Journal of the Optical Society of Korea, Vol. 9, No. 1, March 2005, pp. 1-5

Nano-structuring of Transparent Materials by Femtosecond Laser Pulses

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(Received January 27, 2005 : revised March 12, 2005)

Using tightly focused femtosecond laser pulses, we produce an optical waveguide and optical devices in transparent materials. This technique has the potential to generate not only channel waveguides, but also three-dimensional optical devices. In this paper, an optical splitter and U-grooves, which are used for fiber alignment, are simultaneously fabricated in a fused silica glass using near-IR femtosecond laser pulses. The fiber aligned optical splitter has a low insertion loss, less than 4 dB, including an intrinsic splitting loss of 3 dB and excess loss due to the passive alignment of a single-mode fiber. Finally, we demonstrate the utility of the femtosecond laser writing technique by fabricating gratings at the surface and inside the silica glass.

OCIS codes : 050.1950, 140.3390, 230.7370, 230.1360

I. INTRODUCTION

Although over the past few years the change in refractive index induced by ultraviolet (UV) light in glasses has been investigated, UV-photosensitive glasses were limited due to the requirement for doping with germanium. Owing to ultrashort pulses with high peak power density, the interaction of a femtosecond (fs) laser with matter causes many nonlinear physical phenomenon, such as multi-photon absorption, micro-explosion, photo-darkening, plasma, thermal electron effect and so on. The fs laser can sensitize a wide variety of glasses, such as fused silica glasses and chalcogenide glasses, etc. In recent years, using infrared fs lasers to induce a change in refractive index by the multi-photon absorption process in transparent materials has been widely investigated. The application of the fs laser provides a new technique for making three-dimensional integrated photonic structure in a variety of glasses. This technique has been applied to fabricate photonic structures, such as passive optical waveguides [1,2], gratings [3-5], rare earth-doped waveguide amplifiers [6], and couplers [7-9].

Here we report the fabrication of waveguides and optical devices using a Ti:Sapphire laser. The pulse width was 100 fs, the wavelength was 800nm, and the repetition rate was 1 kHz. The laser beam was guided into a microscope and focused by a 20x objective (NA, 0.42) into the core. The glasses were placed on a computer-controlled stage. The average power of the laser beam was controlled by neutral density filters inserted between the laser and the microscope objective. Using 1kHz pulse trains of 100 fs laser pulses, the optical splitter and U-grooves for the passive fiber alignment are simultaneously obtained. The fiber aligned optical splitter, directly written by fs laser pulses in a fused silica glass, is described and characterized. The excess loss due to the passive alignment of the fibers is 0.3 dB, and the total insertion loss of the optical splitter is less than 4 dB. Moreover, the output field pattern is presented, demonstrating the splitting ratio of the optical splitter at approximately 1:1. Finally, the line and dot gratings with periods from 1 μm to 4 μm, directly written at the surface and inside of the fused silica glass by fs laser pulses with pulse energy of 320 nJ and a 50× microscope objective, are described and characterized.

II. EXPERIMENTS AND RESULTS

1. Waveguide fabrication

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. 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. By scanning the laser focus of a continuous 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 single-mode waveguides and an optical splitter in fused silica glass.

Using 1 kHz pulse trains of 100 fs laser pulses focused by a 0.42 NA microscope objective, the waveguides were written inside a slab of transparent material about 300 μm beneath the surface of the sample with laser power of 300, 400, and 500 nJ as shown in Fig. 1. We translate the sample at a speed of 10 μm/s in a direction perpendicular to the axis of the fs laser beam; the sample resolidifies after being moved away from the laser focus. It can be observed that the diameter of the cross section increases with the rising pulse energy of the fs laser beam. One important parameter for device design is the change in refractive index which can be achieved using a given laser irradiation. The refractive-index change of the waveguides is determined by the coupling of a He:Ne laser into the waveguides. The NA of a step-index waveguide is related to the induced index change ($\triangle$n) by $NA=\sqrt{2n\Delta n}$ for small $\triangle$n, where n is the refractive index of the glass. As the pulse energy was 300-500 nJ, the refractive-index changes were 0.006-0.01. Because the refractive-index change depends on the pulse energy and speed of the sample, we can control the irradiation conditions to create differing refractive-indices and core diameters in the waveguides. A waveguide propagation loss of ~0.86 dB/cm at a wavelength of 1550 nm was measured. In order to analyze the guiding properties of the fabricated waveguides, we measured the guided light intensity distributions in the fabricated waveguides. Near-field mode profiles of the waveguide for 1550 nm light were obtained by using a beam profiler as shown in Fig. 2. The core diameters of waveguides in this figure were controlled by changing the average power of the writing laser. At the core diameter of 8 μm, it is possible to propagate only LP_{01} fundamental mode which is nearly Gaussian. A typical mode profile of a good-quality waveguide was written in the fused silica glass using a focusing lens with a 100 mm focal length, 350 nJ per pulse, a scan speed of 50 μm/s and a 1 kHz repetition rate. The waveguide is a single mode with a near-Gaussian output profile.

