Transition from repetitive to cumulative thermal processing in femtosecond laser induced machining of embedded waveguides

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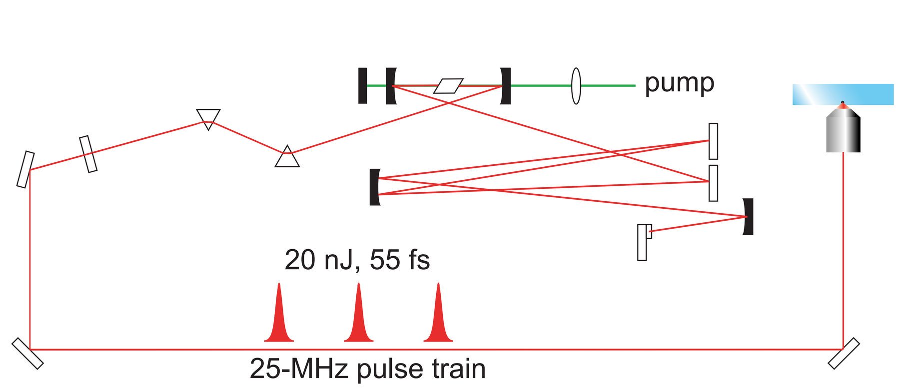
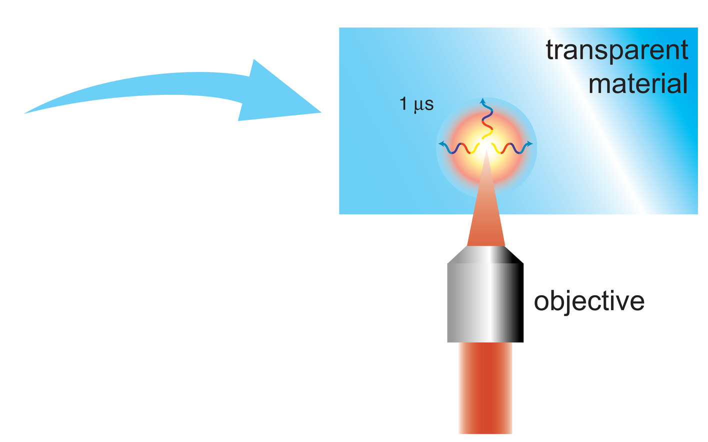
Introduction

Tight focusing of femtosecond pulses results in extremely high intensities even at moderate pulse energies. The high intensity at the focus can lead to nonlinear absorption of laser energy in transparent materials.

At MHz pulse repetition rates, the time interval between pulses is smaller than the heat diffusion time; energy therefore accumulates in the focal volume, heating and melting a micrometer-sized region in the bulk of the material.

Nonuniform cooling of the melted volume results in a permanent change in index of refraction. We exploit this index change to fabricate waveguides and optical components in bulk glass.



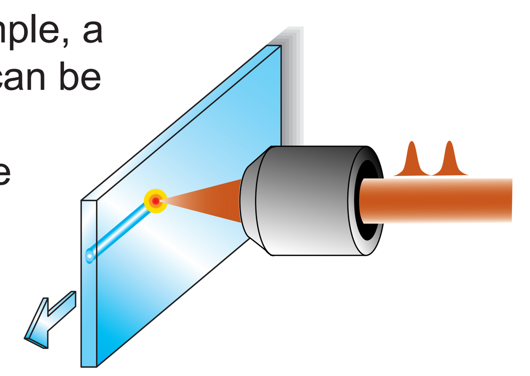


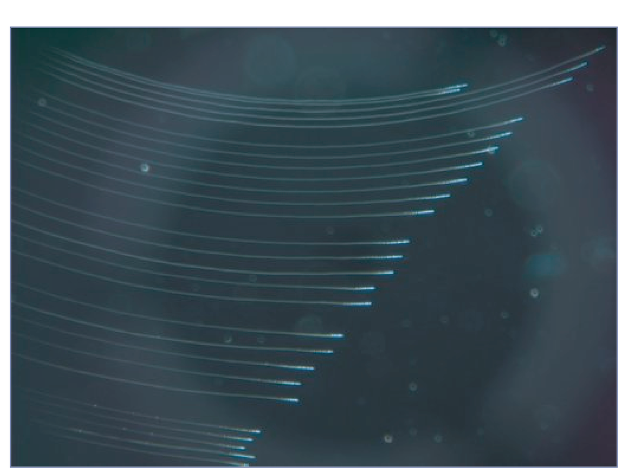
By extending the cavity of a standard Ti:sapphire laser oscillator, we generate a 25-MHz pulse train of 20-nJ pulses — enough energy to produce nonlinear absorption.

Because a thermal mechanism is responsible for the index change, the modified region is larger than the focal volume. The structurally modified region can be made large enough to guide light.

