Measurement of the optical damage threshold in fused quartz

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The damage thresholds of five different types of quartz glass used for the production of spectroscopic cuvettes for liquids were determined with single temporal and spatial mode nanosecond pulses at 532 nm. One of the glasses had a damage threshold of $\simeq$420 J/cm^2, which was more than twice that of the other glasses.

Key words: Optical damage, fused quartz, visible, nanosecond, optical limiting.

The emergence of liquids such as carbon black suspensions[1] and reverse-saturable absorbing dyes[2–4] as practical media for optical limiting applications dictates the use of glass and fused-silica cells as essential parts of the optical device. High-optical-quality glass or fused quartz with a large damage threshold is desired in the making of optical cuvettes. Optical damage of fused silica has been studied at various wavelengths.[5–7] In this paper we report a comparative study on the optical damage thresholds of five types of fused-quartz windows at 532 nm with nanosecond pulses in a tight focusing geometry. All five materials were obtained from NSG Precision Cells, Inc.[8]

We used a single-longitudinal-mode, injection-seeded, Q-switched Nd:YAG laser with 9-ns (FWHM) pulses. Having single-longitudinal-mode pulses is essential in damage studies where large temporal spikes within the pulse are eliminated. Pinholes were placed in the laser cavity to obtain a TEM_{00} spatial mode. The spatially and temporally Gaussian beam was focused to a measured spot size w_0 of $\simeq$7.9 μm (half-width at $1/e^2$ maximum). The spot size and the position of the beam waist were determined with the Z-scan technique.[9,10] Determination of the beam spot size to within a ±5% error is described in detail in Ref. 10 and verified with pinhole beam scans.[11]

The damage study is a multiple-shot test, as each sample of 1.25-mm thickness is scanned along the beam propagation direction from $3Z_0$ before focus to $3Z_0$ after focus, where $Z_0 = \pi w_0^2/\lambda$ is the confocal beam parameter and λ is the wavelength. As the sample moves through the focus, the input energy remains constant so that the fluence changes in a known way. The sample was moved from the detector side toward the focusing lens so that the front surface reached focus first. The sample was irradiated once at each sample position and then moved 60 μm in Z to the new position. Damage was determined by measurement of the input and the output energy to determine changes in the transmittance through the sample for a constant input energy. The experimental configuration is shown in Fig. 1. If the transmittance (the ratio D_2/D_1) remains constant as a function of the sample position, then no damage has occurred, as verified by observation with a Nomarski microscope. However, a decrease in transmittance near the center of the scanning range (i.e., at focus) indicates that damage has occurred. First a Z scan is performed at low energy where no damage occurs. Then the energy is increased by increments of $\simeq$10% and the Z scan is repeated. This process is continued until the sample is damaged. The same position in X and Y on the sample is irradiated until it is damaged. For example, Fig. 2 shows the Z-scan data of sample ED-C at input energies of 152 and 162 μJ. It is clear that the sample is damaged at the higher energy but not at the lower one. The gradual increase in transmittance after focus can be explained as follows: When the sample is damaged very close to focus, i.e., less than

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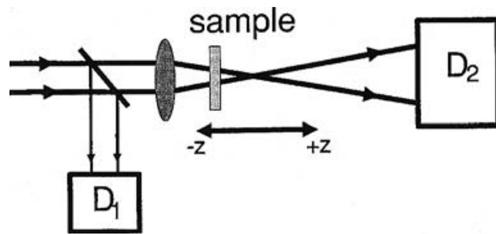

Fig. 1. Experimental setup: the ratio (D_2/D_1) is measured versus sample position Z.

