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LASER-INDUCED DAMAGE MEASUREMENTS WITH 266-nm PULSES†

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The results of a survey of laser-induced damage thresholds for optical components at 266 nm are reported. The thresholds were measured at two pulse durations--0.150 ns and 1.0 ns. The 30 samples tested include four commercial dielectric reflectors, three metallic reflectors, two anti-reflection films, a series of eight half-wave oxide and fluoride films, and twelve bare surfaces (fluoride crystals, silica, sapphire, BK-7 glass, CD*A and KDP). The 266-nm pulses were obtained by frequency-quadrupling a Nd:YAG, glass laser. Equivalent plane imagery and calorimetry were used to measure the peak fluence of each of the UV pulses with an accuracy of ± 15%; the uncertainty in the threshold determinations is typically ±30%.

Key words: Damage thresholds; laser damage; pulsewidth dependence, picosecond pulses; UV lasers.

1. Introduction

There is currently an increasing interest in the application of visible and ultraviolet lasers to inertial confinement fusion research. Fusion target experiments utilizing the second- and third-harmonic wavelengths of the Argus Laser are currently underway or in planning at Lawrence Livermore Laboratory. Fusion experiments at 266 nm on Argus are probable. A prototype KrF-CH_4 Raman-compressed laser system is also being developed which will involve two UV wavelengths - 268 and 248 nm. There is a clear need for a broad data base of the optical properties of materials that are useful near 266 nm.

In response to this need we have performed a survey of damage thresholds at 266 nm at pulse durations of about 100 psec and about 700 psec of some thirty samples comprising a representative set of the materials and coatings currently available. This subnanosecond data complements the 22 nsec data made available last year [1][1]. The thin films tested include four total reflector films, three metallic reflectors, two anti-reflection films, and a series of eight half-wave fluoride and oxide films. The twelve tested bare surfaces include many important UV window materials -alkali-fluoride and alkaline earth-fluoride single crystals, hot-forged lithium fluoride, fused silica, sapphire - and also BK-7 glass, potassium dihydrogen phosphate (KDP) and cesium dideuterium arsenate (CD*A). It must be noted that the samples tested in this survey have not been specifically developed to have high damage thresholds at 266 nm. They are instead representative of current off-the-shelf components.

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[1]Figures in brackets indicate the literature references at the end of this paper.

2. Experimental

The laser used for the 100 psec pulse duration measurements consisted of a dye mode-locked Nd:YAG oscillator, two Nd:YAG and two Nd:glass amplifiers. It has been used in the past for short-pulse 1064-nm damage studies [2]. The 700 psec data were obtained after the installation of an actively mode-locked and Q-switched oscillator which provides pulses with durations ranging from 100 psec to 1.2 nsec [3]. The average pulse duration for the dye mode-locked oscillator was 150 psec, as determined by streak camera photography. There were of course significant fluctuations in the pulse duration, on the order of ± 30 psec, due to the statistical nature of the dye. In this experiment we do not at present have the capability to measure a subnanosecond pulse duration in the UV, so the figure 100 psec is simply our best estimate of the average fourth harmonic pulse length, which we believe to be accurate to within ± 20 psec. The longer UV pulses were obtained from 1064 nm pulses of 1.02 nsec duration from the actively mode-locked oscillator. The accuracy of the 1064 nm pulse duration figure is better than 5%, but again the UV pulse duration of 700 psec is estimated, and has an uncertainty of ~ ±50 psec.

The energy of the 1064 nm, linearly polarized laser pulse is determined by a calorimeter sampling the beam via an uncoated BK-7 beamsplitter (fig.1). Second harmonic generation is done by an angle-tuned KD*P crystal (Type I) with conversion efficiency as high as 80% for 100 psec pulses. For some of the work we used a temperature-tuned CD*A crystal with which we obtained similarly high conversion efficiency. The remaining 1064 nm light after the SHG cell is spatially separated from the second harmonic by a prism set approximately at minimum deviation. The 532 nm beam is similarly sampled for energy content via a BK-7 beamsplitter; it then enters an angle-tuned KDP or temperature-tuned ADP crystal for fourth harmonic generation. The maximum conversion efficiency at this stage was on the order of 30%. The 532 nm light remaining after the cell is spatially separated by a quartz prism.