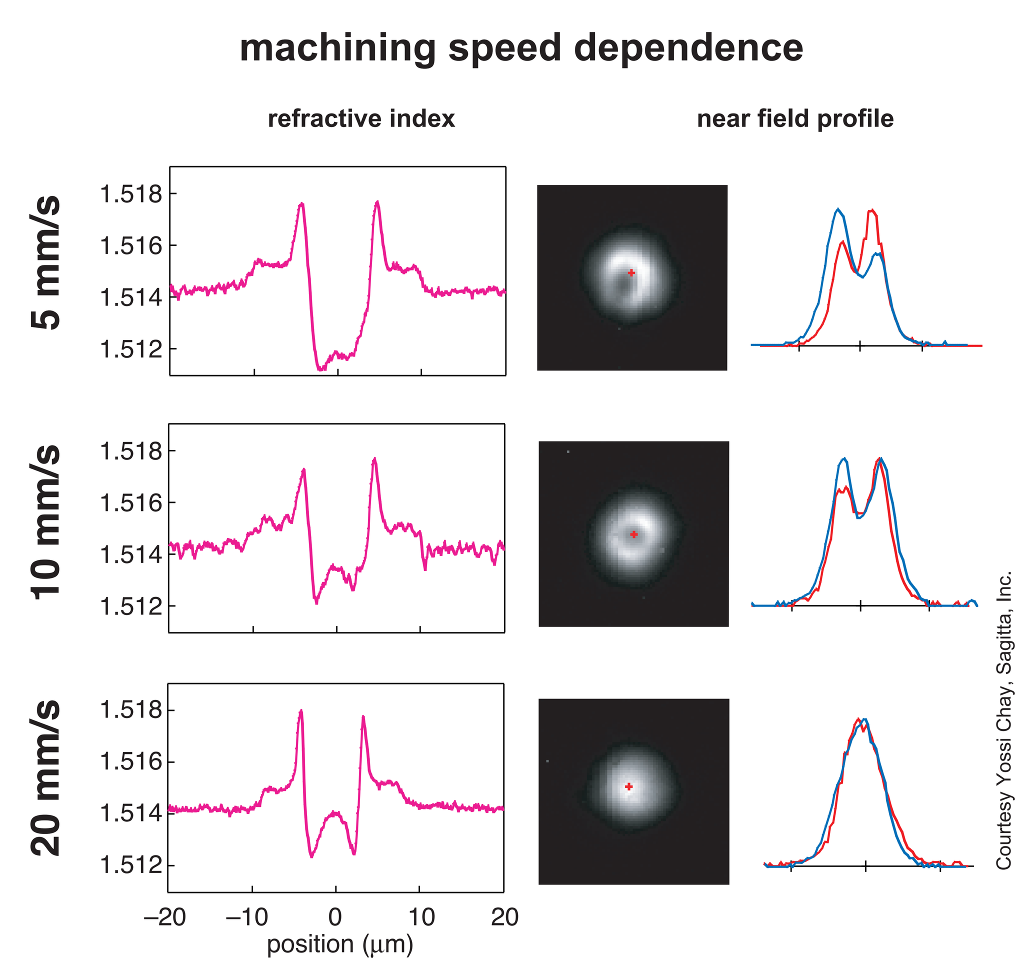
Bulk micromachining of waveguides in silica

By translating the sample, a continuous structure can be machined. The index modifications for these structures depend on the number of pulses and on the material.





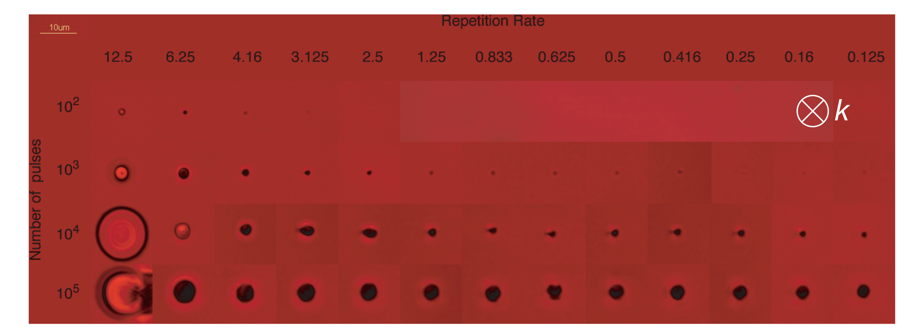
Dark-field optical micrograph of a curved waveguide written in Corning 0211 glass.



