펨토초 레이저를 이용한 광소자 제작

Fabrication of optical devices using femtosecond laser pulses

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Ⅰ. Introduction

In the past few years, a change in refractive index induced by ultraviolet (UV) light in glasses has also been investigated, but the UV-photosensitive glasses were limited due to the requirement of 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-exploring, photo-darkening, plasma, thermal electron effect and so on. A 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 anew technique for making three-dimensional integrated photonic structure in various glasses. This technique has been applied to fabricate photonic structures, such as passive optical waveguides in a variety of glasses [1-2], gratings [3-5], rare earth-doped waveguide amplifiers [6], and coupler [7-9].

Here we report the fabrication of the waveguides and optical device by use of a Ti:Sapphire laser. The pulse width was 100 fs, the wavelength was 800 nm, 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 1-kHz pulse trains of 100-fs laser pulses, the optical splitter and U-grooves for the passive fiber alignment can be simultaneously obtained. Finally, 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 is 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

A. 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

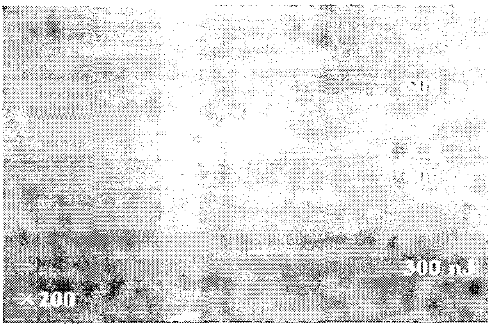


Fig. 1 Optical micrograph of waveguides written inside fused silica glass using a 300-500 nJ, 1 kHz, and 100 fs pulse train focused with a 0.42 NA microscope objective. The sample was translated at 10 μm/s.

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 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 different laser power of 300, 400, and 500 nJ as shown in Fig. 1. We translate the sample at a speed of 10 μm/sin a direction perpendicular to the axis of the fs laser beam and then resolidifies after being moved away from the laser focus. It can be observed that the diameter of the cross section increases with the increasing pulse energy of the fs laser beam and is independent of the moving speed of the sample. 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 (Δn) by for small Δn, 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 different refractive-index change and core diameter of waveguides. Waveguide propagation loss of ~ 0.86 dB/cm at a wavelength of 1550 nm was measured. Near-field mode profiles of the waveguide for 1550 nm light were obtained by using

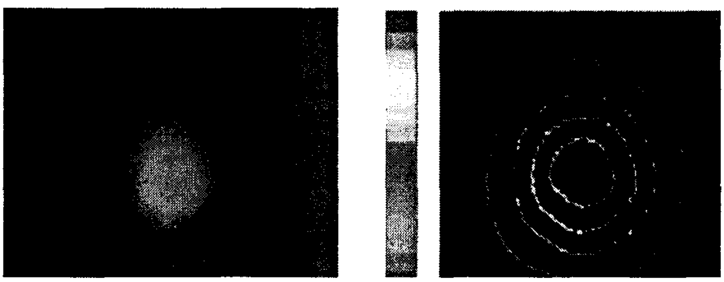


Fig. 2 Near-field pattern of a waveguide written inside fused silica glass using a 350 nJ, 1 kHz femtosecond laser pulses

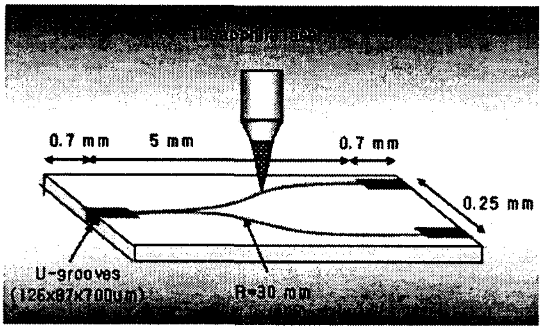


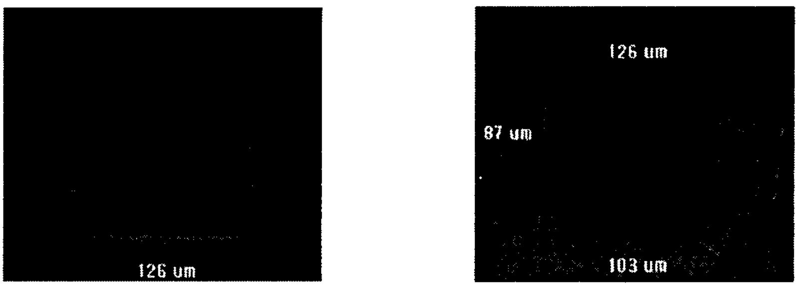
Fig. 3 Schematic diagram of U-grooved optical splitter.

a beam profiler as shown in Fig. 2. A typical mode profile of a good-quality waveguide 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 1 kHz repetition rate. The waveguide is single mode with a near-Gaussian output profile.