The 266 nm optical circuit is shown in figure 2. The beam is focused by a 2 meter focal length lens; the focal plane occurs at approximately 40 cm *beyond* the front surface of the sample. After the lens, the beam is split into two parts by a partially reflecting mirror, with 48% of the energy going to an absorbing glass calorimeter (GG19 glass). A second bare beam-splitter directs energy to a vidicon camera and to a multiple-exposure mirror. The off-set angle of the beamsplitters was 3 degrees. A multiple-exposure photograph of each shot is taken with Plus-X film in a plane optically-equivalent to the plane of the front surface of the sample. The laser spot size at the sample plane was approximately 1.0 mm in diameter.

All the samples were irradiated at about 5° from normal incidence, one shot per site. The damage used was the existence of front surface alteration as determined by visual inspection immediately after the shot or by Nomarski microscopy afterward.

Our standard procedure was to fire enough shots to reduce the threshold uncertainty to ± 10% in 266 nm pulse energy. When the beam profile data were analyzed, there was found to be a significant variation in the beam shape, and particularly in the effective area of the beam, from shot to shot. In some cases this variation produced a narrowing of the uncertainty of the peak fluence value at threshold, but in others it increased the uncertainty. Generally the fluence uncertainties are greater for the short pulses, since these were obtained from a dye mode-locked laser instead of the very amplitude-stable AMQO

The multiple-exposure images of the beam were analyzed by the same techniques used for the 1064 nm laser damage experiments at their laboratory [4]. Experience has shown that the combination of the very stable absorbing glass calorimeter and our photocalibration codes yield peak fluence values accurate to within ± 10%.

3. *Results and Discussion*

The damage thresholds for the bare surfaces tested are shown in table 1. There is variation of about one order of magnitude for the group. The first eight samples listed are a series prepared in 1976 similarly and for intended damage testing at 1.06 microns. There is relatively little variation in thresholds for the series, the average being about 1 J/cm^2 at 100 psec and 2-3 J/cm^2 at 700 psec. We hypothesize that the general clustering of these thresholds may be due more to the surface finishing techniques than to any intrinsic behavior.

The remaining samples on the table are from various sources. The silica and BK-7 in particular are substrates intended for coating damage studies at 1.06 microns. The silica sample was particularly damage resistant, at least in a relative sense. The polishing techniques used for this sample, although developed for 1.06 micron, are somewhat more advanced than the simple hand polishing used for our fluoride samples. It is thus conceivable that with improved surface preparation the flouride damage thresholds might be considerably higher.

In light of the widespread application of silica optics in UV laser systems, it is encouraging to note that the silica threshold is as high as it is.

An unexpected result is that, at least for the short pulses, the BK-7 threshold was almost as high as the silica and higher than the fluorides, in spite of its high bulk absorption coefficient of about 6 per cm at 266 nm. We interpret this result as further evidence that surface properties are to a large extent masking the bulk properties of these samples.

The KDP sample threshold of about 6.5 J/cm^2 at 700 psec is a relatively high threshold and is encouraging given the application of KDP in second harmonic generation from 532 nm to 266 nm.

The bottom two LiF samples in table 1 were also damage tested at 1.06 microns by Dave Milam <u>et. al</u>. at Lawrence Livermore Laboratory. We found essentially no difference between the single-crystal and hot-forged LiF; the same was found at 1.06 microns. Although 1.06 micron damage thresholds for these samples were rather disappointingly low, at 266 nm they were the highest thresholds measured.

