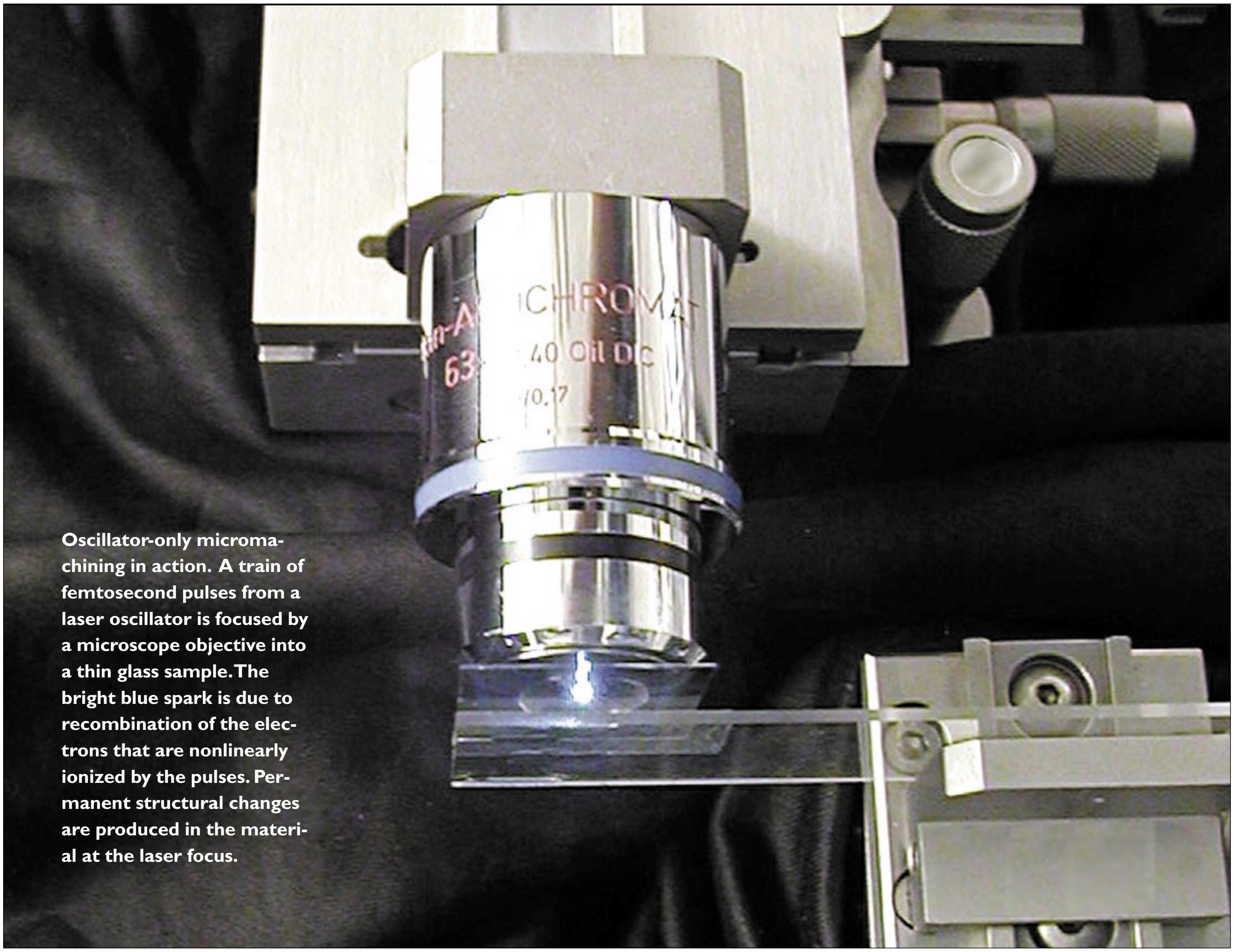

Oscillator-only micromachining in action. A train of femtosecond pulses from a laser oscillator is focused by a microscope objective into a thin glass sample. The bright blue spark is due to recombination of the electrons that are nonlinearly ionized by the pulses. Permanent structural changes are produced in the material at the laser focus.

