Deterministic single shot and multiple shot
Bulk laser damage thresholds of borosilicate glass at 1.064 μm

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Abstract

We measured the single-shot and multiple-shot optical breakdown thresholds leading to optical damage of borosilicate glass, specifically BK7 glass, at 1.064 μm. We used 8-ns, single-longitudinal-mode, TEM_{00} laser pulses tightly focused inside a BK7 glass window. The radius of the focal spot was measured using surface third harmonic generation; it is equal to 7.5 μm. With this tight focus, the laser power at the breakdown threshold of BK7 glass is below the SBS threshold, and the effect of self focusing is small.

We found the single-shot and multiple-shots optical breakdown thresholds to be deterministic. At the single-shot damage threshold, the optical breakdown in BK7 glass occurs on the trailing edge of the laser pulse, in contrast to fused silica in which the breakdown always occurs at the peak of the laser pulse. However, the multiple-shot damage threshold of BK7 glass occurs at the peak of the last laser pulse.

Our single shot damage threshold for BK7 glass is 4125 J/cm^2, and our multiple shot damage threshold ranges from 3974 J/cm^2 for 2-shot damage to 3289 J/cm^2 for 31-shot damage. We also compare damage morphologies of BK7 glass with those of fused silica.

I. Introduction

BK7 glass is an important optical material. The intrinsic optical damage threshold of BK7 glass is important in the development and application of high power lasers because this threshold imposes the highest limit to system performance. However, we are not aware of any previous reports of the intrinsic damage threshold of BK7 glass.

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The intrinsic single shot and multiple shot damage thresholds of BK7 glass should be measured in such a way that they are free from the influence of SBS, and they need to be corrected for the effect of self focusing. In order to measure the intrinsic single shot and multiple shot damage thresholds of BK7 glass which meet the above requirements, we used an injection seeded Nd:YAG laser, operating on a single longitudinal mode. The pulse-to-pulse energy variation is less than 1.5%. By tight spatially filtering of the laser beam we made its spatial mode very close to be TEM_{00}. We precisely measured the focal spot size by measuring the surface third harmonic signal. By studying the temporal profiles of the incident and transmitted pulses, we can measure precisely the laser power at breakdown. From this information, we were able to calculate the damage threshold irradiance and fluence.

We will describe our experimental set-up and technique in part II, and we will discuss our experimental results on the optical breakdown process in part III. We will compare the broadband light emitted from the optical breakdown in BK7 glass with that from fused silica in part IV. Finally, we will compare damage morphologies in BK7 glass and in fused silica in part V.

II. Experimental set-up and technique

II.1. Properties of optical breakdown

A 1.064 μm nanosecond pulsed laser can excite electrons from the valence band of BK7 glass into the conduction band by multiphoton ionization and by impact ionization. When the free electron density reaches the critical density, the plasma frequency is equal to the laser frequency,

$$\omega_p^2 = \frac{e^2 n}{m^* \varepsilon \varepsilon_0} = \omega_{laser}^2 . \qquad \text{[Eq. 1]}$$

Here e is the electron charge, n is the free electron density, m^* is the effective electron mass, ε is the relative permittivity of the medium, and ε_0 is the free space permittivity. For our 1.064 μm laser the critical density of free electrons in BK7 glass is 2.25 x $10^{21}/\mathrm{cm}^3$.

When optical breakdown begins, the following phenomena occur simultaneously [1].

a. A drastic decrease in the transmitted laser power occurs as the incident laser pulse is absorbed, reflected, and scattered by the dense breakdown plasma in the focal region.

b. The generation of a high-density plasma in the focal region creates a bright flash of white light.

c. At the onset of optical breakdown the dense plasma starts to block a probe beam.

In our experimental set-up, we detected the optical breakdown by using fast phototubes to record the incident and transmitted pump beams, a photomultiplier tube to record the broadband light generated by the optical breakdown at the focal region, and a screen to display a transmitted probe beam.

