (as would be used in the Pockels cell) has not been grown using this new growth process. Therefore we assume that the effects of the deuteration on the damage behavior is minimal.

Laser damage in KDP has been linked to contamination. The contamination includes soluble and insoluble, organic and inorganic material. Montgomery and Milanovich[20] have recently developed a KDP growth process that successfully removes contaminants by the combined use of UV/ozone treatment coupled with continuous-flow ultrafiltration. The use of different filter pore sizes showed that the highest damage thresholds could be obtained using the smallest (0.05 µm) pore size (Table 1).

To date damage threshold measurements have only been carried out at a pulse length of 10-ns. To scale to the lower 3-ns pulse length of the Nova Upgrade we assume a conservative $\tau^{1/2}$ scaling. This gives conditioned damage thresholds of 15-16 and 35 J/cm² at 355 and 1064 nm (3-ns), respectively for KDP prepared by the improved growth process. These are significantly greater than the required thresholds of 12 and 18 J/cm².

Table 1. Effect of growth solution filter pore size on damage threshold of KDP at 355 and 1064 nm (10-ns). Data are from Montgomery and Milanovich[20].

Filter pore size (μm)	Conditioned Damage Threshold (J/cm^2) 355 nm	1064 nm
> 0.2	—	18
0.2	22	37
0.05	29	> 64

5. SUMMARY

The results from the damage measurements given in the previous section are summarized in Table 2. They represent the current state-of-the-art for high damage threshold optical materials at 1.06 and 0.35 μm. The data are given in terms of a useful set of simple pulse-length-scaling relationships that can be used in laser design or determining safe laser operating limits. On the basis of these and other data we have designed a 1.5-2 MJ Nd:glass, solid state laser for use in achieving fusion ignition. In addition we use several of these relationships on a daily basis for selecting safe operating conditions on our current 120 kJ (1ω) and 50-70 kJ (3ω) Nova laser.

Table 2. Pulse-length scaling relationships for damage thresholds of various optical materials to be used on the 1-2 MJ Nova Upgrade.

	1.06 mm		0.351 mm	
Material	Damage Threshold (J/cm^2)*	Pulse Length Range (ns)	Damage Threshold (J/cm^2)*	Pulse Length Range (ns)
Fused silica (surface)	$22\,t_p^{0.4}$	0.1-55	$9\,t_p^{0.5}$	0.6-10
Laser glass (surface)	$22\,t_p^{0.4}$	1-16	N/A	—
HfO_2/SiO_2 multilayer coatings	$19\,t_p^{0.3}$	1-16	N/A	—
SiO_2 Sol-gel AR coating	$11\,t_p^{0.5}$	1-16	$10\,t_p^{0.4}$	0.6-10
KDP (bulk)	$20\,t_p^{0.5}$**	10	$9\,t_p^{0.5}$**	10

* t_p = pulse length (ns)
** assumes $t_p^{0.5}$; extrapolation valid only for $t_p < 10$-ns

6. REFERENCES

1. LLNL ICF Program, "Nova Upgrade Campaign", Vol. 1 and 2, LLNL technical reports UCRL-TB-104287 and 104288, Aug. 29, 1990.

2. A. J. Morgan, F. Rainer, F. P. De Marco, R. P. Gonzales, M. R. Kozlowski, and M. C. Staggs, "Expanded Damage Test Facilities at LLNL", in Laser Induced Damage in Optical Materials: 1989, NIST Special Publication 801, SPIE Vol. 1438 (Oct. 1990), p. 47.

3. D. Milam, C. W. Hatcher, and J. H. Campbell, "Platinum Particles in the Nd:doped Disks of Phosphate Glass in the Nova Laser", in Laser Induced Damage in Optical Materials, NBS Special Publ., 746 (1988) p. 120.

4. Fundamentals of Damage in Laser Glass, National Materials Advisory Board, Division of Engineering, National Research Council, Washington, DC, NMAB-271 (1970).

5. R. P. Gonzales and D. Milam, "Evolution During Multiple-Shot Irradiation of Damage Surrounding Isolated Platinum Inclusions in Phosphate Laser Glass", in Laser Induced Damage in Optical Materials, NBS Spec. Publ. 746, (October 1985), p. 128.