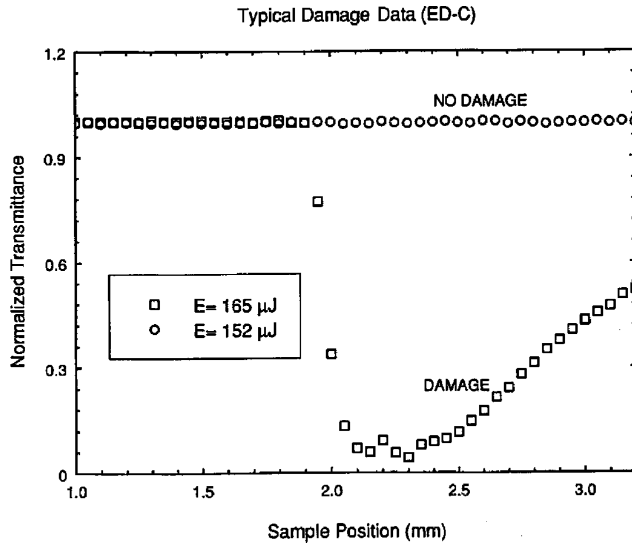

Fig. 2. Typical damage data on sample ED-C, where the sample shows no damage at 152 μJ (circles) but is damaged at 165 μJ (squares).

Z_0, the damage spot is very small and most of the beam is scattered. As the sample moves away from focus, the beam at the sample becomes larger than the damage spot and a smaller fraction of the beam is scattered. Therefore an increasing transmittance can be seen as the sample moves away from focus. A new site on the sample (i.e., different X, Y position) is scanned at the same energy to verify that damage occurs. The sample is then placed on a new site at the Z position where the onset of damage occurred, which was always less than Z_0 from focus, and the energy increased until damage occurred. We obtained the same results for each sample, showing the uniformity of the surfaces. This last procedure is the more common N-on-1 method used in damage-threshold measurements.[5,12,13] The advantage of using the Z-scan method is that it saves one the task of determining the focal position. In fact, this method can itself be used as a way to determine the position of the focus to within Z_0.

Table 1. Damage Threshold of Fused-Quartz Windows

Sample	Energy (μJ)	Fluence (J/cm²)	Irradiance (GW/cm²)
ED-C	160	170	16
ED-A	120	130	12
IR	175	185	18
ES	390	420	40
OX (UV)	160	170	16

Table 2. Manufacturing Methods of Fused-Quartz Samples

Sample	Method
ED-C	Chemical vapor deposition (CVD)-soot-remelting silica produced by vapor axial deposition (VAD), dehydrated by heating of the soot in Cl_2 before vitrification, containing less than 1 part in 10^6 (ppm) of OH and 1000 ppm of Cl.
ED-A	CVD-soot-remelting silica produced by VAD, containing approximately 100 ppm of OH and no detectable Cl.
IR	Type I vitreous silica produced by melting of natural quartz powder in a plasma torch containing several ppm of OH.
ES	Type III vitreous silica produced by flame hydrolysis of SiCl in hydrogen–oxygen flame containing approximately 1200 ppm of OH and 50 ppm of Cl.
OX (UV)	Type II vitreous silica produced by melting of natural quartz powder in hydrogen–oxygen flame containing approximately 150 ppm of OH.

Damage was always observed on the front surface of the samples, as verified by Nomarski microscopic inspection. The results of the above measurements are summarized in Table 1, in which the damage-threshold energy, fluence, and irradiance of each sample are listed. The reported values have an absolute uncertainty of ±10% in energy, ±35% in fluence, and ±45% in irradiance. However, as the samples were tested systematically in the same experimental configuration, the relative errors are estimated to be ≃10%. The methods by which each of the five fused quartz samples was manufactured are supplied by NSG Precision Cells, Inc.[8] These are summarized in Table 2. The same polishing technique was used on all samples.[8]

In conclusion, we have measured the damage thresholds of fused-quartz windows used in the manufacture of optical cuvettes. We find that ES fused quartz, which is a type III vitreous silica, exhibits the largest damage threshold. This threshold is larger than that of the other fused-quartz windows by more than a factor of 2.

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