Micromachining using ultrashort pulses from a laser oscillator

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In recent years femtosecond laser pulses have been used to micromachine a great variety of materials. Ultrashort pulses cleanly ablate virtually any material with a precision that meets or exceeds that of other laser-based techniques, making the femtosecond laser an attractive micromachining tool.[1] In transparent materials, where micromachining relies on nonlinear absorption, femtosecond lasers allow three-dimensional microfabrication with submicrometer precision.[2, 3] These lasers can produce three-dimensionally localized refractive index changes in the bulk of a transparent material, opening the door to the fabrication of a wide variety of optical devices. Until recently, micromachining of transparent materials was believed to require amplified laser systems. We have found, however, that transparent materials can also be micromachined using tightly focused trains of femtosecond laser pulses from an unamplified laser oscillator. In addition to reducing the cost and complexity of the laser system, femtosecond laser oscillators enable micromachining using a multiple-shot cumulative effect. We have used this new technique to directly write single-mode optical waveguides into bulk glass.

When a femtosecond laser pulse is tightly focused inside a transparent material, the laser intensity at the focus becomes high enough to induce nonlinear absorption through a combination of multiphoton absorption, tunneling ionization, and avalanche ionization.[4-6] If the absorption deposits enough energy in the material, permanent structural changes are produced. These structural changes are confined to the focal volume because of the nonlinear nature of the absorption. To micromachine a three-dimensional device, the laser focus is scanned around inside the bulk of the transparent material, producing structural changes in the irradiated regions.

Morphology of structural changes

For 100-fs, 800-nm pulses from a Ti:Sapphire laser, the intensity threshold to induce permanent structural change in borosilicate glass* is 2.8 X 10^{17} W/m^2.[3] The laser energy required to reach this threshold intensity depends on how tightly the laser beam is focused. For example, with a 0.45 numerical aperture (NA) microscope objective—the 20^X magnification objective found on most optical microscopes—the intensity threshold is reached with a pulse energy of 30 nJ.

Figure 1 shows a hexagonal array of structures produced about 100 μm beneath the surface of a glass sample using single, 100-fs, 50-nJ laser pulses incident perpendicular to the plane of the image and focused by a 0.45-NA objective. The diameter of the structures in the image is less than 1 μm and is limited by the resolution of the imaging microscope. Scanning electron microscopy and atomic force microscopy of structures brought to the surface by polishing or fracturing samples reveal that the structures can be as small as 250 nm.[2] Side-view microscopy shows that the structures are oblong and about 4 μm long, reflecting the shape of the focal volume of the 0.45-NA objective. We have written structures like the ones shown in Fig. 1 several millimeters deep in a variety of different materials and used them to store binary data in three dimensions.[2]

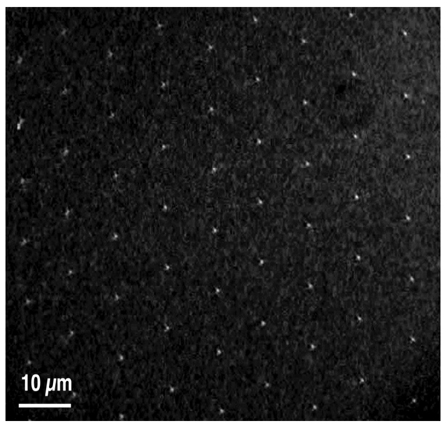

Figure 1. Optical micrograph of a hexagonal array of structures produced in bulk glass using single, 100-fs, 50-nJ laser pulses focused by a 0.45-NA microscope objective. The laser beam is incident perpendicular to the plane of the image.

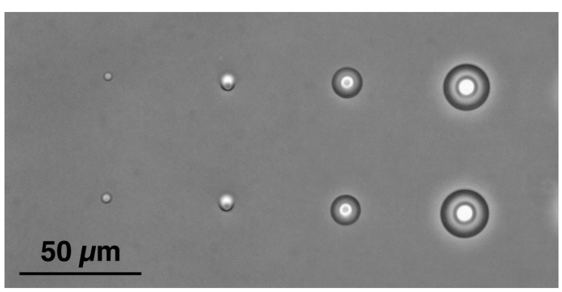

Figure 2. Optical micrograph of structures produced in bulk glass using multiple, 30-fs, 5-nJ laser pulses arriving at a 25-MHz repetition rate and focused by a 1.4-NA microscope objective. From left to right, the number of incident pulses is 10^2, 10^3, 10^4, and 10^5. The laser beam is incident perpendicular to the plane of the image. The rings seen in the structures on the right are indicative of regions of different refractive index.