6. J. H. Pitts, "Modeling Laser Damage Caused by Platinum Inclusions in Laser Glass", in Laser Induced Damage in Optical Materials, NBS Spec. Publ. 746, (October 1985), p. 537.

7. J. H. Campbell, E. P. Wallerstein, J. S. Hayden, D. Warrington, A. J. Marker, "Elimination of Platinum Inclusions in Phosphate Laser Glasses", LLNL report UCRL-53932 (1989).

8. F. Rainer, R. M. Brusasco, J. H. Campbell, F. P. DeMarco, R. P. Gonzales, M. R. Kozlowski, F. P. Milanovich, A. J. Morgan, M. C. Staggs, I. M. Thomas, S. P. Velsko, and C. R. Wolfe, "Damage Measurements on Optical Materials for use in High-Peak-Power Lasers", in Laser Induced Damage in Optical Materials: 1989, NIST Special Publication 801, SPIE Vol. 1438, Oct. 1990, p. 74.

9. F. Rainer, R. P. Gonzales and A. J. Morgan, "Laser Damage Database at 1064 nm", in Laser Induced Damage in Optical Materials: 1989, NIST Special Publication 801, SPIE Vol. 1438 (Oct. 1990), p. 58..

10. S. E. Stokowski, D. Milam and M. J. Weber, "Laser Induced Damage in Fluoride Glasses: A Status Report", in Laser Induced Damage in Optical Materials, NBS Spec. Publ. 541, (October 1978), p. 99.

11. D. Milam, "1064-nm Laser Damage Thresholds of Polished Glass Surfaces as a Function of Pulse Duration and Surface Roughness", in Laser Induced Damage in Optical Materials, NBS Spec. Publ. 541, (October 1978), p. 164.

12. I. M. Thomas, "High Laser Damage Threshold Porous Silica Antireflective Coating Appl. Opt 25, (1986), p. 1481.

13. I. M. Thomas, J. G. Wilder, W. H. Lowdermilk and M. C. Staggs, "High Damage Threshold Porous Silica AR Coatings", in Laser Induced Damage in Optical Materials: 1985, NBS Spec. Publ. 727, (1986), p. 164.

14. D. Milam, I. M. Thomas, C. Weinzapfel and J. G. Wilder, "Pulse Duration Dependence on 1064-nm Laser Damage Thresholds of Porous Silica Antireflective Coatings on Fused Silica Substrates", in Laser Induced Damage in Optical Materials: 1985, NBS Spec. Publ. 727, (1986), p. 211.

15. I. M. Thomas and J. H. Campbell, "A Novel Perfluorinated AR and Protective Coating for KDP and Other Optical Materials", in Laser Induced Damage in Optical Materials: 1990, (these proceedings).

16. M. R. Kozlowski, C. R. Wolfe, M. C. Staggs and J. H. Campbell, "Large Area Laser Conditioning of Dielectric Thin Film Mirrors", in Laser Induced Damage in Optical Materials: 1989, NBS Spec. Publ. 801, (Oct. 1990), p. 376.

17. C. R. Wolfe, M. R. Kozlowski, J. H. Campbell, F. Rainer, A. J. Morgan and R. P. Gonzales, "Laser Conditioning of Optical Thin Films", in Laser Induced Damage in Optical Materials: 1989, NBS Spec. Publ. 801, (Oct. 1990), p. 360.

18. M. R. Kozlowski, M. C. Staggs, F. Rainer and J. H. Stathis, "Laser Conditioning and Electronic Defects of HfO_2 and SiO_2 Thin Films", in Laser Induced Damage in Optical Materials: 1990, (these proceedings).

19. M. Schildbach, L. L. Chase and A. V. Hamza, "Investigation of Laser Conditioning of Multilayer Coatings by Laser-Induced Neutral Emission", in Laser Induced Damage in Optical Materials: 1990, (these proceedings).

20. K. Montgomery and F. Milanovich, "High-Laser-Damage-Threshold KDP Crystals", J. Appl. Phys. (in press).

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