Femtosecond Laser-Induced Microexplosions in Transparent Materials

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The field of laser-induced damage in transparent materials has been under investigation since optical breakdown was first observed by Maker *et al.* in 1963 [1]. The nonlinear absorption mechanisms (multiphoton and tunneling ionization and avalanche ionization) responsible for optical breakdown and damage in transparent materials are strongly intensity-dependent. The femtosecond laser is therefore an ideal tool to study these processes as the high intensity necessary to produce breakdown (on the order of 10^{13} W/cm^2) can be reached with very little energy (as little as 5 nJ per pulse with a 100 femtosecond pulse). Femtosecond lasers have therefore revolutionized the field of laser micromachining as the low energy per pulse yields minimal collateral damage and hence high resolution in micromachining applications.

After reviewing some of the fundamentals of surface and bulk damage in transparent materials, this talk will present an overview of work being done in our laboratory on tightly focusing femtosecond pulses into the bulk of transparent materials with an emphasis on materials processing and micromachining.

When high-intensity optical radiation interacts with a transparent material, energy can be absorbed through the nonlinear absorption mechanisms of multiphoton and tunneling ionization [2] and avalanche ionization [3, 4]. If a laser pulse is tightly focused into the bulk of a material, this absorption produces a microscopic, hot electron plasma within the focal volume, which then expands into the surrounding material, forming a cavity inside the sample. We have previously reported the production of 200-nm diameter damage structures inside transparent solids using this technique [5,6]. In addition, we have studied the dynamics of the plasma expansion [7], and the thresholds for damage in several materials [8].

The threshold energy for creation of damage can be measured very precisely using a dark-field scattering technique. The 100-fs, 800-nm pump pulse is focused using microscope objectives with numerical apertures between 0.25 and 1.4 NA into the glass sample. The focal volume is probed at a lower numerical aperture with a He-Ne laser, and the directly transmitted He-Ne light is blocked. When damage occurs, some of the He-Ne light is scattered around the beam block to a detector. Figure 1 shows the energy threshold obtained using this technique for Corning 0211 for a range of numerical apertures. Taking into account the effects of self-focusing, the spot size at each numerical aperture can be estimated and a threshold intensity can be fit to the data. At the highest numerical aperture (1.4 NA), the threshold energy is only 5 nJ [9]. This low

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threshold energy has opened up a whole new mode of machining in the bulk of transparent materials, because this pulse energy is attainable with just a laser oscillator, operating at MHz repetition rates. Because the time between pulses from a MHz oscillator is smaller than the typical thermal diffusion time, successive pulses cumulatively heat the sample in the focal volume, leading to a damage mechanism fundamentally different from the mechanism for damage produced by amplified femtosecond lasers operating at kHz repetition rates. Figure 2 shows optical images of damage in Corning 0211 glass made with various numbers of pulses from a long-cavity femtosecond oscillator operating at a 25 MHz repetition rate, illustrating a new thermal machining effect. We have used this technique to machine waveguides and waveguide splitters.

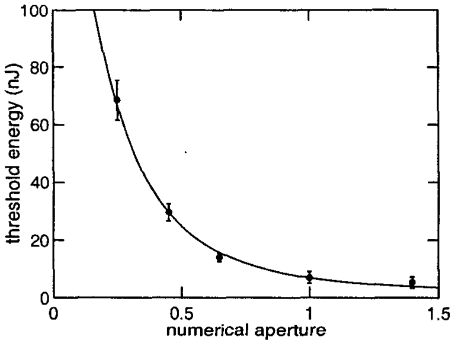

Figure 1: Dependence of threshold energy for producing structural change on NA of the focusing objective for 100 fs pulses in Corning 0211. From Ref 9.

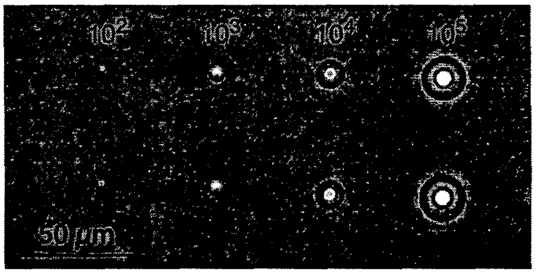

Figure 2: Optical micrograph of damage in Corning 0211 glass showing thermal damage mechanism. The laser operates at 25 MHz, and is incident perpendicular to the plane of the figure. The number of shots per spot is indicated at the top.

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