The 30 nJ required to produce the structures in Fig. 1 is well within the range of cavity-dumped laser oscillators, opening the door to micromachining of bulk glass using unamplified femtosecond lasers.[7] If the laser pulse is focused more tightly, the laser energy required to produce permanent structural change is even less than 30 nJ. For example, using a 1.4-NA oil-immersion microscope objective (63^X, Zeiss, Inc.), the threshold in glass for a 100-fs laser pulse is only 5 nJ.[3] After taking into account losses in the microscope objective, the prism compressor used to compensate for dispersion, and other delivery optics, 12 to 15 nJ from the laser is sufficient to cause structural changes. This pulse energy is currently achievable with commercially available Ti:Sapphire laser oscillators.

We modified a Ti:Sapphire laser system** by inserting a one-to-one, 2-m long imaging telescope into the laser cavity to achieve laser pulse energies in the range necessary for micromachining.[8, 9] The telescope increases the length of the cavity, but does not change the cavity's spatial modes. The increased length results in a lower repetition rate—25 instead of 87 MHz—which in turn allows more gain to build up in the laser crystal before the laser pulse depletes it. The increased gain results in a laser pulse energy of 20 nJ.

By focusing pulses from this long-cavity laser oscillator using a 1.4-NA objective, we produced permanent structural changes in glass. The structures produced using single laser pulses are very similar to those shown in Fig. 1. Because of shorter confocal parameter of the 1.4-NA objective, however, the structures are less oblong than those produced with a 0.45-NA objective. Side-view microscopy reveals that they are about 1.5 μm in length.

In addition to greatly reducing cost and complexity, oscillator-only micromachin-

* In each instance in which glass is cited in this article, the type of glass used was Corning 0211.

** The laser system used was produced by KMLabs.

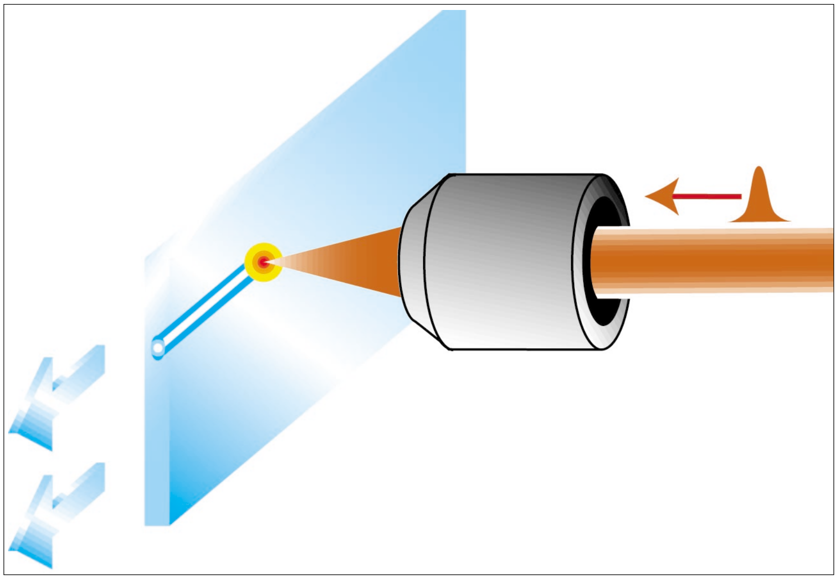

Figure 3. Procedure for directly writing waveguides inside bulk glass using a femtosecond laser oscillator. The sample is translated at 20 mm/s perpendicular to the incident direction of a 25-MHz train of 30-fs, 5-nJ laser pulses that are focused by a 1.4-NA microscope objective.

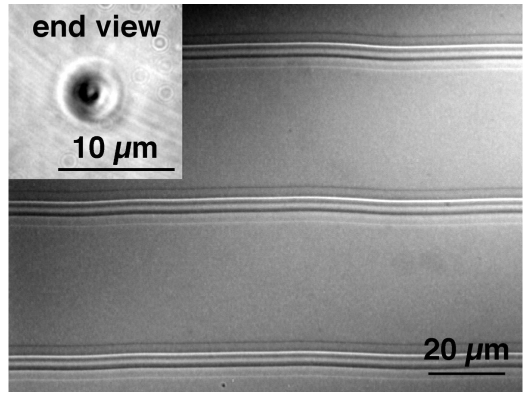

Figure 4. Optical micrograph of waveguides written in bulk glass using the technique illustrated in Fig. 3. The inset shows the end view of one of the waveguides.

