Femtosecond laser micromachining of bulk glass at oscillator energies

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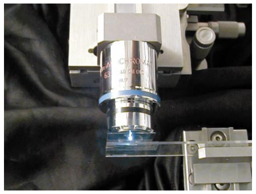
Introduction



Femtosecond laser pulses offer many advantages for precision micromachining of transparent materials. One obstacle for widespread use of this technology is the complexity and cost of the amplified laser systems usually required.

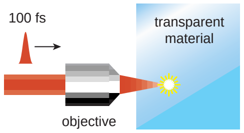
We combine a high-energy Ti:Sapphire laser oscillator and tight laser focusing to create damage in optical glass without amplification.

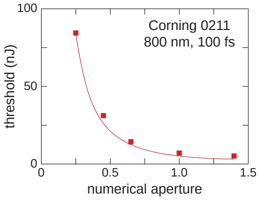
- **In the single-shot regime, we create sub-micron damage spots.**
- **For multiple shots at high repetition rate, we generate micron-sized thermal damage.**
- **Using this technique we can machine single-mode waveguides inside optical glass.**

Experimental technique

Extremely tight focusing and a femtosecond long-cavity laser oscillator allow the damage threshold of optical glass to be reached without amplified pulses.

Tight focusing: Femtosecond laser pulses are tightly focused in the bulk of a transparent material. At the focus, the intensity is high enough to cause absorption through nonlinear processes (field and avalanche ionization). When enough energy is deposited, the material is damaged.





Optical damage: The energy required to damage the material is lower with tighter focusing.

- The dependence of the energy threshold on numerical aperture (NA) gives the intensity required for damage:

$$I_0 = 2.5 \times 10^{13}\ \mathrm{W/cm^2}.$$

- For the 1.4 NA objective, only 4 nJ of laser energy is required for damage (~ 8 nJ before the objective).
- Standard objectives with NA larger than 0.65 focus well only in microscope cover-slip glass (Corning 0211).

Long-cavity oscillator: To achieve the energy necessary for damage without amplification, we extended the cavity length of our Ti:Sapphire laser by 4 m. The average power of the laser remains about the same, but the repetition rate is decreased, giving higher energy per pulse. With this laser, we obtain 20-nJ pulses in a stable, 25-MHz pulse train, with a 50-nm (FWHM) bandwidth.

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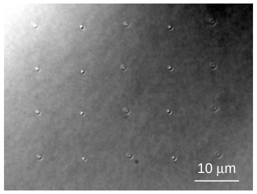
Damage morphology and mechanisms

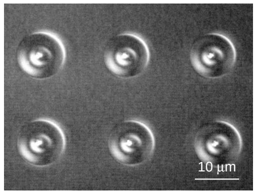
We use optical microscopy to characterize the damage produced both by single laser pulses and by multiple, 25-MHz repetition-rate pulses.

Single-shot damage



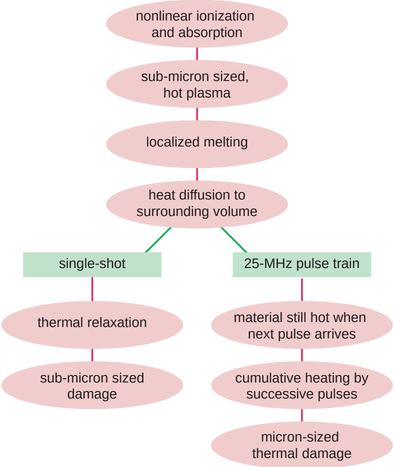
Optical microscope image of damage produced with single 10-nJ, 100-fs laser pulses. Determination of the diameter of the structures is limited by the 0.5-μm resolution limit of the microscope.

25-MHz, multiple-shot damage



Optical microscope image of damage produced with 25,000 successive 5-nJ, sub-100-fs pulses arriving at 25 MHz. The damage shows concentric rings of 10- and 5-μm diameter with a 1-μm diameter bubble at the center.

Mechanisms



nonlinear ionization and absorption
sub-micron sized, hot plasma
localized melting
heat diffusion to surrounding volume

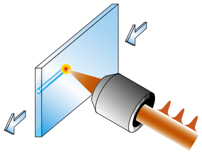
single-shot
thermal relaxation
sub-micron sized damage

25-MHz pulse train
material still hot when next pulse arrives
cumulative heating by successive pulses
micron-sized thermal damage

Waveguide machining

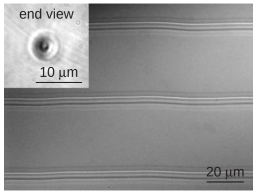
We machine waveguides inside bulk glass and examine the propagation of light through the structures.

Writing waveguides



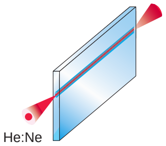
The thermal damage produced with the 25-MHz laser results in an increased index of refraction at the core of the damage spot. By rapidly scanning the focal spot inside the glass a waveguide is formed.

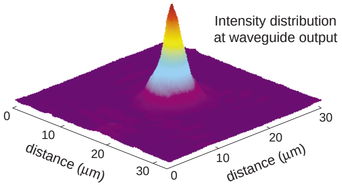
Waveguide morphology



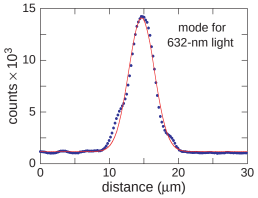
Waveguides written with 4.5-nJ, sub-100-fs pulses focused by a 1.4 NA objective. The sample was translated at 20 mm/s. We machined waveguides as long as 15 mm.

Waveguide mode





Intensity distribution at waveguide output



The mode of the waveguide is well fit by a Gaussian. From the divergence of the cone of light emitted at the output of the waveguide, we estimate that the change in refractive index at the core is 2×10^{-4}.

By combining thermal and explosive micromachining, we can create a variety of structures and devices using only a low-cost femtosecond laser oscillator.