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

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Introduction

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.

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.

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

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 cools 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.

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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