2. Optical device fabrication

A schematic diagram of the 1×2 optical splitter is presented in Fig. 3. The length of the splitter is 5 mm, and the separation of the two branches is 0.25 mm. The optical splitter was fabricated by fs laser pulses inside a fused silica glass with a pulse energy of 400 nJ and a scan speed of 10 μm/s. The relative coupling into the two branches depends on their splitting angle, and in this case the radius of the curved waveguides was 30mm, resulting in equal amounts of light into the two branches. Further, we machined U-grooves in the one-input and two-output ports of the splitter with a pulse

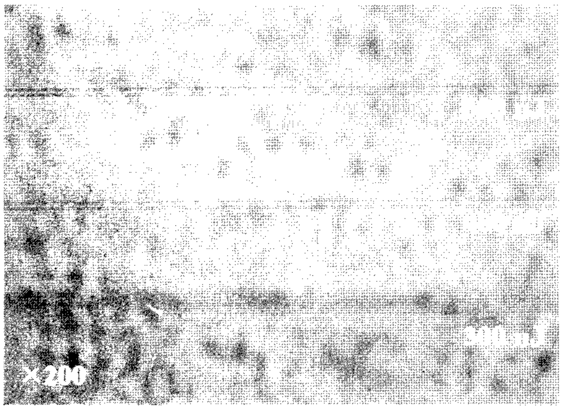


FIG. 1. Optical micrograph of waveguides written inside fused silica glass using a 300-500 nJ, 1kHz, and 100 fs pulse train focused with a 0.42 NA microscope objective. The sample was translated at 10 μm/s.

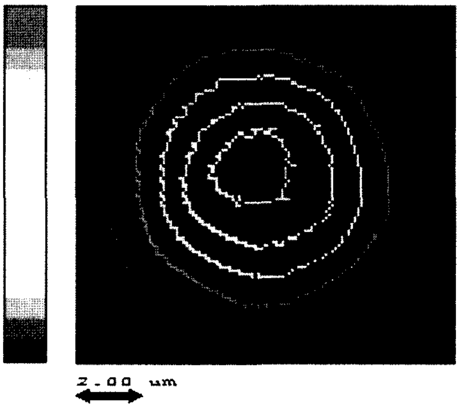


FIG. 2. Single-mode near-field profile at 1550nm for a good-quality directly written waveguide in fused silica glass (20× objective lens with 0.42 NA, 350 nJ pulse energy, two scans at 50 μm/s).

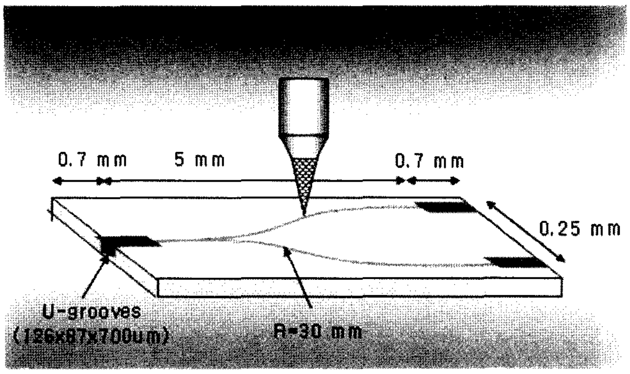
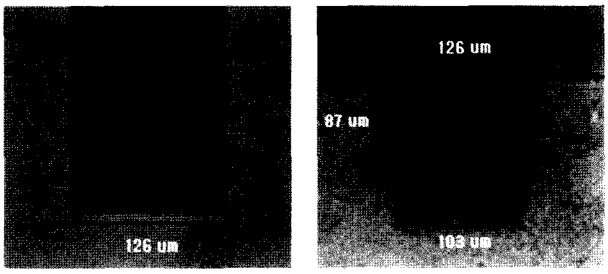


