Numerical aperture dependence of damage and white light generation from femtosecond laser pulses in bulk fused silica

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ABSTRACT

The femtosecond laser has become an important tool in the micromachining of transparent materials. In particular, focusing at high numerical aperture enables structuring the bulk of materials. At low numerical aperture and comparable energy, focused femtosecond pulses result in white light or continuum generation. It has proven difficult to damage transparent materials in the bulk at low NA. We have measured the threshold energy for continuum generation and for bulk damage in fused silica for numerical apertures between 0.01 and 0.65. The threshold for continuum generation exhibits a minimum near 0.05 NA, and increases quickly near 0.1 NA. Greater than 0.25 NA, no continuum is observed. The extent of the anti-stokes pedestal in the continuum spectrum decreases strongly as the numerical aperture is increased to 0.1, emphasizing that slow focusing is important for the broadest white light spectrum. We use a sensitive light scattering technique to detect the onset of damage. We are able to produce bulk damage at all numerical apertures studied. At high numerical aperture, the damage threshold is well below the critical power for self-focusing, which allows the breakdown intensity to be determined. Below 0.25 NA, the numerical aperture dependence suggests a possible change in damage mechanism.

Keywords: Ultrafast lasers, laser-induced damage, laser micromachining, self-focusing, white light continuum generation, numerical aperture

1. INTRODUCTION

The nature of the interaction of femtosecond laser pulses with transparent materials depends sensitively on how tightly the pulses are focused into the material. When femtosecond pulses of sufficient energy are tightly focused into a transparent material, permanent damage is produced in the bulk of the material via nonlinear absorption[1-3]. This ability to locally alter the refractive index of the bulk of a transparent material has been exploited in many micromachining applications, including the direct writing of optical waveguides and waveguide splitters into bulk glass[4-8]. When femtosecond pulses of sufficient power are slowly focused into a transparent material, white-light supercontinuum generation is observed, resulting in the formation of a broad flat pedestal on the blue side of the pulse spectrum that can extend into the ultraviolet[9]. This supercontinuum generation has found numerous applications in ultrafast spectroscopy[10] and recently in precise frequency metrology[11]. Supercontinuum generation with tightly-focused pulses is not observed, and there is conflicting evidence as to whether or not permanent damage can be produced in bulk transparent materials with slowly focused pulses[12]. The fact that otherwise identical laser pulses produce damage when tightly focused, but supercontinuum when slowly focused highlights the focusing angle or numerical aperture (NA) as an important parameter governing how femtosecond laser pulses interact with and propagate in transparent materials[13]. Laser-induced breakdown verses self-focusing has been studied numerically with picosecond pulses[14], and the crossover from supercontinuum generation to optical breakdown as the numerical aperture is increased has been observed for picosecond pulses in CO_2 gas[15].

Here, we report a systematic study of the energy threshold for bulk damage and white-light generation for femtosecond pulses in fused silica as a function of the numerical aperture of the external focusing optics. We find that bulk damage can be produced at all numerical apertures investigated ($0.01 < NA < 0.65$), but that white light generation does not occur at 0.25 NA or higher. The morphology of the damage is found to be different for high and low numerical aperture.

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The dependence of the extent of the blue broadening in the supercontinuum as a function of numerical aperture is also studied.

2. EXPERIMENTAL

The laser is a multipass-amplified Ti:Al_2O_3 laser operating at 1 kHz with a center wavelength of 800 nm and a pulse duration of 50-60 femtoseconds. These focusing studies depend critically on the spatial mode quality of the laser beam. To achieve a good mode profile, the central portion of the main beam diffracts through an iris several meters upstream from the experiment, and the central spot of the resulting Airy pattern is enlarged with a telescope to about 8 mm, while the other fringes are spatially filtered close to the focusing lens. This provides a very smooth near-Gaussian beam. Spot size and beam quality in front of the focusing lens are evaluated using a CCD camera.

Various lenses or objectives are mounted after the Airy pattern is spatially filtered, and the fused silica sample (ESCO, UV-grade Q1) is positioned with 3D translation near the focus of this lens, both normal to the beam propagation and flat relative to the transverse translation. The pulse energy is adjusted with neutral density filters and a waveplate/polarizer combination, and is measured on a calibrated photodiode.