ing allows us to exploit a cumulative thermal effect. Because of the 25-MHz repetition rate of the laser oscillator, the time between successive pulses, at 40 ns, is shorter than the roughly 1 μs it takes for energy deposited by one pulse to diffuse out of the focal volume. Consequently, a train of pulses irradiating one spot in the sample raises the temperature of the material around the focal volume. Over many pulses, a volume of material much larger than the focal volume melts, then nonuniformly resolidifies after the pulse train is turned off. This cumulative thermal effect can only be accomplished with a high repetition rate laser.[3]

Figure 2 shows structures produced in glass using 25-MHz trains of 30-fs, 5-nJ laser pulses focused by a 1.4-NA microscope objective. The number of pulses used to produce these structures increases by factors of ten, from 10^2 on the left to 10^5 on the right. We can make two observations from Figure 2. First, the size of the structures is much larger than the size of those produced by single laser pulses. Second, the size increases with increases in the number of laser pulses. Side views of the structures show that they are spherically symmetric. These observations are consistent with a cumulative thermal mechanism. For a given number of laser pulses, the temperature of the material exceeds the melting temperature out to some maximum radius. The larger the number of pulses, the larger the radius out to which the glass melts. Because of temperature gradients, the glass cools and resolidifies nonuniformly, leading to variations in density and therefore in refractive index of the material as seen in Fig. 2.

Nonthermal mechanisms for producing the structures shown in Fig. 2 can be ruled out for several reasons. First, the laser pulse train never directly irradiates most of the material where refractive index changes are observed. Only the submicrometer-sized focal volume at the center is directly irradiated, whereas the structures shown in Fig. 2 extend up to 10 μm from the focal spot. Second, the increase in size of the structure that accompanies increases in the number of pulses accurately fits a model based on thermal diffusion and melting.

By exploiting this cumulative heating at high repetition rate, a tightly focused train of femtosecond laser pulses can be used as a point source of heat located in the bulk of a transparent sample. The amount of energy that is deposited in a micrometer-sized volume can be controlled with nanojoule precision by varying the number of incident pulses. No other technique allows for such precise deposition of energy in such small volumes in bulk material.

Fabrication of optical devices

The cumulative thermal effects discussed above provide a new tool for micromachining transparent materials. By scanning the laser focus of a continuous 25-MHz pulse train inside the sample, the refractive index can be changed in regions of any desired three-dimensional shape. We have used this technique to write diffraction gratings, single-mode optical waveguides, and waveguide splitters inside bulk glass.[3]

Figure 3 illustrates how single-mode waveguides are written inside a slab of transparent material. A 1.4-NA oil-immersion microscope objective focuses a 25-MHz train of 30-fs, 5-nJ pulses about 100 μm beneath the surface of the sample. We translate the sample at a speed of 20 mm/s in a direction perpendicular to the laser beam. The material surrounding the focus melts and then resolidifies after being moved away from the laser focus. Figure 4 shows the cylindrical structures produced in glass using this method. To examine the optical properties of the resulting waveguides, we cleaved the ends of the glass sample to produce clean input and output faces. The inset shows the end face of one such waveguide.

To examine the guiding properties of the waveguides shown in Fig. 4, we coupled light from a He:Ne laser into one end of the waveguide and imaged the output onto a CCD camera. Figure 5 shows the near-field output mode of a 10-mm long waveguide. The output mode is well-fit with a Gaussian profile showing this technique produces single-mode waveguides.

Waveguides can also be directly written into bulk glass by loosely focusing 1-μJ amplified femtosecond laser pulses into the sample using a 0.1-NA lens.[10,11] Irradiation with a single laser pulse produces a cylindrically shaped structure similar to those in Fig. 1 but with a larger diameter

