Morphology and mechanisms of femtosecond laser-induced structural change in bulk transparent materials

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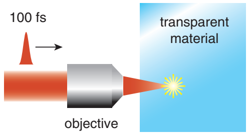
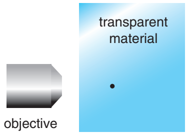
Introduction



When a powerful femtosecond laser pulse is tightly focused inside a transparent material, the laser intensity in the focal volume can be high enough to induce nonlinear absorption of laser energy by the material.



If enough energy is deposited, permanent structural changes are produced. Because the absorption is nonlinear, the structure is formed in the **bulk** of the material without affecting the surface.

Motivation

Characterization of the morphology of the structural change and identification of the mechanism for producing these structures is essential for the successful application of femtosecond lasers for micromachining bulk transparent materials. Here, we examine the morphology of the structures produced by single pulses using optical and electron microscopy and introduce a new mechanism for producing structural change using high repetition-rate pulse trains.

Key results

- **Structure size only determined by focal volume near threshold**
- **Transition from small density change to explosively-formed void with increasing laser energy**
- **High repetition-rate femtosecond pulse trains can provide a bulk point source of heat inside transparent materials**

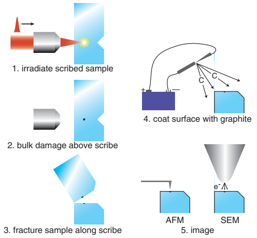
Single shot — electron microscopy

We use electron microscopy to probe details in the morphology of the structures produced by femtosecond laser pulses that cannot be resolved optically.

Introduction

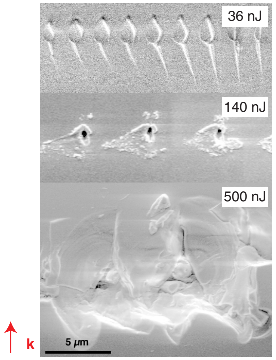
Optical microscopy does not reveal many detailed features of the structural change morphology because these details are at the optical resolution limit. Because these small-scale features may reveal information about the mechanism for producing the structural change, we obtain higher resolution images of the structures using electron microscopy.

Sample preparation



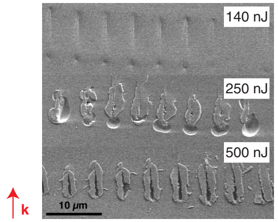
Because scanning electron microscopy (SEM) is a surface imaging tool, the structures must be brought to the surface of the sample before imaging. We fracture samples that have been densely filled with structures. The fracture plane goes through some of the structures, allowing side-view electron microscopy.

1.4-NA focusing



SEM image of structures produced by single 100-fs pulses with different energy focused by a 1.4-NA oil-immersion microscope objective.

0.45-NA focusing



SEM image of structures produced by single 100-fs pulses with different energy focused by a 0.45-NA microscope objective.

Density change to void transition

At laser energies just above threshold, a small density change is produced in the glass, most likely by melting and nonuniform resolidification or by nonthermal bond breaking and structural rearrangment. At higher laser energies, an explosive expansion of the laser-produced plasma carries material out of the focal volume, leaving a void or less dense region with a denser surrounding halo.

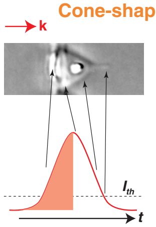
Single shot — optical microscopy

Optical microscopy reveals the shape of the structures produced in bulk material by tightly-focused femtosecond laser pulses.

Introduction

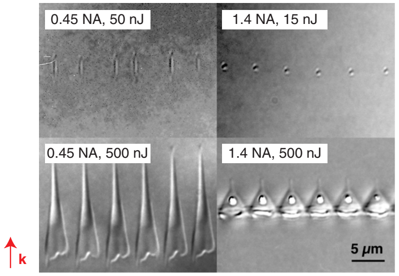
Using optical microscopy, we examine the laser energy and focusing angle dependence of the structural change morphology. For reference, the intensity threshold for producing a structural change for 100-fs pulses is 2.8 x 10^{13} W/cm^2 for the borosilicate glass (Corning 0211) used in these studies, corresponding to 30 nJ and 5 nJ with 0.45 and 1.4 numerical aperture (NA) focusing, respectively.

Cone-shaped structures



Successive time slices of the pulse are absorbed upstream from the laser focus, forming the cone. The second half of the pulse is absorbed by the plasma formed by the peak of the pulse, leading to extensive cracking at the base of the cone.

Microscopy results



Side-view differential interference contrast microscope image of structures produced by single 100-fs laser pulses with different laser energy and focusing parameters.

Implications for micromachining

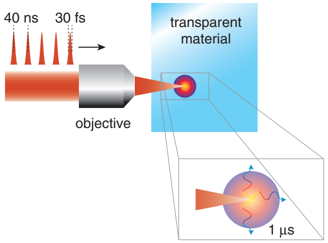
The extent of the structural change is determined by the focal volume of the microscope objective for pulse energies near the threshold, allowing precise three-dimensional refractive index patterning of transparent materials. At higher laser energy, larger refractive index changes are produced, but the structural change extends outside the focal volume.

Multiple shot at high repetition rate

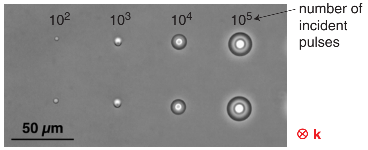
At high repetition rate, multiple laser pulses provide a sub-micrometer-sized heat source located in the bulk of a transparent material.

Introduction

The time required for energy nonlinearly absorbed in the focal volume to diffuse into the surrounding material is about 1 μs. If the time interval between successive laser pulses is less than this thermal diffusion time, then energy is deposited into the focal volume at a rate that is faster than it can escape, providing a sub-micrometer-sized heat source located in the bulk of the material. Material melted by this bulk heat source resolidifies nonuniformly due to the temperature gradients, leading to refractive index changes.

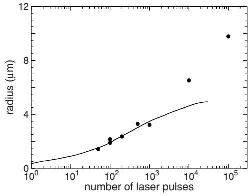


Optical microscopy



Optical microscope image of structures produced by 25-MHz trains of 30-fs pulses focused by a 1.4-NA microscope objective for different number of incident pulses.

Modeling



Radius of the structure produced by 25-MHz trains of 30-fs laser pulses as a function of the number of incident pulses. The line represents the predicted radius based on the diffusion equation. The discrepancy at high pulse numbers is likely due to the change in the thermal properties of the glass as it heats and melts.

Applications

By translating the sample at 20 mm/s perpendicular to the incident direction of the femtosecond pulse train, we directly write single-mode optical waveguides into bulk glass. This ability to directly write waveguides in three dimensions may become important for the fabrication of telecommunications devices and in photonics device packaging. In addition, thermally-induced chemical reactions could be driven in bulk material using this technique, perhaps altering the solubility properties of the material for the fabrication of micromechanical systems.

With this technique, we can precisely (+/- 1 nJ) deposit thermal energy into a sub-micrometer-sized volume inside the **bulk** of a transparent material.

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