II.2. Experimental set-up

We used a single-longitudinal-mode, injection-seeded, Q-switched YAG laser operating at 1.064 μm. The temporally smooth pulse is repeatable with a pulse-to-pulse amplitude variation of less than 1.5 %. In order to extract a single laser pulse or a set of N pulses from our 10-pulse-per-second laser while keeping the laser oscillator locked to the seed laser we used a beam shutter synchronized to the Q-switch signal. The shutter opened 40 msec before the first pulse and closed at 40 msec after the last pulse. The pulse energy was varied using a half wave plate and a high-energy cube polarizer. We used a 200-μm-diameter wire die and an adjustable iris to spatially filter the laser beam to make it a close approximation to a TEM_{00} profile. We also used two fast phototubes (Hamamatsu, R1193U-01) to record the temporal profiles of the incident and transmitted pump beams, and a photomultiplier (Hamamatsu, 1P28) to record the broadband light emitted from the optical breakdown region. A HeNe probe beam co-aligned with the high power beam was displayed on a screen positioned downstream from the sample. The sample was mounted on a motorized 3-dimensional translation stage, and we focused the pump beam into the sample with a 1-inch focal length, best form lens manufactured by CVI. The experimental set-up is shown in Fig.1.

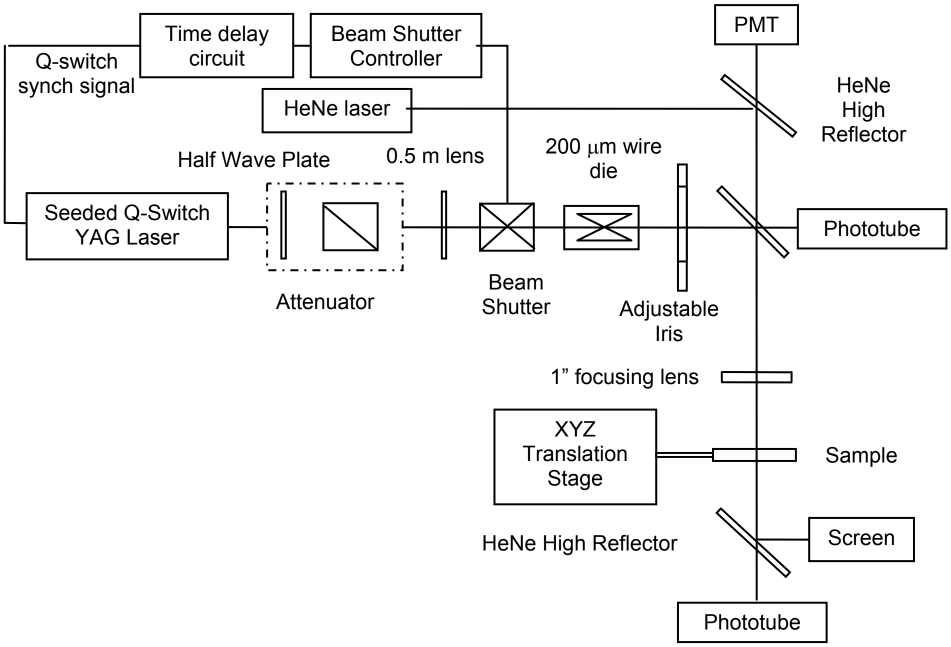


Fig. 1: Experimental set-up

II.3. Spatial and temporal profiles of laser pulses

II.3a. Spatial beam profile measurement

Figure 2 shows the spatial profile of the beam before the focusing lens. The spatial profile is close to the TEM_{00} mode, ensuring that it focuses to a nearly diffraction-limited spot size without hot spots.

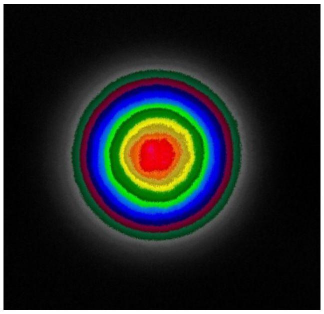


Fig. 2: The spatial profile of our laser beam before the focusing lens.

II.3b. Temporal profile of laser pulses

The temporal profile of the high power 1064 nm pulse is shown in Fig. 3.

