Anti Reflection Coating Damage Threshold Dependence on Substrate Material

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ABSTRACT

This paper presents a study of the laser damage threshold (LDT) of ion beam sputtered (IBS) Ta_2O_5/SiO_2 AR coated and uncoated samples ranging from low grade plate glass through neutral density glass to laser grade fused silica substrates. We find that the damage threshold varies by just over a factor of 3 from 9 to 33 J/cm^2 for 1064nm pulsed laser light with 20ns pulse length and 20 Hz repetition rate. The damage threshold of the uncoated samples ranges from 80 J/cm^2 to greater than 200 J/cm^2. We have estimated the single pulse temperature increase in the uncoated neutral density glasses to be as much as 400-500^{o}C at the damage fluence. This is unexpected as multiple pulse exposure would rapidly bring the glass up to melting temperatures. A possible explanation is saturation of the absorption at high fluence levels resulting in lower temperature than estimated. We conclude that the absorption level in the IBS coating is too low to give a significant contribution to the LDT of the AR coated samples.

Keywords: Laser Damage, Anti-reflective coatings, Ion Beam Sputtering, Neutral Density Glass

1. INTRODUCTION

The Laser damage Threshold (LDT) of coated optics is governed by the surface and material properties of the substrate as well as the properties of the optical coatings [1][2][3]. However, it is not always clear which of these factors is the most important in limiting the LDT of an optical component. We have investigated the LDT of both uncoated and coated substrates with a broad range of surface quality and absorption levels. For anti-reflection (AR) coatings all the light transmits through the coating and the coating-substrate interface as opposed to high-reflection (HR) coatings where the light gets reflected before reaching the substrate-coating interface. For this study, a simple IBS AR coating was selected to enhance the effect of the substrate properties.

1.1 Surface properties

Several surface properties can have an impact on LDT. The most obvious is cosmetic defects such as digs and scratches either left over from the polishing process or generated during handling. These defects can initiate laser damage by locally enhancing the electromagnetic field or by acting as absorption centers. An optimized polishing process can produce laser grade surfaces with no defects according to the standard MIL inspection procedures (for example MIL-PRF-13830B). State of the art polishing techniques can result in surfaces where defects are hard to detect even with sensitive optical methods such as dark field Nomarski microscopy.

Subsurface damage from the polishing process can similarly lead to a lower LDT. Subsurface damage originates from the polishing process as larger size polishing particles are used in the initial shaping of the substrate surface [4]. This process step can lead to fractures propagating into the substrate surface. The subsequent polishing with finer and finer polishing particles is designed to remove the damage from the previous step. However, it is difficult to directly observe subsurface damage making it hard to ensure that the final optic is free from it.

Surface micro roughness is another factor that can influence the LDT. A rough surface can result in local electromagnetic field enhancement which reduces the LDT. The roughness is typically measured using a phase sensing Nomarski microscope setup or with a small aperture white light interferometer. A typical polishing process will result in a surface roughness on standard substrate materials such as BK7 and fused silica, in the 5-10 Angstrom rms range. A so called super polish process can further be applied to get the surface roughness down below 1 Angstrom rms.

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Surface contamination can also influence the LDT. Contaminations might originate from residues from the polishing process or from storage and cleaning processes that the optic undergoes before coating. Some substrate materials have intrinsic properties that contribute to surface contamination such as being hygroscopic or porous.

1.2 Bulk material properties

In addition to the substrate surface properties, bulk properties of the substrate can also limit the LDT of the optic. Most high power laser applications use high grade fused silica substrates with very low bulk absorption, inclusions and defects. However, some laser crystal materials and optical glasses (for example doped phosphate glasses and high index glasses) can have non-negligible absorption losses and bulk material defects. Bulk properties, such as voids and inclusions, can limit the obtainable quality of the polished surfaces. In most cases the bulk properties are mainly important for application where the light passes through the optical coating and into the substrate such as for AR and dichroic coated windows.