We tested eight half-wave layers of fluorides and oxides on silica substrates, as shown in table 2. With the exception of the yttrium oxide, the thresholds are clustered very closely together and are essentially the same at both pulse durations, and are lower than either the AR films or the high reflector films on dielectric substrates. Given the clustering and the error bars of the measurements, it is tenuous to assign any systematic correlation between the thresholds and bulk material properties such as band gap or index of refraction.

The relative magnitudes of the damage thresholds within the set correlate in a qualitative way with the thresholds for quarter-wave layers of the same materials for 22 nsec pulses reported at this conference last year by Newnam and Gill [1].

We also tested several total reflector and anti-reflective films. The thresholds are listed in table 3. We identify the samples only by a letter because in most cases the coating designs are proprietary, and we consider it to be ill-advised to try to distinguish between designs based only on this limited sampling. The dielectric reflectors average about 1.0 J/cm^2 at 100 psec and 1.8 J/cm^2 at 700 psec.

The AR film thresholds were slightly higher than the reflectors at 100 psec, in contrast to the situation at one micron, in which AR films are typically a factor two weaker than high reflectors. For the 700 psec duration, the AR's were on the average about as strong as the HR's. The metallic reflectors exhibited much lower thresholds than the dielectric reflectors. Finally, we turn to the pulse duration dependence.

The bare surface data are shown plotted versus pulse length in figure 3. The clustering of the fluoride samples is evident. The average pulse length is about $\tau^{0.5}$. The pulse length dependence of the single-layer films is shown in figure 4. The exponential factor of the pulse length dependence averages out to nearly zero. The pulse length dependence of the dielectric reflectors is shown in figure 5. The dependence is between about τ^{0} and $\tau^{0.5}$.

4. Conclusions

Because only one sample of each specific type was tested, minor distinctions between materials should not be made on the basis of this data. Our conclusions are that 100 psec the current generally available threshold is about 1 J/cm^2 with a few important exceptions (silica and KDP). At 700 psec, 2-3 J/cm^2 damage thresholds are to be expected at this time, again with the exceptions of silica, KDP, and lithium fluoride.

5. Acknowledgements

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References

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Table 1. Bare surface damage thresholds (J/cm^2) for 266 nm.

Material	Fluence (J/cm^2) 100 psec	700 psec
LiF	0.60 ± 0.39	
BaF_2	0.50 ± 0.13	2.06 ± 0.72
SrF_2	0.47 ± 0.12	1.54 ± 0.51
CaF_2	0.65 ± 0.15	2.37 ± 0.83
MgF_2	1.32 ± 0.32	2.69 ± 0.41
LaF_3	1.80 ± 0.80	3.10 ± 0.70
Al_2O_3	0.75 ± 0.26	
Silica	3.00 ± 0.96	10.00 ± 3.00
BK-7	2.90 ± 0.84	1.94 ± 0.71
CD*A	1.10 ± 0.27	
KDP	>(1.70 ± 0.25)	6.48 ± 1.40
LiF		14.30 ± 2.50
LiF (hot forged)		14.40 ± 2.50

Table 2. Damage thresholds (J/cm^2) for single-layer films ($\lambda/2$ at 266 nm) at 266 nm.

	100 psec	700 psec
Y_2O_3	0.10 ± 0.035	0.26 ± 0.04
ZrO_2	0.51 ± 0.26	0.62 ± 0.14
SiO_2	0.72 ± 0.26	0.44 ± 0.13
AlF_3	0.65 ± 0.15	0.50 ± 0.07
LaF_3	0.70 ± 0.21	0.74 ± 0.20
MgF_2	0.80 ± 0.32	1.24 ± 0.33
P1	0.95 ± 0.25	0.66 ± 0.10
P2	0.85 ± 0.23	---

Table 3. Film damage thresholds (J/cm^2) for 266 nm pulses.