When using singlet lenses, the numerical aperture is determined from the $1/e^2$ beam radius, $r_{e^{-2}}$, incident on the lens and the specified focal length, *f,* of the lens by the relation

$$NA = \sin\left(\tan^{-1}\left(\frac{r_{e^{-2}}}{f}\right)\right). \quad (1)$$

Focal lengths from 300 mm to 63 mm and an input beam size around 7-8 mm yield numerical apertures between 0.01 and 0.06. Above 0.065 NA, the spherical aberration introduced by a singlet lens prevents diffraction limited focusing, and microscope objectives (which are corrected for spherical aberration) were used to obtain numerical apertures between 0.08 and 0.65.

The threshold for white light generation is obtained by measuring the pulse energy at which the spectrum of the pulse has broadened such that 720-nm radiation is just visible to the dark-adapted eye, viewed through a color filter. This criterion is chosen because 720 nm is near the long-wavelength edge of the typical white light pedestal. Once the energy threshold is determined for a given numerical aperture, the energy is increased by 60% and 100% and the spectrum at these energies is recorded with a spectrometer. Because at some numerical apertures damage occurs below the white light threshold, the sample is always translated at 20 mm/s while spectra are collected, so that each pulse is incident on a fresh section of the sample.

The damage threshold is measured with a scattering technique[16]. A helium-neon laser is copropagated with the 800-nm pulse through the focusing lens into the sample. The transmitted He:Ne is collected with a microscope objective at a numerical aperture higher than that used for focusing, and this collected light is blocked. When the 800-nm pulse produces permanent damage, some of the He:Ne light is scattered into a larger angle, and focused past the beam block where it can be detected. Because damage produced at low numerical apertures accumulates very slowly, we took the threshold to be the highest energy at which 10^4 pulses produced no detectable scattering.

The BK7 singlet lenses used in our experiment do not introduce appreciable dispersion, and therefore we minimize the temporal duration of the pulse using a measurement made just in front of the focusing lens. However, because of the multiple elements and different glasses in high-NA microscope objectives, dispersion cannot be ignored, and the pulse must be pre-chirped to compensate for this dispersion. It has been shown that, using only a simple pulse compressor, nearly all of the dispersion introduced by most high-NA microscope objectives can be compensated for[17]. Since it was not possible with our apparatus to measure the pulse duration at the focus of the objective, we minimized the damage threshold by adjusting the pulse compressor and took this threshold to correspond to the shortest pulse duration we measured in front of the objective.

3. RESULTS

The energy threshold for white light generation was found to depend on the position of the focus relative to the sample surface. For consistency and for ease of interpretation, thresholds were only taken with the focus within the sample. In this case, the threshold for white light generation decreases as the focus is moved into the sample from the surface, exhibiting a minimum at a depth of around one confocal parameter (several confocal parameters at the higher NAs) where the confocal parameter, *b*, is given by

$$b = 2z_r = \frac{2\lambda}{\pi}\frac{1-NA^2}{NA^2}, \tag{2}$$

where λ is the laser wavelength. This minimum threshold was recorded.

The characteristic white-light spectrum exhibits a broad pedestal with a sharp cutoff in the blue region of the spectrum. The blue broadening was taken as the shortest wavelength in the pedestal above the background, and is expressed as the difference in energy between this cutoff wavelength and the 800-nm (1.55 eV) pump wavelength. It was ascertained that for a given numerical aperture at the proper depth within the sample, the blue broadening was greatest when the energy was increased 60% above the threshold energy. Figure 1 shows that the blue broadening at both 60% above threshold and twice threshold decreases strongly with numerical aperture, emphasizing that to obtain the broadest white light spectrum, slow focusing should be employed. No white light was observed at numerical apertures of 0.25 or greater, even up the highest laser energy available from the system (10 μJ).

The damage threshold similarly depends on the depth of the focus within the sample. For the 0.25 NA and 0.45 NA objectives, where the damage threshold corresponds to a power significantly below the critical power for self-focusing, the bulk damage threshold is greater than the surface damage threshold and constant for many confocal parameters into the sample. We therefore measure the damage threshold with the focus located a couple of confocal parameters into the sample. The 0.65 NA objective is deisgned to optimally focus through 170 um of glass, and hence focusing with this objective gives a minimum threshold around this depth. At lower numerical apertures, however, where self-focusing plays an important role, the damage threshold decreases as the focus is translated into the sample, and plateaus consistently at about one confocal parameter. The threshold is taken at the depth of this plateau.