1.3 Coating properties

The optical coating is usually the limiting factor for the LDT of a coated optical component. The deposited material often has inferior properties to that of the bulk coating material [2][3]. With low energy deposition method such as thermal and electron beam evaporation, the coating is porous and often not fully oxidized leading to absorption. High energy deposition methods such as Ion Beam Sputtering (IBS), produces coatings with density very close to that of the bulk material and with very low absorption levels. However, all deposition processes tends to enhance defects in the substrate surface. Additional defects can also be introduced in the coating process itself. As a result, coated surfaces tend to damage at significantly lower fluence then that of an uncoated substrate surface.

For AR coatings, the light intensity extends through the whole coating, the coating-substrate interface and into the bulk substrate material. This is not the case for a high reflector (HR) coating where the light is reflected in the outer layers of the coating before it penetrates down to the substrate-coating interface. As a result, AR coatings and dichroic coatings tested at a transmissive wavelength, tends to have lower LDT than HR coatings. This is easily illustrated by a typical thin film polarizer coating which is designed to reflect all s-polarized light and transmit all p-polarized light at typically 45deg or 56deg angle of incidence. The s-polarized light does not penetrate down to the substrate-coating interface, while the p-polarized light transmits through the coating and into the bulk of the substrate. We have seen that the LDT of such a coating typically is at least a factor 2 higher if tested using s-polarization compared to the same coating tested with p-polarization.

1.4 Laser parameters

The LDT of optics is highly dependent on the laser parameters such as wavelength of operation, pulse length, repetition rate and, of course, intensity. Substrate and coating properties, especially absorption, depends on wavelength. The damage mechanisms change drastically going from continuous wave (CW) operation to nanosecond pulse to femtosecond pulsed operation. In CW operation, the peak electromagnetic field strength is relatively low, but the average power can be very high making heating due to absorption the driving damage mechanism. In femtosecond pulsed applications, the average power is relatively low, but the peak electromagnetic field strength can be extremely high making field dependent effects like dielectric breakdown and multi photon absorption driving damage mechanisms. In the nanoseconds pulsed regime, both absorption and field effects can be important.

2. SAMPLES AND EXPERIMENTS

2.1 Samples

To span a large range of substrate material properties, we picked substrates ranging from laser grade fused silica substrates to generic soda lime float glass. We also choose to use absorbing neutral density (ND) glass as a way of having samples with easily characterized absorption levels. An overview of the different samples is shown in Table 1. We prepared 2 samples for each type; one uncoated and one AR coated on one side. The BK7 equivalent glass was a Chinese manufactured optical borosilicate crown glass named K9. The ND glass samples were stock samples obtained from Edmund Optics and manufactured by Hoya Corporation. The soda lime float glass sample was made from commercial grade plate glass (visual green tint) with no special preparation.

2.2 Sample characterization

The samples were all cleaned and inspected for cosmetic surface quality. The Fused Silica and K9 samples had no observable digs or scratches even when inspected under high intensity fiber light against a black background. The ND glass samples also had a surprisingly good cosmetic surface quality surpassing 10-5 according to the MIL-PRF-13830B inspection method. The float glass samples had, as expected, poor surface quality with numerous stains and defects distributed across the surfaces.

The rms surface roughness of the samples was measured with a small aperture white light Zygo interferometer. The results are listed in Table 1. The Fused Silica samples had the lowest surface roughness (~ 5 Angstroms), while the ND glass samples had a rms surface roughness over 10 Angstroms with the ND 2.5 glass as high as 20 Angstroms. The plate glass varied from as low as 5 Angstroms to 15 Angstroms between different measurement sites. This is attributed to the visually observed staining on the float glass surfaces.

The neutral density rating of the ND glass samples refer to the transmission at visible wavelengths. Since all our LDT testing was performed at 1064nm, we also measured the total transmission through these samples at 1064nm using a Varian Cary 500 spectrophotometer. The transmission values are shown in Table 1 together with the resulting absorption coefficient calculated using the measured sample thickness and correcting for the Fresnel reflection losses on the surfaces.