Dielectric reflectors	100 psec	700 psec
a	1.30 ± 0.25	3.85 ± 1.1
b	0.50 ± 0.12	0.405 ± 0.085
c	0.92 ± 0.20	1.86 ± 0.55
d	0.85 ± 0.23	1.54 ± 0.26
e	---	1.43 ± 0.26
Metallic reflectors		
a	0.23 ± 0.06	0.60 ± 0.21
b	0.10 ± 0.04	0.066 ± 0.013
c	0.13 ± 0.05	0.045 ± 0.017
AR films		
a	1.10 ± 0.27	1.20 ± 0.12
b	1.60 ± 0.54	0.72 ± 0.16

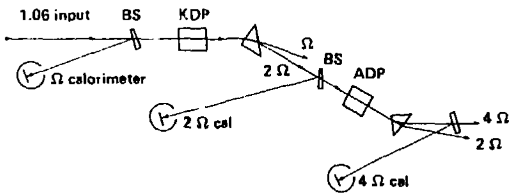

Fig. 1 Fourth-harmonic generation optics

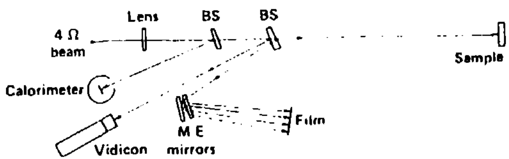

Fig. 2   266-nm damage experimental apparatus

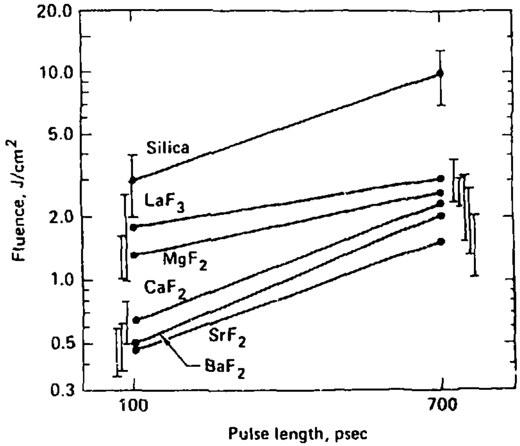

Fig. 3 Pulse-length dependence of damage thresholds for bare surfaces

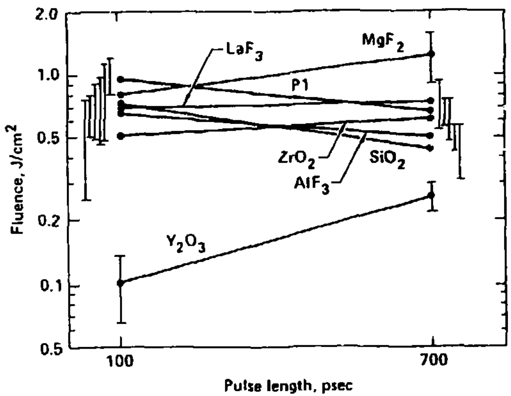

Fig. 4 Pulse-length dependence of damage thresholds for single-layer films

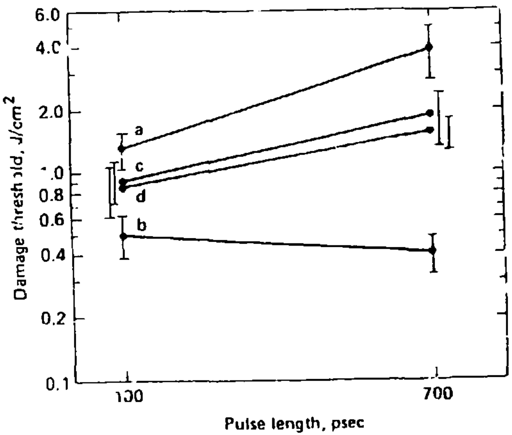

Fig. 5 Pulse-length dependence of damage thresholds for dielectric reflectors