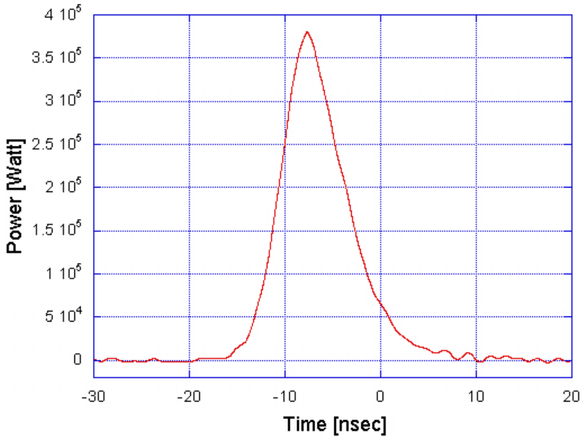


Fig. 3: The temporal profile of our laser pulse, the FWHM is 8 nsec.

If we unseeded our laser, then it would run multimode. The gain bandwidth of YAG is about 30 GHz, and the free spectral range of our laser was 250 MHz. However, not all of the cavity modes under the gain curve actually are above the lasing threshold. If we assume that there were eight equally spaced modes under the gain curve that oscillated with random (uncorrelated) phases, then these modes would interfere with each other to produce an output pulse which consisted of a multitude of high-intensity spikes as shown in Fig. 4. The power of the highest spike can be four times higher than the maximum power of the seeded pulse of the same energy (red curve). The lasing bandwidth of Nd:YAG is 30 GHz. From the uncertainty relation $\Delta t\ \Delta\omega \geq 1$, we can estimate the duration of these high intensity spikes to be about 15 psec.

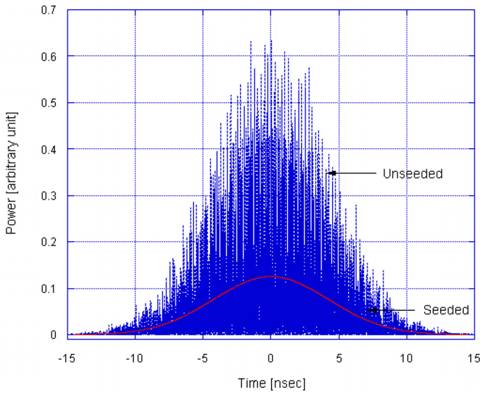


Fig. 4: A simulated temporal profiles for an unseeded laser pulse and a seeded pulse of the same energy.

If we use an unseeded laser to measure the damage threshold of the BK7 glass, then for each unseeded ns laser pulse, the BK7 glass interacts with a series of high power ps laser pulses. If the damage mechanism is proportional to the laser irradiance, for an unseeded pulse (multiple longitudinal mode) the apparent damage threshold fluence would be smaller than for a seeded pulse (single longitudinal mode). Moreover, the temporal profile of a multimode laser varies from pulse to pulse, so when an unseeded laser is used to measure the damage threshold fluence, the threshold appears to be statistical, reflecting the statistical properties of the unseeded laser. Thus we chose a single longitudinal mode laser with a repeatable temporal profile and very low pulse-to-pulse energy variation.

II.3c. Method of measuring and locating the beam waist

In this measurement, we wished to measure the laser fluence at breakdown, and also study the morphology of the material damage created by optical breakdown. This study can be precise only if we knew the exact location and the size of the focal spot in our sample. We measured the location and the size of the beam waist by measuring the surface third harmonic signal generated by the broken symmetry at the air-sample interface. The bulk third harmonic signal exists, but it is much weaker than the surface third harmonic signal [2] which obeys the relation

$$Energy^{(3\omega)} \approx \int_0^\infty \int_0^{2\pi} I_w^3 \exp\left(-6 * \frac{r^2}{w^2}\right) r d\theta dr \approx \frac{1}{w^4}, \qquad \text{[Eq. 2]}$$

where w is the beam radius at $1/e^2$ on the surface of the sample,

$$w^2 = w_0^2 \left(1 + \frac{(z - z_0)^2 \lambda^2}{(\pi w_0^2)^2}\right), \qquad \text{[Eq. 3]}$$

w_0 is the radius of the beam waist, and z_0 is the location of the beam waist. Fig. 5 showed the surface third harmonic signal with respect to the nominal location of the window input face.

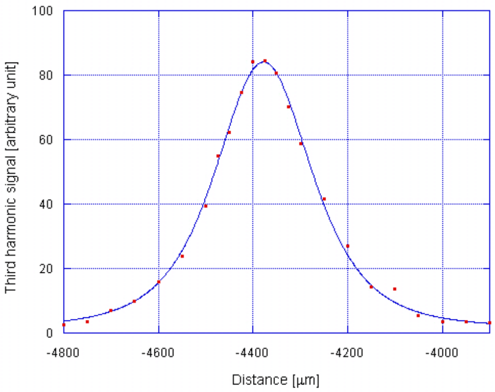


Fig. 5: Surface third harmonic signal as a function the nominal location of the sample. The dots are the measured signals and the solid line is a least-square fit to $1/w^4$.