Sample	**Sample thickness (mm)**	**Surface quality**	**Surface roughness**	**Measured Transmission at 1064nm (%)**	**Absorption coefficient at 1064nm (cm^{-1})**
ND 0.15 glass	2.18	<10-5	~ 13 A rms	45.6	3.23
ND 0.9 glass	2.5	<10-5	~ 12 A rms	6.57	10.5
ND 2.5 glass	2.66	<10-5	~20 A rms	2.58	13.4
BK7 equivalent glass (K9)	6.35	<10-5	~ 10 A rms	-	-
Fused Silica	6.35	<10-5	~ 5 A rms	-	-
Soda Lime plate glass		Float glass	5-15 A rms	-	-

Table 1. Sample overview

2.3 AR coating

One sample of each type was AR coated for 1064nm 0deg angle of incidence, with a simple two layer coating optimized for fused silica consisting of an approximately 45nm Ta_2O_5 layer and a 238nm SiO_2 layer. All samples were coated in the same coating run. The coating was deposited using an ion beam sputtering (IBS) system. The resulting reflectivity was measured on a fused silica witness sample with a Perkin Elmer Lambda 1050 spectrophotometer with a Universal Reflectivity Attachment at 8^o angle of incidence. The result is shown in Figure 1.

2.4 Laser damage threshold testing

The laser damage threshold testing of the samples were performed at Spica Technologies [5]. The test wavelength was 1064nm with 20ns full width half maximum pulse length and a 20 Hz repetition rate. The light was incident normal to the sample with linear polarization. The spot diameter ($1/e^2$) was varied from 1.0mm to 0.36mm. It was necessary to reduce the spot size to achieve high enough fluence to damage some of the samples. 10 sites were tested for each fluence level with 200 pulses per site. The samples were inspected for damage using a 100X Nomarski microscope.

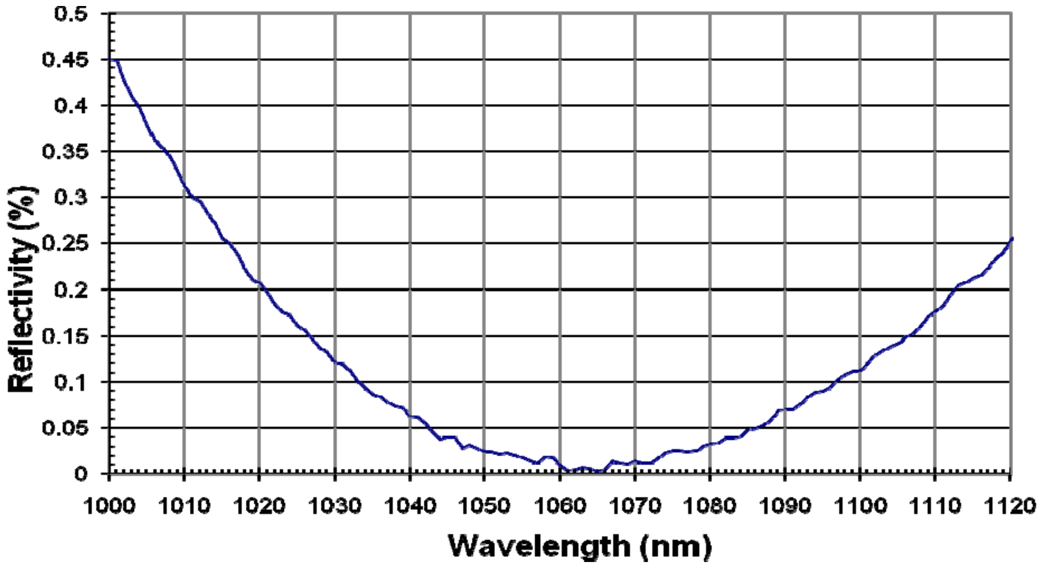

Figure 1: Measured reflectivity at 8° angle of incidence of AR coating fused silica witness sample

3. RESULTS AND DISCUSSION

3.1 Laser damage threshold results

Figure 2 shows the laser damage frequency as function of laser fluence for the AR coated samples. The damage frequency is defined as percentage of sites damaged out of total number of tested sites for a given fluence. As expected, the highest absorbing ND glass ND 2.5 starts to damage at the lowest fluence levels. First damage is observed at 9 J/cm^2. The other ND samples then follows with observed damage at 14-15 J/cm^2. More surprisingly, the low quality plate glass sample starts to damage at 16 J/cm^2 and does not exhibit damage in all of the tested sites even up to 40 J/cm^2. This is consistent with a damage threshold dominated by local defects in the surface of the sample which is expected with the plate glass sample.

