Laser induced microexplosions and applications in laser micromachining

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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 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^{17} W/m^2) can be reached with very little energy (as little as 5 nJ per pulse with a 100-fs 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. Furthermore, focusing the pulse with high numerical aperture microscope objectives allows machining of the bulk without affecting the surface, because the intensity is only above the breakdown threshold in the focal volume.

After reviewing some of the fundamentals of surface and bulk damage in transparent materials, we 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 is 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, resulting in a permanent index change. If the focused pulse is energetic enough, the expanding plasma forms 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].

Because optical breakdown exhibits an intensity threshold, the pulse energy necessary to cause damage decreases as the numerical aperture of the focusing objective is increased. For a 100-fs pulse focused with a 1.4 NA oil-immersion objective, the bulk damage threshold of Corning 0211 glass is just 5 nJ [9]. This low threshold energy opens up a new method 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 thermal diffusion time in glass, successive pulses cumulatively heat the sample at the focus. When many pulses are incident on the same volume, a small region of the sample melts. Subsequent cooling of this region results in a permanent change in index.

By translating a glass sample transverse to the laser propagation direction, we used this technique to machine waveguides and waveguide splitters in microscope slide glass, and have evaluated the effect of translation speed on the resulting waveguides. Figure 1 shows refractive index profiles of the cross sections of such waveguides produced at different translation speeds, as well as the resulting near-field modes of laser light coupled into the guides. Waveguides are 50 mm long, and the laser is a 25 MHz long-cavity Ti:Al_2O_3 oscillator operating at 800 nm. Pulse energy delivered to the sample is 10 nJ in a 55-fs pulse. As can be seen from the figure, single-mode propagation is obtained for the waveguide fabricated at the highest translation speed (20 mm/s); the waveguides made at lower speeds produced a donut-shaped mode. We are currently evaluating the morphology dependence of the repetition rate of the laser and the laser pulse energy, with the goal of optimizing the waveguide properties. The oscillator-only micromachining technique is particularly attractive because it enables the manufacture of three-dimensional photonic devices.

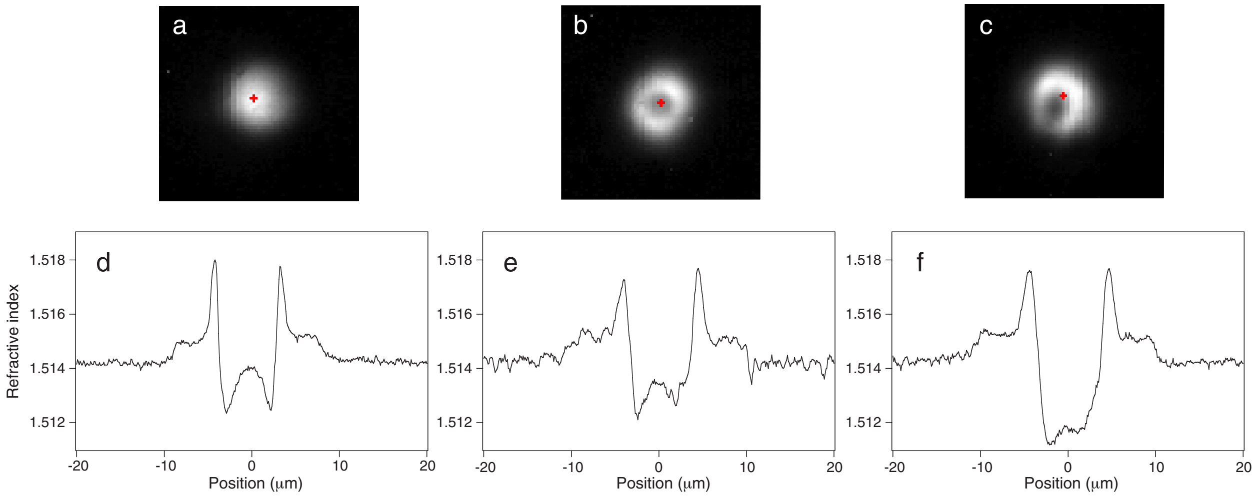

Figure 1: Waveguide evaluation. Frames a, b, c, show the near-field mode of 1550 nm laser light coupled into waveguides fabricated by translating the sample at 20 mm/s, 10 mm/s and 5 mm/s, respectively (cross shows mode centroid). Frames d, e, f show refractive index profiles obtained using the refractive near-field technique of each of these waveguides. Single mode propagation is obtained with the waveguides made at 20 mm/s, where the central bump in the index is most pronounced.

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