The surface third harmonic signal is a maximum when the beam waist coincides with the sample surface. From our fit to $1/w^4$, we obtain the focus spot size of $w_0 = 7.45$ µm. Additionally, from the curve fitting, we can determine z_0 which is the location of the window such that the beam waist is on the window's surface. Using this information we can precisely position the focal spot a chosen distance behind the input surface of the sample.

III. Laser induced damage thresholds in BK7 glass

To avoid the complication of surface damage, we position the focus 3.0 mm behind the front surface. We measured single-shot and cumulative multiple-shot damage thresholds for bulk BK7 glass at a 1 Hz repetition rate. Fig. 6 shows the single-shot and cumulative multiple-shot damage thresholds of BK7 glass for linearly polarized light.

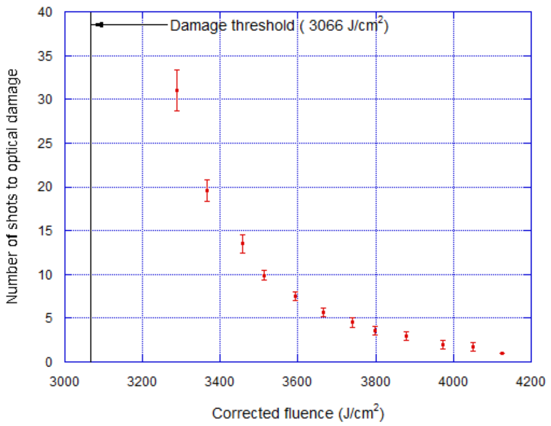


Fig. 6: Single shot and multiple shot damage thresholds of BK7 glass for linearly polarized light, 8 nsec FWHM pulse duration.

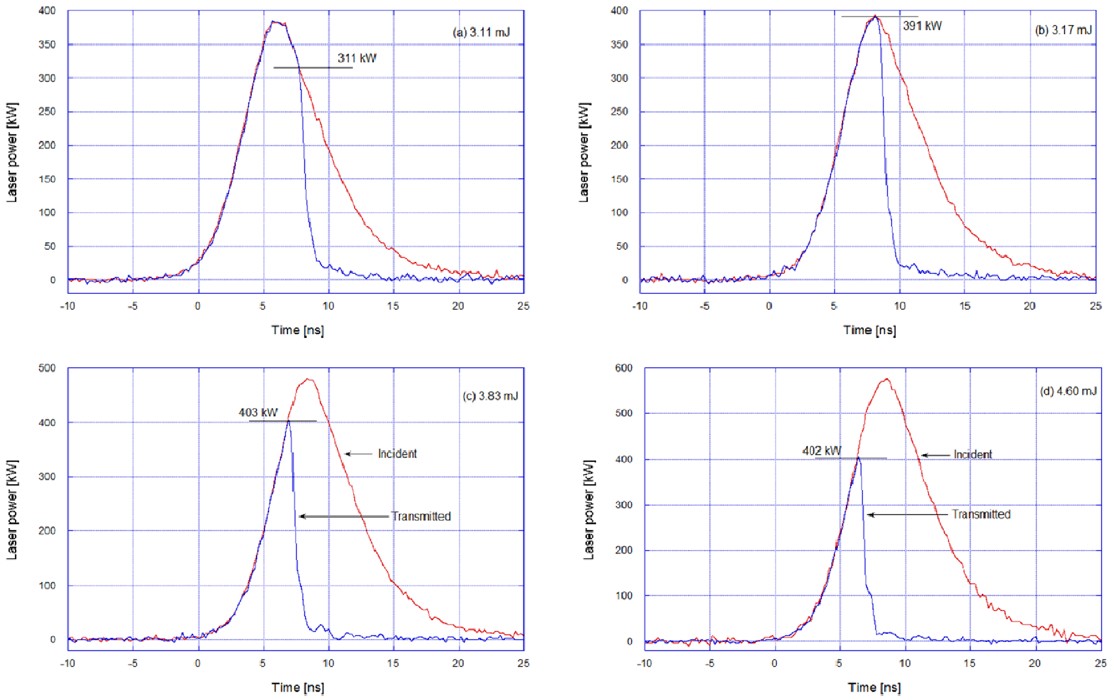
The damage thresholds shown in Fig. 6 were corrected for the effect of self focusing. Since the focusing depth is larger than 10 Rayleigh ranges, the correction factor follows the following formula [3],