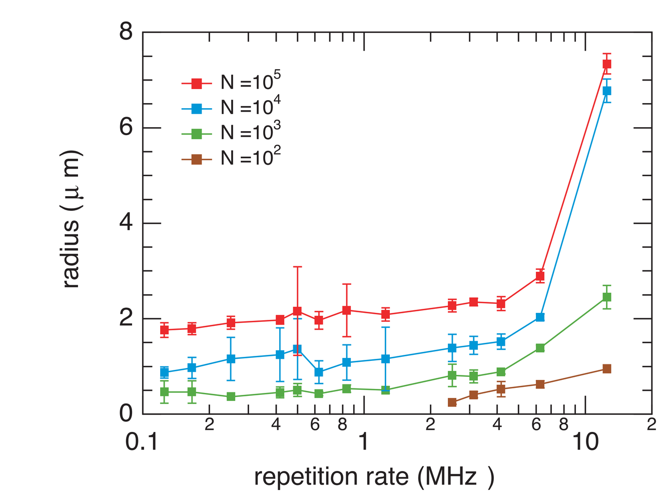
Index profile at 633 nm and near-field mode at 1550 nm for various machining speeds. Waveguides machined at 20 mm/s support single-mode operation.

Repetition-rate dependence of bulk micromachining

The heat diffusion time of a material determines the time required for heat deposited in the material to diffuse out the focal volume. When the interval between consecutive pulses is less than the heat diffusion time (cumulative regime), heat accumulates from pulse to pulse, producing structures larger than the focal volume. When the time between pulses exceeds the diffusion time (repetitive regime), each pulse acts independently, and the radius of the structure is independent of the laser repetition rate.



Top view optical microscope image of dots written in As_2S_3 for various numbers of pulses and repetition rates (beam incident perpendicular to image).

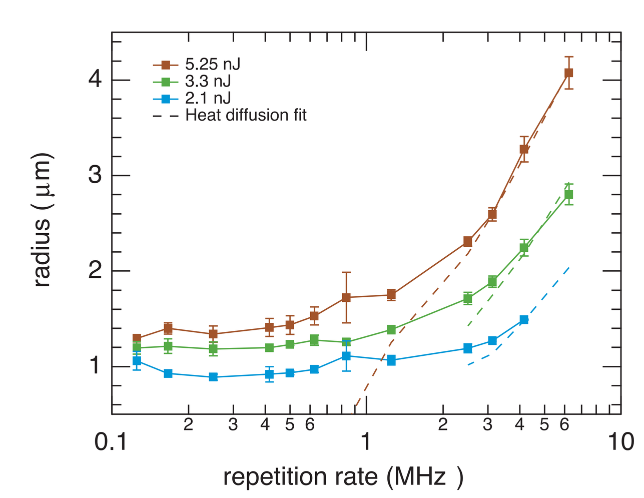


Repetition-rate and pulse-number dependence of the radius of structures produced in As_2S_3.

Below 3 MHz 100 pulses are not enough to form visible structures.

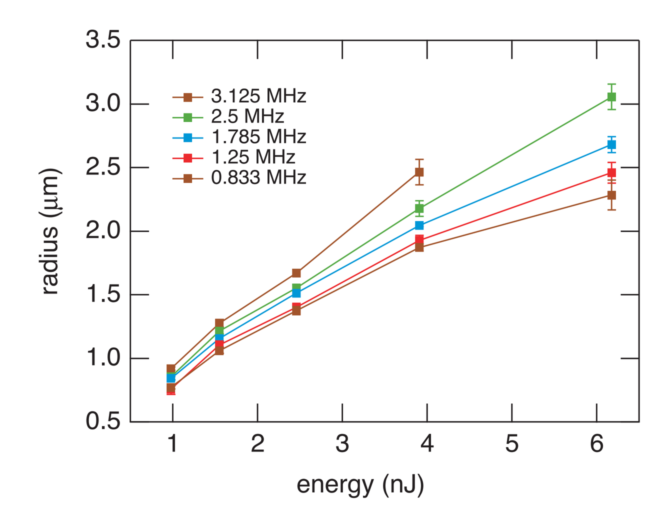
Comparison to heat diffusion calculation

We applied a numerical solution for the heat diffusion equation to simulate the growth of structures in the cumulative regime. To decrease our measurement error we machined continuous structures and measured the cross-sectional radius. The dashed lines in the graph below give predicted values for the cross-sectional radius of the structures from the heat diffusion equation.



Repetition-rate and pulse energy dependence of the cross-sectional radius of structures (2500 pulses per irradiated spot).

The crossover from the repetitive to the cumulative regime occurs around 1 MHz. This can be seen by the steep increase in radius for laser repetition rates above 1 MHz and the relatively flat section below 1 MHz. However, the heat diffusion time for As_2S_3 is 8 µs, corresponding to a repetition rate of 0.125 MHz.



Pulse energy and repetition-rate dependence of the cross-sectional radius of structures (12500 pulses per irradiated spot).

For pulse energies less than 1.0 nJ the repetition rate has a negligible effect on the cross-sectional radius. The transition point from repetitive to cumulative regime depends both on the laser pulse energy and the laser repetition rate.

Future directions

We are investigating the index profile of structures written with laser repetition rate and energy parameters in the repetitive and cumulative regimes. The index profiles will clarify the role of the energy deposition and cooling rate in the machining of embedded waveguides, allowing optimization of the index change.

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