The fused silica sample starts to exhibit damage at 26 J/cm^2 and the K9 sample at 33 J/cm^2. This give us a range in the onset of observed damage for the AR coated samples from 9 to 33 J/cm^2 going from the strongly absorbing ND glass to the laser quality K9 glass.

The tested laser damage frequencies for the uncoated samples are shown in Figure 3. The onset of damage is at a much higher fluence than for the AR coated samples. Both the ND 0.9 and the ND 2.5 sample starts to damage at about 80 J/cm^2. However, some induced local stress was observed with Nomarski microscope inspection as a color change at lower fluence before onset of catastrophic damage (Figure 4). The lowest absorbing glass sample, ND 0.15, does not exhibit damage all the way up to a fluence of 160 J/cm^2.

The other samples also showed very high laser damage thresholds. The K9 sample showed damage starting at around 175 J/cm^2. No damage was observed for the fused silica or the plate glass samples up to the maximum obtainable fluence of 200 J/cm^2.

3.2 Estimation of local heating

The observed laser damage threshold is surprisingly high, especially for the un-coated absorbing ND glasses. If we ignore heat dissipation during the 20ns duration of the laser pulse and assume all the absorbed laser energy is converted to heat, we can estimate the local heating in the surface of the ND glasses caused by a single laser pulse using the measured absorption coefficients listed in Table 1.

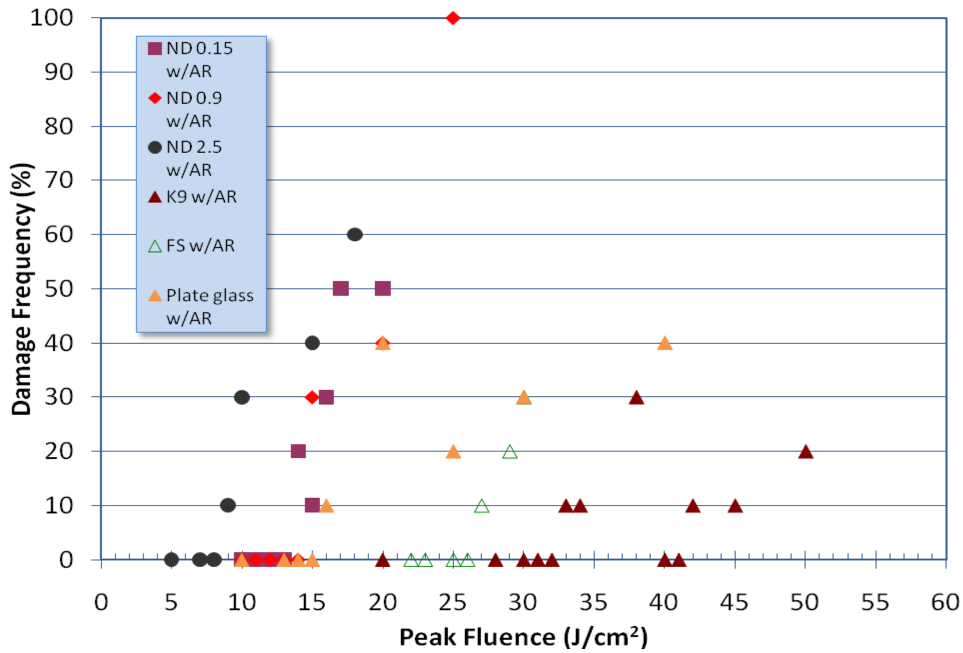

Figure 2. Laser Damage Frequency for the 6 AR coated samples.