$$Corr = \frac{1}{1 - {}^{P}/_{P_{sf}}} \qquad \text{[Eq.4]}$$

$$P_{sf} = \frac{0.148\,\lambda^2}{n n_2} = 2.82\ MW \qquad \text{[Eq.5]}$$

The single-shot damage threshold fluence is 4125 J/cm^2 after making 15% correction for self focus. The corrected two-shot damage threshold fluence is 3974 J/cm^2. At 3879 J/cm^2 damage occurred on either the third or fourth pulse, and at 3289 J/cm^2 we have 31-shot damage threshold, with a standard deviation of 2.4 pulses. When the laser fluence was reduced to 3066 J/cm^2, damage did not occur after even when we tested 10 locations with 1000 shots each. We call this the damage threshold; the included correction factor for this threshold is 12%. We believe that if the pulse energy variation of our laser were smaller than the current value of 1.5%, our measured multiple-shot damage thresholds would be even more deterministic.

We also recorded temporal profiles of the incident and transmitted pulses at the single-shot damage threshold and at higher pulse energies. Fig. 7 shows typical profiles for several pulse energies with the powers at the time of breakdown indicated on the plots.



Figs. 7: Temporal profiles of the incident and transmitted pulses at different incident pulse energies in BK7 glass for single shot damage, (a) 3.11 mJ (b) 3.17 mJ, (c) 3.83 mJ, and (d) 4.60 mJ.

The pulse energy of 3.11 mJ corresponds to the single shot damage threshold. At this pulse energy breakdown occurred on the falling edge of the pulse at the power of 311 kW. For an incident energy of 3.17 mJ (Fig. 7b), about 1.5% above the single pulse damage threshold, the breakdown occurs at the peak of the pulse where the power is 391 kW. Figs. 7c, and 7d show the traces of incident and transmitted beams at higher pulse energies of 3.83 and 4.60 mJ, where the breakdown occurs on the rising edge of the pulse at 403 and 402 kW, respectively.

We interpret these results as evidence that breakdown is caused by a cumulative process of electron built up in the conduction band, which occurs at different power levels depending on the incident pulse energy. The observation of breakdown on the falling edge of the pulse for single pulse damage is evidence that the electron-hole recombination time is of the order of ns. This behavior is in distinct contrast with that of fused silica, in which breakdown always occurs at the peak of the pulse, and there is no multiple shot damage thresholds [3, 4].

We also measured the pulse energy that was transmitted prior to the time of breakdown in BK7, as a function of the incident pulse energy, for energies exceeding the single pulse damage threshold (see Fig. 8). At the single shot damage threshold, the energy transmitted before breakdown exceeds half the incident pulse energy. However, as the incident pulse energy increases, the transmitted energy decreases.