Figure 2 shows the energy thresholds for damage and white light generation for all of the numerical apertures under investigation. Side view optical microscopy of fused silica samples exposed to pulse energies from two to five times the damage threshold at numerical apertures throughout the range studied confirm that bulk damage is produced in all cases, and that the surface is not affected.

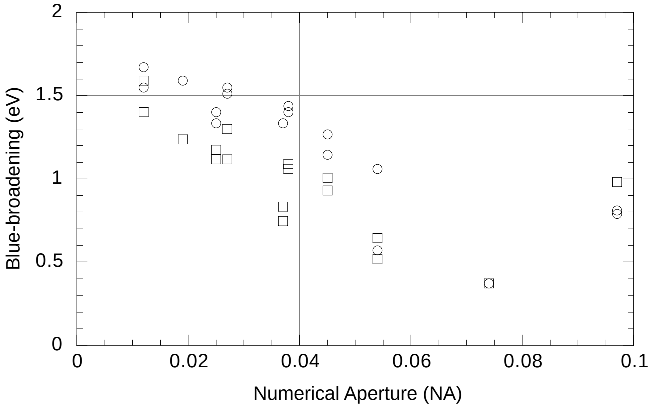

Fig. 1: Blue broadening of continuum vs numerical aperture for 60% above threshold (circles) and 100% above threshold (squares).

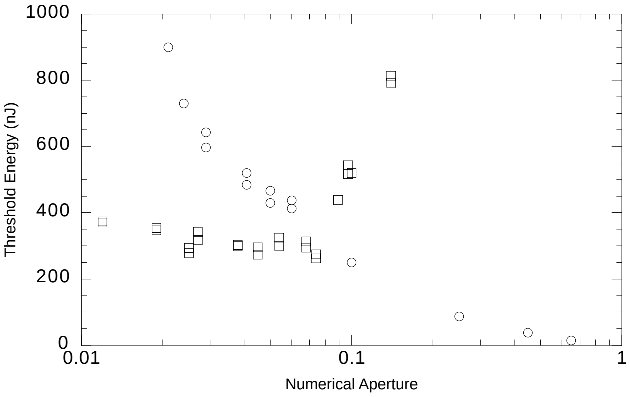

Fig. 2: Threshold energy for onset of bulk damage (circles) and continuum generation (squares) for 55-fs pulses at 800 nm.

4. DISCUSSION

We have found that numerical aperture divides the interaction of focused short pulses with transparent materials into three regimes: for a numerical aperture of 0.25 NA and above, bulk damage is produced for energies above threshold, and continuum is never observed. The onset of damage is abrupt and deterministic. In the range of 0.15 to 0.05 NA, we observe white light generation but multiple shots show the accumulation of bulk material modification, that quickly causes the white light to disappear. Finally, below 0.05 NA, it is possible to damage the bulk, but this happens only at energies significantly above the threshold for white light generation.

This dramatically different behavior can be understood in the following manner. The pulse energies in the high-NA regime correspond to powers below the critical power for self-focusing, and hence the external focusing dominates. The beam rapidly collapses, producing intensities greater than 10^{13} W/cm^2 and allowing the production of a critical density plasma via nonlinear absorption[2]. Much of the pulse energy is thus deposited into the material at the focal volume either through nonlinear absorption or subsequent linear absorption of the plasma, causing bulk material modification. No continuum is produced before the focus because the pulse does not propagate at high intensity for an appreciable distance, and so there is no interaction length over which self phase modulation can accumulate or an optical shock can form[13]. Even at higher pulse energies, above the critical power, the absorption of energy at the focus prevents subsequent recollapse of the pulse via self-focusing.

At low NA, self-focusing acts to increase the pulse intensity, but over a longer distance. A low density electron plasma is formed that counteracts self-focusing, preventing the formation of a critical density plasma and single-shot damage. Continuum is generated by the accumulation of self phase modulation modified by other nonlinear effects (self-steepening, space-time focusing)[13]. As the NA is increased, diffraction causes the divergence of the pulse earlier, and hence there is less interaction length and less blue-broadening.