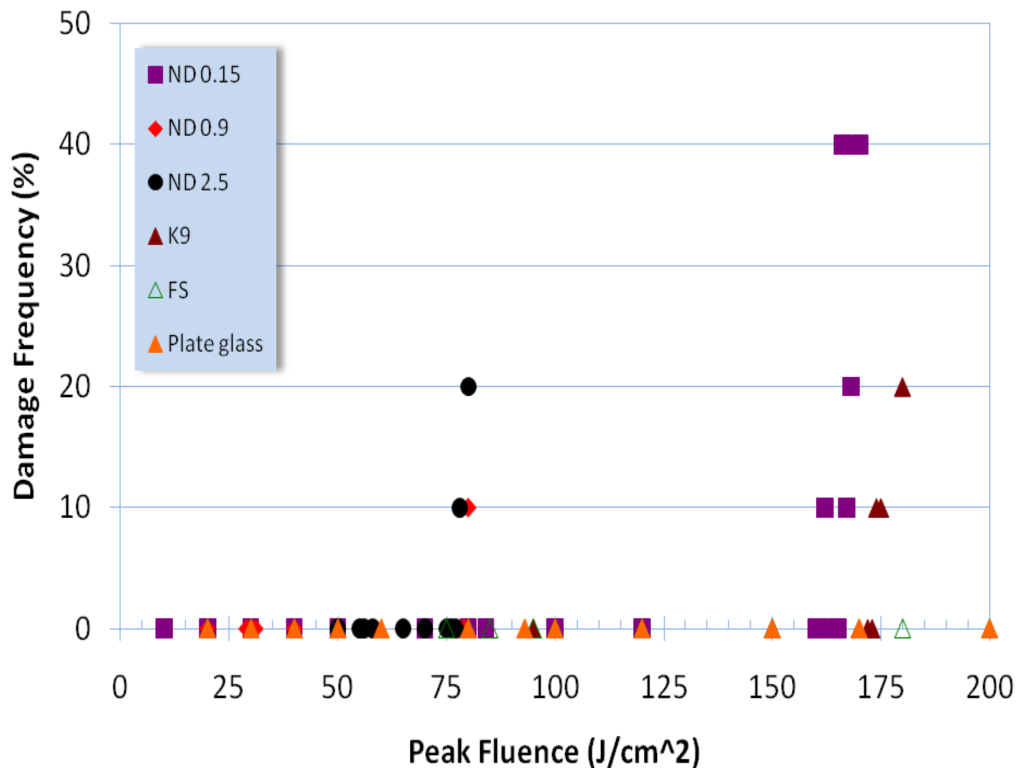

Figure 3. Laser Damage Frequency for the 6 un-coated samples.