FIG. 3. Schematic diagram of U-grooved optical splitter.

energy of 30 μJ as shown in Fig. 4. The optical interconnection between fibers and optical waveguides is essential for low-cost packaging of multichannel planar lightwave circuit (PLC)-type optical devices [10]. In the study of optical devices technology, passive alignment has become a critical issue. A novel packaging process using a fs laser micromachining has been developed for passive alignment of PLC-type optical devices. The size of the U-groove is $126 \times 87 \times 700$ μm and the allowable margin of error was controlled within ± 1 μm. Fiber aligned one-input and two-output channels of the U-grooved optical splitter are shown in Fig. 5. Our packaging technique is to insert and directly align the single mode optical fiber and the waveguide of the optical splitter with engraved U-grooves, directly formed using the fs laser micromachining technique. This packaging technique requires neither the use of optical fiber array blocks in the active alignment nor difficult etching processes such as reactive ion etching through photo lithography. One major advantage of this method is that it substantially obviates one or more of the limitations and disadvantages of the conventional techniques, which are time-consuming and considerably high in cost. The loss is less than 4 dB for two channels, including an intrinsic splitting loss of 3 dB. This means that the excess loss is less than 1 dB. Note that the excess loss is the sum of the propagation loss of the waveguide (0.86 dB/cm), the radiation loss of the 1×2 optical splitter, and the coupling loss (0.3dB) between the optical splitter and a single-mode fiber. To examine the guiding properties of the optical splitter, we coupled a 1550nm laser beam into the input channel of the optical splitter and imaged the output onto a CCD camera. Fig. 6. shows the far-field pattern of the optical splitter's output, demonstrating that the splitting ratio of the optical splitter with a length of 5 mm is approximately 1:1.



(a) (b)

FIG. 4. Machined U-groove; (a) top view, (b) side view.

FIG. 5. Fiber aligned one-input and two-output channels of U-grooved optical splitter.

3. Grating fabrication

In addition to waveguides, we also fabricate gratings using an 800 nm Ti:Sapphire laser. The laser pulses were focused on the surface and inside of the fused silica glass through a $50\times$ microscope objective. We found that when the laser pulses were focused on the surface of the sample, an efficient ablation of the glass surface occurred at energies of 300 nJ and higher. The ablation region is determined not only by the spot size of the laser beam and the pulse energy but also by the scan speed and the number of laser pulses. Under optimized conditions, each grating line was drawn by scanning the focused laser beam through the sample in a direction perpendicular to the direction of the propagation of the laser beam, but parallel to the surface of the sample. The scan speed was 20 μm/s and only a single scan was performed for each grating line. Gratings with a 3-μm period were written on the surface of fused silica glasses through the use of fs laser pulses with a pulse energy of 320 nJ. An optical microscope image of a 3-μm period line grating written on the surface of fused silica

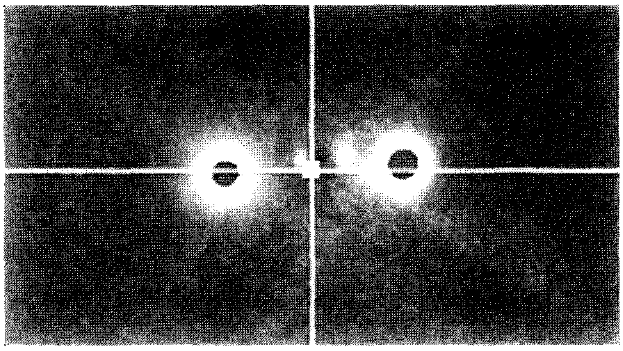


FIG. 6. Far-field pattern of the optical splitter's output with a 1550 nm laser beam coupled into the input waveguide. The splitting ratio is approximately 1:1.

glass is shown in Fig. 7 (a). We measured their diffraction pattern using unpolarized normally incident light at a wavelength of 633 nm as shown in Fig. 7 (b). In addition, a 4-μm period cross- line grating was written by fs laser pulses under the same conditions. An optical micro scope image of a 4-μm period cross-line grating written on the surface of fused silica glass is shown in Fig. 8 (a). As shown in Fig. 8 (b), a pronounced diffraction pattern was observed when a focused 633nm He:Ne laser beam was directed to the grating.