B. Optical device fabrication

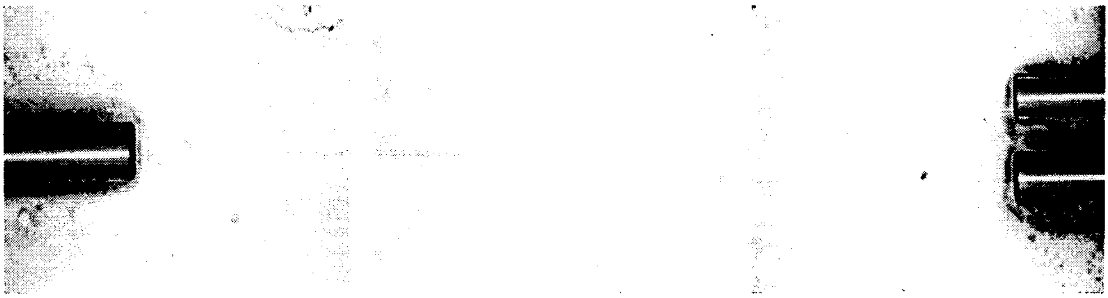
A schematic diagram of the 1×2 optical splitter is presented in Fig. 3. The length of the splitter is 5 mm, and the separation of the two branches is 0.25 mm. The optical splitter was fabricated by fs laser pulses inside fused silica glass with a pulse energy of 400 nJ and scan speed of 10 μm/s. The relative coupling into the two branches depends on their splitting angle, and in this case the radius of the curved waveguides was 30 mm results in equal amounts of light into the two branches. The laser beam was guided into a microscope and focused by a 20x objective (NA, 0.42) into the core.

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. Using 1 kHz trains of 100-fs laser pulses with a pulse energy of 30 μJ, we machined U-grooves in one-input and two-output port of the splitter as shown in Fig. 4. The size of the U-groove is 126×87×700 μm and the allowable margin of error was controlled within ±1 μm. Fiber aligned on-input and two-output channels of U-grooved optical splitter is shown in Fig. 5. Our packaging technique is to insert and align directly the single mode optical fiber and a waveguide of the optical splitter with engraved U-grooves, which are directly formed by fs laser micromachining technique.



(a) (b)

Fig. 4 Machined U-groove; (a) side view (×500), (b) top view (×500)



(a) (b) (c)

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

This packaging technique does not require the use of optical fiber array blocks in the active alignment and difficult etching processes such as reactive ion etching through photo lithography. It has advantages that substantially obviate one or more of limitations and disadvantages of the conventional techniques, which involve time-consuming and considerable cost. The loss is less than 4 dB for two channels, including 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 waveguide (0.86 dB/cm), the radiation loss of the 1×2 optical splitter, the coupling loss (0.3 dB) between the optical splitter and a single-mode fiber. To examine the guiding properties of the optical splitter, we coupled a 1550 nm laser beam into input channel of the optical splitter and imaged the output onto a CCD camera. Figure 6 shows the far-field pattern of the optical splitter's output, demonstrating the splitting ratio of the optical splitter with length of 5 mm is approximately 1:1.

C. Grating fabrication

In addition to waveguides, we have also fabricated gratings using a 800 nm Ti:Sapphire laser. The pulse energy was 320 nJ and the pulse width was around 100 fs. The laser pulses were focused on the surface and inside of fused silica glass through a 50×microscope objective. It was found that when the laser pulses were focused on the surface of the sample and efficient ablation of glass surface occurs 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 the optimized conditions each grating line was drawn by scanning the focused laser beam through the sample in a direction perpendicular to the direction of propagation of the