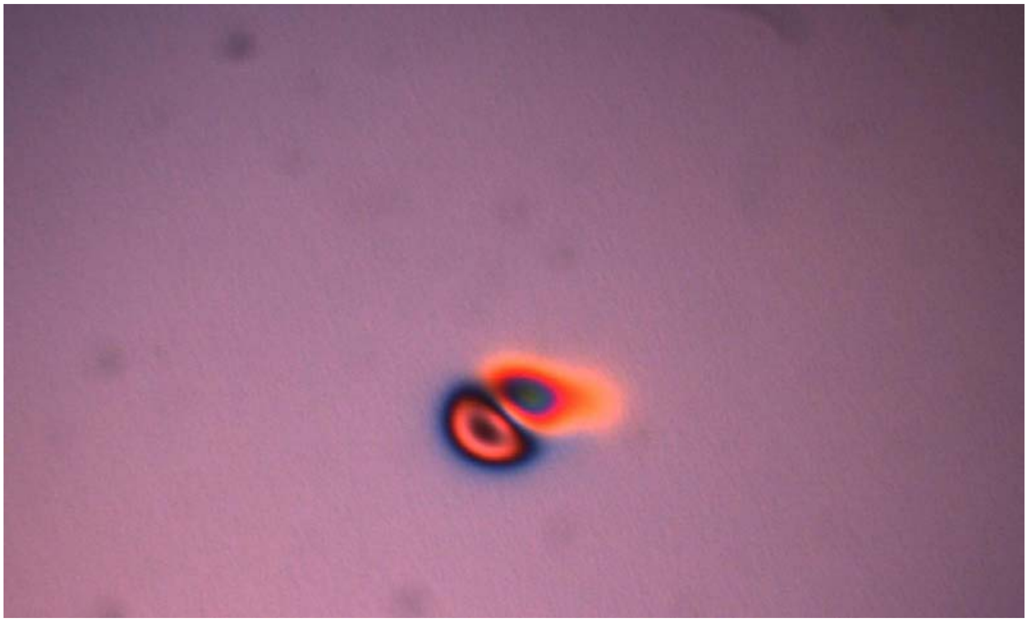

Figure 4. Image of stress induced changes in the ND 2.5 sample at fluence levels below observed permanent damage. Courtesy Spica Technologies.

The absorbed laser pulse energy, ΔE (Joules), in an infinitesimal small volume $\Delta V = \Delta A \cdot \Delta z$ (m^3) is:

$$\Delta E = \Delta A \cdot \left(I_0 - I_0 \cdot e^{-\alpha \cdot \Delta z} \right) \qquad (1)$$

Where I_0 is the laser fluence (Joules/m^2), ΔA is the irradiated area (m^2), and Δz is the propagation distance (m) along the infinitesimal volume. Since ΔA is small (infinitesimal), the fluence can be considered to be constant across the area. Since Δz is also small, we can approximate ΔE by:

$$\Delta E = \Delta A \cdot I_o (1 - e^{-\alpha \cdot \Delta z}) \approx \Delta A \cdot I_0 \cdot \alpha \cdot \Delta z = I_0 \cdot \alpha \cdot \Delta V \qquad (2)$$

If all the absorbed energy gets converted to heat, the volume ΔV experiences a temperature increase:

$$\Delta T = \frac{\Delta E}{C \cdot \Delta V \cdot \rho} = \frac{I_0 \cdot \alpha \cdot \Delta V}{C \cdot \Delta V \cdot \rho} = \frac{I_0 \cdot \alpha}{C \cdot \rho} \qquad (3)$$

where C is the specific heat capacity (Joules/(kg·K)) and ρ is the density (kg/m^3) of the substrate material.

The single pulse heating of our ND glass samples as function of laser pulse fluence is shown in Figure 5. We have used the listed values for BK7 optical glass for the specific heat capacity of the substrate (858 Joules/(kg·K)) and the density of the substrate (2510 kg/m^3) . It is assumed to be close to the actual values for the ND glass samples. The peak fluence, and therefore the highest temperature increase, occurs in the center of the laser beam at the entrance face of the sample. The fluence corresponds to the peak fluence reported in the laser damage tests at this location.

The fluence levels where damage was observed are indicated in Figure 5. We can see that the ND 2.5 sample is estimated to have almost 500^o Kelvin temerature increase from just one pulse at the damage fluence level. The ND 0.9 would have a worst case temperature increase of almost 400^o Kelvin and the ND 0.15 sample would have around 250^o Kelvin .