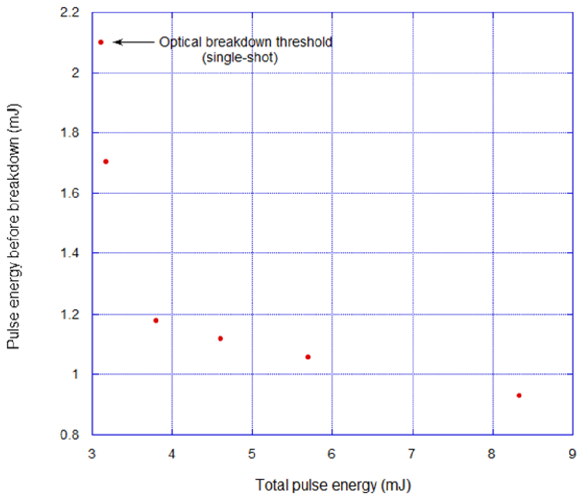
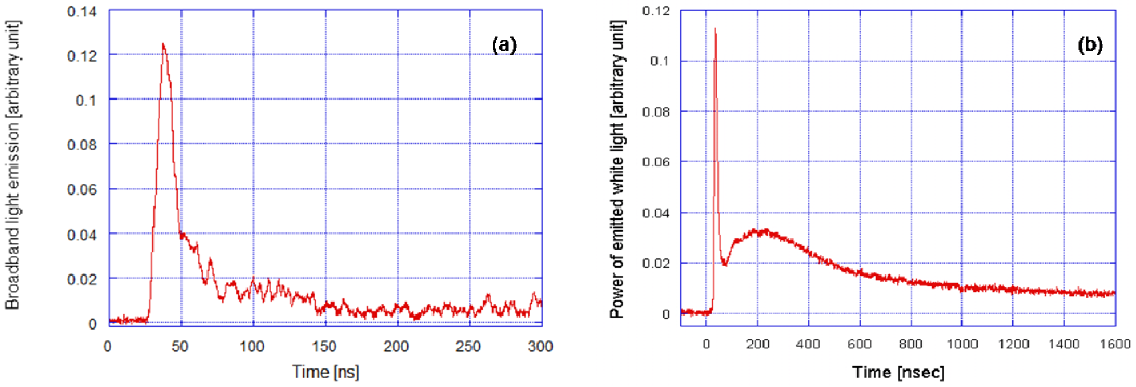


Fig. 8: Laser pulse energy before breakdown versus the incident pulse energy

IV. Broadband light emission from breakdown BK7 glass and fused silica

One signature of the optical breakdown is the broadband light emitted from the focal region. The temporal profile of this broadband light emitted from BK7 glass is different the one emitted from fused silica [3, 4]. Fig. 9 compares temporal profiles of the broadband light from BK7 glass (a) and fused silica (b).



Figs. 9: Temporal profiles of the broadband light emitted from the focal region in (a) BK7 glass and (b) fused silica.

The broadband light emitted by fused silica consisted of a short pulse and a long pulse. The FWHM widths of the short and long pulses are about 20 and 700 nsec. The broadband light emitted from BK7 glass is different. Its short pulse has nearly the same duration as silica's, but its long pulse decays much faster than silica's.

V. Optical damage morphology

We also studied damage morphologies in BK7 glass. We cut and polished the damaged samples along the propagation direction of the pump beam, to obtain the side views of the damage. The end views are not very informative. Fig. 10a shows a damaged spot created by a laser pulse whose energy is slightly above the damage threshold. The optical damage shown in Fig. 10a is very reproducible. We also compare the damage morphologies in BK7 glass with the ones in fused silica (fig. 10b); they are noticeably different, and both of them are reproducible.

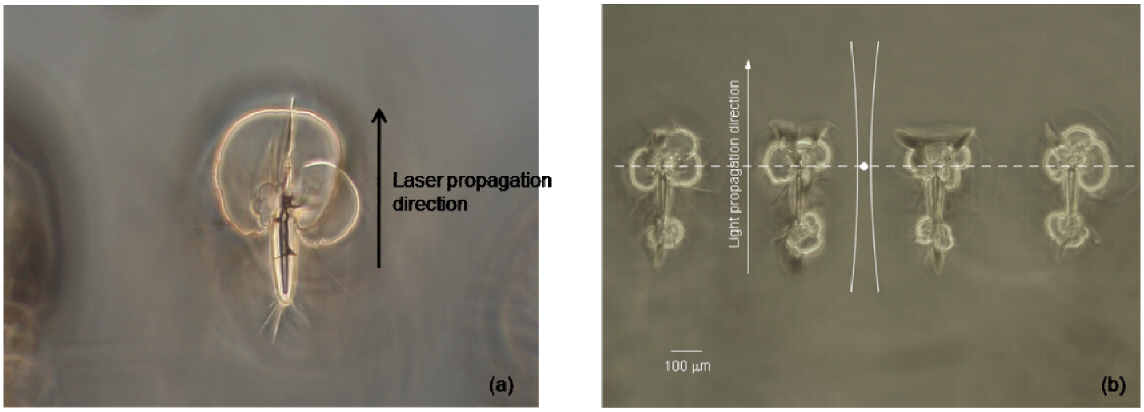


Fig. 10: Damage morphologies in (a) BK7 glass (b) fused silica

IV. Conclusion

We have shown that the single-shot and multiple-shot optical damage thresholds in BK7 glass for an 8 ns (FWHM) pulse with a 7.5-μm beam radius are deterministic. We were able to observe the deterministic behaviour because we used a well controlled laser operating on a single longitudinal mode, with a spatial mode close to TEM_{00}, and with a pulse energy that varies less than 1.5 % from pulse to pulse.