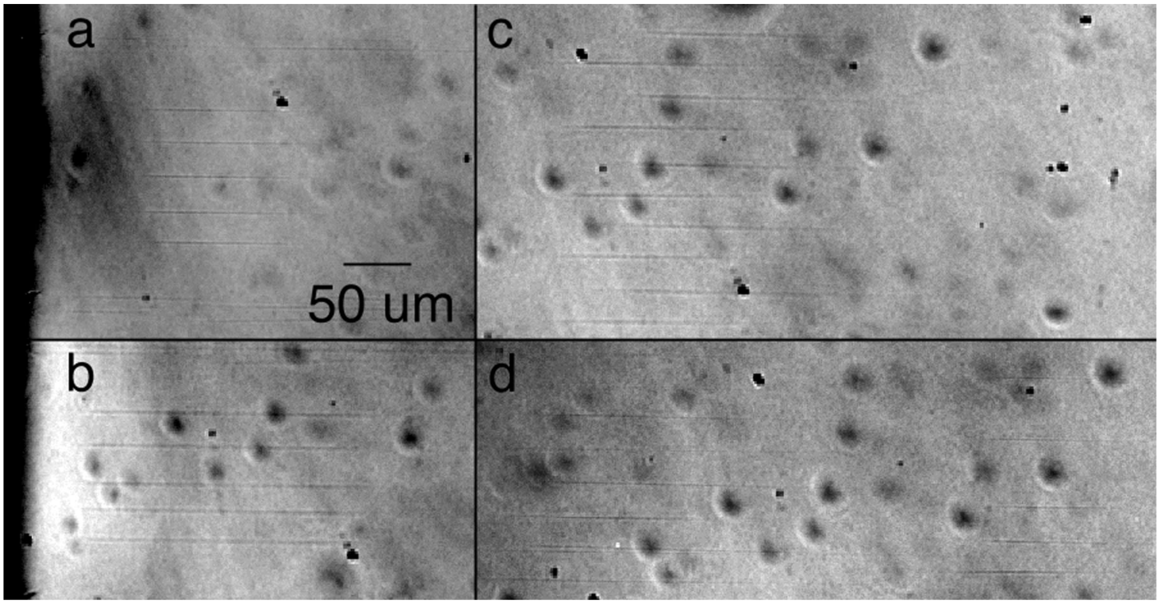

Fig.3: Side view optical microscope images of damage structures produced at 0.055 NA (a and b) and 0.025 (c and d). 5 exposures of 10^4 pulses each were made in each sample, separated by 25 um. Pulse energies were a) 850 nJ (2x threshold) b) 1300 nJ (3x threshold) c) 2050 nJ (3x threshold) and d) 3260 nJ (5x threshold). There was no visible damage at 0.025 NA for 3x threshold.

The slow accumulation of damage at low numerical apertures is an indication of a damage mechanism different from that resulting from the critical density plasma formed at high-NA. A preliminary optical microscopy study also supports a different damage mechanism. Figure 3 contrasts the damage morphology resulting from femtosecond pulses focused at 0.055 NA and at 0.025 NA. At the higher NA, damage structures comparable in length to the 170 um confocal parameter are visible in the bulk. (130 um long in a, and 220 um in b.) At the lower NA, however, the damage appears before the focus, and outlines the edge of the focusing pulse. At the higher energy, there is also axial damage at the focus. The origin of this new damage morphology is unclear. Efimov, *et al.* have observed the formation of color centers in the bulk of some silicate glasses under slowly-focused femtosecond irradiation. They attribute this to the linear and two-photon absorption of the blue edge of the supercontinuum[18]. Additionally, ultraviolet radiation is known to cause densification of silica[19] and is widely used in writing fiber Bragg gratings. It is possible, then, that it is the continuum itself slowly causing color center formation or densification over many laser shots via two-photon (instead of multiphoton) absorption. Further analysis of the silica samples is needed to fully characterize this low-NA damage mechanism.

5. CONCLUSION

We have studied the numerical aperture of the external focusing as a critical parameter in the interaction of femtosecond laser pulses with transparent materials. At high NA, single shot, catastrophic damage occurs and continuum generation is not observed. At low NA, continuum generation is produced, but bulk material modification accumulates over time at energies above the continuum generation threshold. Bulk micromachining is only practical for numerical apertures of 0.25 and above, where self-focusing effects are minimal and spot size and focal position can be accurately predicted. Further, as the NA is increased, the energy necessary to effect material modification decreases, minimizing collateral damage. While white light continuum can be produced at a range of NAs up to 0.1, the spectrum is broadest at the lowest NA. Also at the lowest NA, white light is produced well below the damage threshold. Further experiments will help to elucidate the fundamental mechanisms of short-pulse-material interaction.

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