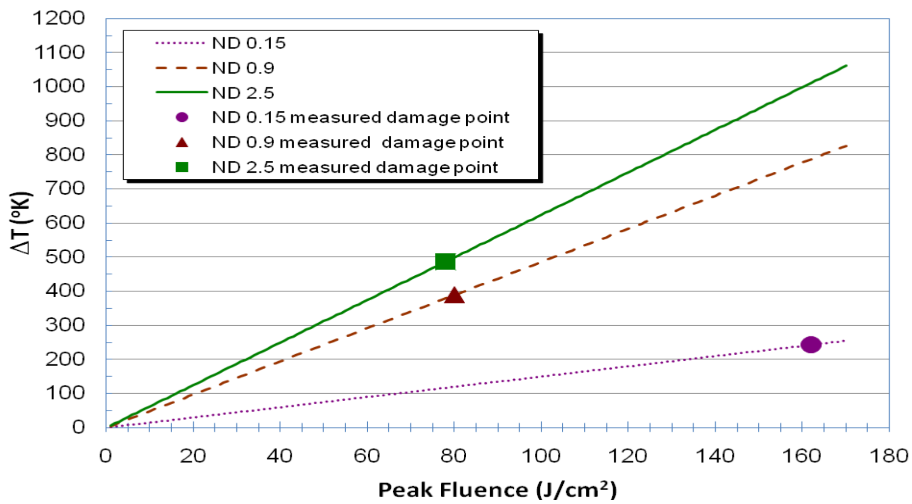

Figure 5. Estimated local heating in degrees Kelvin of the ND glass samples as function of laser peak fluence when irradiated with a single laser pulse

3.3 Discussion of results

Observed damage thresholds of AR coated laser quality substrates agrees well with previously reported results for IBS AR coatings on laser quality substrates [6][7]. The LDT on absorbing ND glass and on low grade plate glass is as we expected lower, with the ND 2.5 sample showing damage at the lowest fluence level of 9 J/cm^2. The K9 sample had the highest onset of damage at 33 J/cm^2. The LDT therefore only varied over the range 9 to 33 J/cm^2 for substrates with a large range of surface quality and absorption levels.

The LDT of the uncoated samples is much higher than for the AR coated samples. This is not surprising for the K9 and fused silica samples, but it is surprising for the plate glass sample. The plate glass sample is not polished and therefore does not have sub surface damage associated with the polishing process, but it does have staining and cosmetic defects from handling. The observed high LDT indicates that the test sites were in an area of the plate glass surface with a low defect density and staining. However, the surface was not characterized well enough ahead of testing to directly correlate the local surface quality with the test sites.

Most surprising is the high LDT observed on the uncoated ND glass samples. The estimation in section 3.2 gives a temperature increase in the surface of the glass for a single pulse at the damage fluence on the order of 400-500^o Kelvin for the ND 0.9 and ND 2.5 samples. The tests were performed with 20 Hz pulse repetition rate and a total of 200 pulses per site. Although a calculation of the heat dissipation in the 50ms time period between pulses is beyond the scope of this work [8], it is likely that a significant portion of the heat has not fully dissipated before the next pulse hits the site. The local heating should then quickly lead to melting of the glass and a lower damage level than what we observed. However, our temperature estimation assumes that the absorption coefficient of the glass stays constant when under laser irradiation. This might not be the case for these high fluence levels. A possible explanation of the observed high LDT is that we are saturating the absorption of the ND glass which would result in lower heating than our estimate.

It has not been possible to obtain details of the composition of the ND glasses from the manufacturer. However, it is likely that the absorption is due to the glass being doped with metallic ions. It would be possible to saturate the absorption of the metallic ions if the lifetime of the excited states is longer than the 20ns pulse duration. Similar non-linear effects have been reported in the semiconductor doped color glasses Schott OG515 and OG530 and Hoya Y52 for 80ns pulse lengths [9].

It is also interesting to note that if we assume the 283nm thick AR coating had the same absorption coefficient as the ND 2.5 glass, it would have a total absorption of 380ppm. IBS coatings typically have absorption levels at the 1ppm level [10][11]. This means that although the absorption in the surface of the uncoated ND glass samples is much higher than in the AR coating, the LDT is also much higher. We can conclude that absorption in the AR coating is not explaining the low LDT levels of AR coated substrates versus un-coated substrates.

4. CONCLUSIONS

We have observed that the laser damage threshold for AR coated substrates ranging from low quality plate glass through absorbing neutral density glass to laser grade substrates ranges from 9 to 33 J/cm^2 for 1064nm, 20 Hz, 20 ns pulses. The LDT on simultaneously prepared un-coated samples range from 80 J/cm^2 to greater than 200 J/cm^2. The LDT on the uncoated neutral density glass samples is unexpectedly high compared to our estimated single pulse temperature increase from the absorbed laser energy. One possible explanation is saturation of the absorption in the neutral density glass samples. Based on the high LDT of the ND glass samples, we can conclude that absorption levels in the AR coating is not a significant contributor to the LDT of the AR coated samples.

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