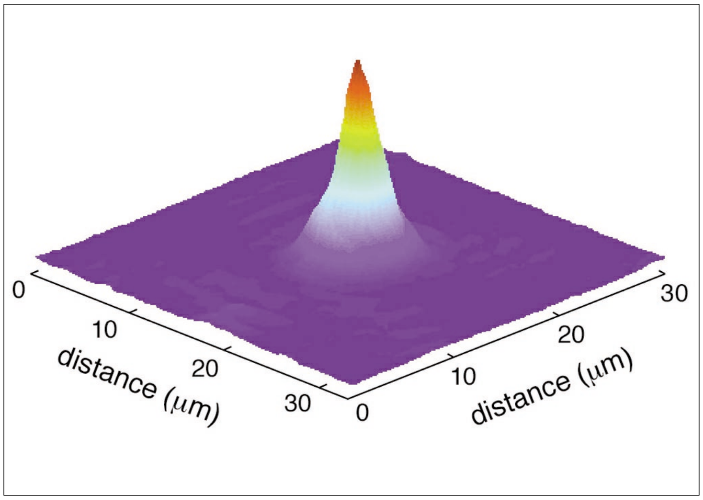

Figure 5. Near-field output mode of a waveguide produced using the technique illustrated in Fig. 3. To obtain this mode, light from a He:Ne laser was coupled into one side of a 10-mm long waveguide and the output imaged onto a CCD camera.

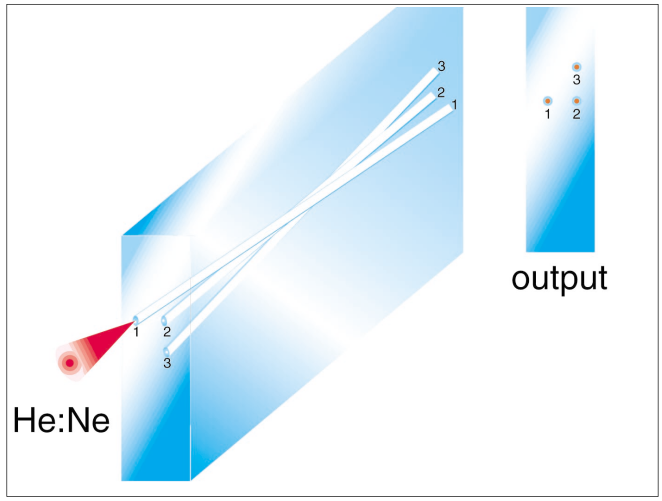

Figure 6. A three-dimensional waveguide splitter made by intersecting three waveguides in the bulk of a glass sample so that they cross each other. Light coupled into one of the waveguides leaks into the other two at the intersection, resulting in three outputs.

and length. By translating the sample at about 20 μm/s along the axis of a 1-kHz train of such pulses, the cylindrical structures connect smoothly, forming an optical waveguide. The low numerical aperture used in this technique allows waveguides to be written tens of millimeters inside the material. The cumulative thermal mechanism described in this paper, however, does not require a laser amplifier and offers a much higher machining speed.

Conclusions and future directions

Two important conclusions can be drawn from the work we present here. First, unamplified laser pulses with energy of less than 50 nJ can produce submicrometer-sized structures in bulk glass when focused with moderate to high numerical aperture microscope objectives (0.45 to 1.4 NA). The low pulse energy greatly simplifies the laser requirements and improves the machining speed for three-dimensional binary data storage, internal engraving and refractive index patterning, and other micromachining applications. Second, the high repetition rate of femtosecond laser oscillators allows us to exploit a cumulative thermal mechanism for producing structural change in bulk glass. Nonlinear absorption is still responsible for energy deposition into the material, but the structural change is produced by thermal diffusion, melting, and nonuniform resolidification. This technique also provides a unique means for precisely depositing heat into a micrometer-sized volume in the bulk of a transparent material.

Using this thermal micromachining technique, we wrote single-mode optical waveguides into bulk glass. More complex devices can be built up by combining single-shot and thermal micromachining. For example, Fig. 6 illustrates how a three-dimensional waveguide splitter can be manufactured by intersecting three waveguides inside a transparent material. Some of the light coupled into one of the waveguides leaks to the other two at the intersection, making a waveguide beamsplitter. Because the three waveguides do not all lie in the same plane it is very difficult to fabricate such a splitter using conventional, photolithographic techniques. Preliminary work in our lab has produced such a three-dimensional splitter with three equal-intensity outputs. A periodic line of single-shot structures, like those shown in Fig. 1, written inside the core of a waveguide, could act as a Bragg grating which transmits only certain wavelengths. Using Bragg gratings of different periods in each of the waveguides in Fig. 6, one could produce a wavelength selective splitter. Three-dimensional photonic devices such as the wavelength selective splitter described above are important for the telecommunications industry. As we have shown, such devices can be produced with just a femtosecond laser oscillator.

Acknowledgments

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