In the single-pulse damage, breakdown can occur on either the leading or trailing edge of the laser pulse, depending on the incident pulse energy. In multiple-shot damage breakdown always occurs at the peak of the pulse. We also studied the white light emitted by the breakdown in BK7 glass and compared it with that of fused silica. Our result also showed that the damage morphologies in BK7 glass were reproducible and different from those in fused silica.

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Deterministic single shot and multiple shot bulk laser damage thresholds of borosilicate glass at 1.064 micron

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Questions and Answers

Q. You showed this graph where you identified the point where damage started within the pulse duration. How did you get the blue curve?

A. Oh, because if you look at the optical setup.

Q. Is this a transmission measurement?

A. The phototube, practically we monitor the transmitted curve (blue) and the incident curve is the red one.

Q. Yes, okay. So, when your blue curve starts dropping, it doesn't mean that that is where the damage starts?

A. No. I think. I'm not sure. That could be the start of optical breakdown, because that's where it happens very drastically. Even though we tried to use a very fast phototube. The rise time is about 680 picoseconds. I wish that I could have a faster one with a rise time of, say, 240 picoseconds. Then I can have better resolution. But, if we look at the incident temporal profile and the transmitted one, they follow each other really well until this point where we see a drop in the transmitted light. So, I believe that the damage did not happen here until sometime previously. I don't think the damage started anywhere in this region. We have a sharp drop is here so this is where optical breakdown is.

Q. The point where the two curves depart corresponds to an electron density of about 10^{22}.

A. Actually, it's about 10^{1} or so. Let me say because that's why I didn't show this line. So, this one, when I talk about the rate equation, the critical density for borosilicate glass is about 2.2 or 2.3, so it takes some time to get to 10^{21}, but that time is fast.

Q. I think that Michael Bass and Sanders from Sandia did an experiment maybe twenty or thirty years ago using a streak camera. The onset of the breakdown plasma,… I think the resolution of their streak camera was a couple of picoseconds,… so the plasma begins and shuts off in a couple of picoseconds from those measurements.

A. Yes.

Q. I think it was Bass and Sanders from Sandia.

A. Thanks.

Q. You told us that you did not see changes in your samples after several shots, but did you try to put your sample into an interferometer?

A. No.

Q. Because, actually the refractive index will change by a small amount. Actually what you see is the accumulation of self-focusing because of lenses that are imprinted after the laser shots.

A. Yes. I did use phase contrast microscopy, and I couldn't see it. You are right. You are right.

Q. You observed a very deterministic measurement as you mentioned. That means you put two pulses in there and saw no damage and after an hour, you put the third pulse in and you saw damage. So, the sample knows you put two pulses in there, so you must have done something to the sample.

A. You are right.

Q. So, what's your explanation? I mean, the sample has been damaged by those first two pulses. But, you don't see evidence of damage in your transmission spectrum?

A. No, no, I don't see the damage. I looked at the probe beam through that region and I didn't see anything that the refractive index would modify. That's why I used phase contrast microscopy in order to see it, because this technique can see very small changes in refractive index. I didn't see anything.

Q. So you suspect that it's an index change rather than something else, like a birefringence change.

A. I expect, but I didn't see it. All possibilities, right? I cannot observe that anything has changed but I know that something has occurred.

Q. Definitely something has changed because the sample knows that.

A. But I don't know what it is. If I know, then it would be good, but I don't know.

Q. Second question. You monitored the third harmonic. How did you distinguish the third harmonic from the fundamental, the scattered light?

A. This morning, a gentle man already gave a talk about that. I can change the polarization to circular,…

Q. You can use a spectrometer, right?

A. No, I don't need to. One way is to change the polarization and if it disappears if it's the third harmonic,… then I can move from the front to back then I can get the distance. The third harmonic generated on the front surface and then the third harmonic from the back surface,… I think that this is a very definite way to do it.

Q. Because the third harmonic is more sensitive to the power.

A. Yes. That's one way to do it.