When the laser pulses were focused inside the fused silica glass, a modification of the optical properties was observed along the optical axis of the laser pulses. The visible laser damage can be formed only inside the focused region because nonlinear optical processes, such as multiphoton absorption, occur in regions with high optical intensity above the damage threshold. Modification of the sample is visible in a transmitted light optical microscope. Fig. 9. shows the microscope image of 2-μm period line and dot grating directly written inside fused silica glass by fs laser pulses with pulse energy of 320 nJ and a 50×microscope objective as the focusing lens. Each line represents the optical modification inside the glass in the region where laser pulses were focused. The scan speed was 10 μm/s, and only a single scan was performed for each line. The lines and dots are separated by 2 μm and the focus spot was 500 nm.

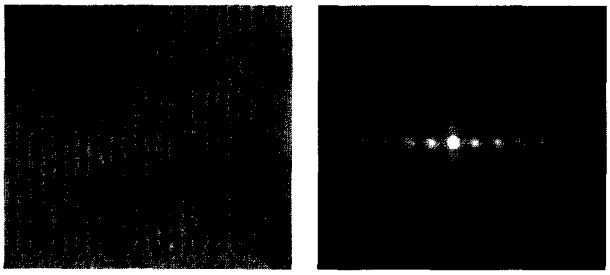

(a) (b)

FIG. 7 (a). Microscope image of a 3-μm period line grating directly written on the surface of fused silica with 320nJ pulse energy, and (b) diffraction pattern observed with He:Ne laser.

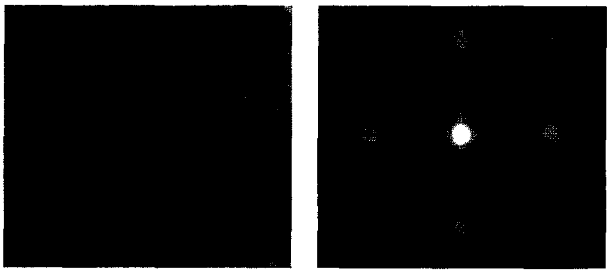
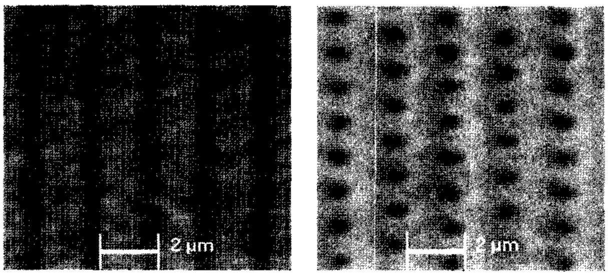

(a) (b)

FIG. 8 (a). Microscope image of a 4-μm period cross-line grating directly written on the surface of fused silica with 320nJ pulse energy, and (b) diffraction pattern observed with He:Ne laser.



(a) (b)

FIG. 9. Microscope image of a 2-μm period (a) line and (b) dot grating directly written inside fused silica with 320 nJ pulse energy. Line width and dot diameter are 0.5 μm

III. CONCLUSION

We have demonstrated that an optical splitter and U-grooves, which are used for the passive fiber alignment, can be simultaneously fabricated in a fused silica glass through the use of near-IR femtosecond laser pulses. The output optical field pattern of the optical splitter was observed, and a refractive-index change of 0.006-0.01 was obtained with the NA method. The fiber aligned optical splitter has a low insertion loss, less than 4dB, including an intrinsic splitting loss of 3dB and excess loss due to the passive alignment of a single-mode fiber. Gratings with a 3-μm and 4-μm period were written on the surface of fused silica glass by fs laser pulses, and their diffraction patterns were measured with a He:Ne laser. In addition, line and dot grating were written inside fused silica glass through the use of fs laser pulses, demonstrating its ability to fabricate nano patterning inside planar waveguides and circuits. In conclusion, the fs micromachining technique is a novel means of fabricating silica PLC devices; it is simple and produces accurate passive alignment. Future research could include an investigation into the fabrication of photonic bandgap structures, such as three-dimensional Bragg grating and photonic crystals.

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