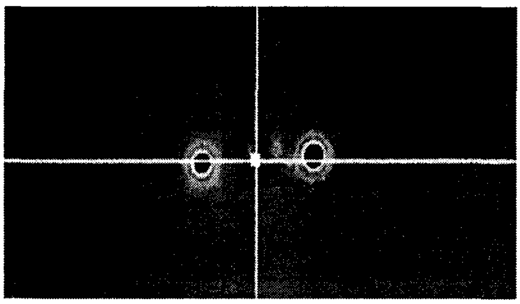
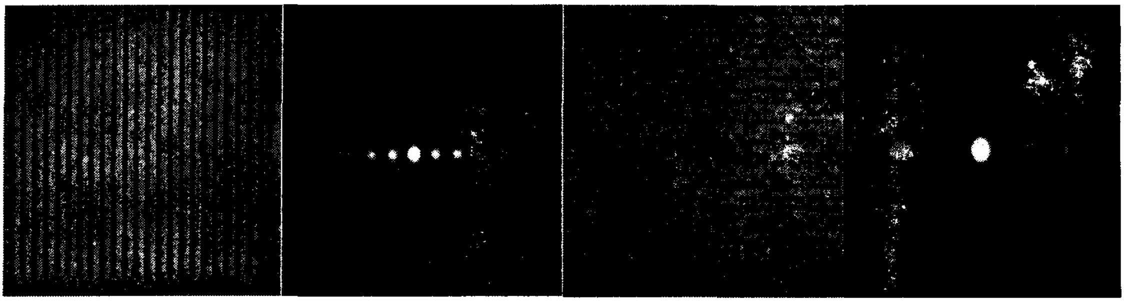


Fig. 6 Far-field pattern of the optical splitter's output with a 1550 nm laser beam coupled into the input waveguide. The splitting ratio is approximately 1:1

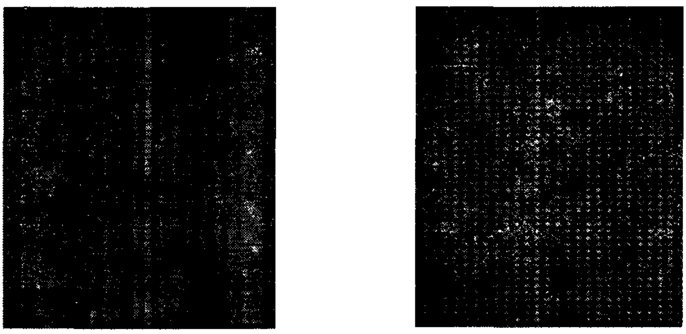


(a) (b) (c) (d)

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

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 at the surface of fused silica glasses by fs laser pulses with pulse energy of 320 nJ and a 50× microscope objective as the focusing lens. An optical microscope image of a 3-μm period line grating written at the surface of fused silica 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). Also, a 4-μm period cross-line grating was written by fs laser pulses at the same condition. An optical micro scope image of a 4-μm period cross-line grating written at the surface of fused silica glass is shown in Fig. 7(c). As shown in Fig. 7(d), a pronounced diffraction pattern was observed when focused 633 nm He:Ne laser beam was directed to the grating.

When the laser pulses were focused inside of fused silica glass, a modification of the optical properties was observed along the optical axis of the laser pulses. The visible laser damages can be formed only in the focused region of the inside, because the nonlinear optical process such as multiphoton absorption occurs in a region with high optical intensity above damage threshold. The modification of the sample is visible in transmitted light optical microscope. Figure 8 show the line and dot grating written inside fused silica glass by fs laser pulses with pulse energies of 320 nJ and a 50× microscope objective as the focusing lens. Each line represents the optical modification inside the glass in the region of the focus of laser pulses. The scan speed was 10 μm/s and only a single scan was performed for each grating line. The lines and dots are separated by 1 μm and



(a) (b)

Fig. 8 Microscope image of a 1-μm period line and dot gratings directly written inside fused silica with 320 nJ pulse energy.

focus spot was 500 nm. An optical microscope image of a 1-μm period line and dot grating written inside the glass are shown in Fig. 8.

Ⅲ. Conclusions

We have demonstrated that an optical splitter and U-grooves, which are used for the passive fiber alignment, are simultaneously fabricated in a fused silica glass by using near-IR femtosecond laser pulses. The output optical field pattern of the optical splitter was observed, and the 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 4 dB, including intrinsic splitting loss of 3 dB and excess loss due to the passive alignment of a single-mode fiber. Gratings with a 3-μm and 4-μm period were written at the surface of fused silica glasses by fs laser pulses, and their diffraction patters were measured with He:Ne laser. Also, line and dot grating with 1-μm period written inside fused silica glass by fs laser pulses, demonstrating it will provide opportunity to fabricate nano patterning inside planar waveguides with less than 500 nm dimensions. In conclusion, the fs micromachining technique is a novel means of fabricating silica PLC devices; it is simple andproduces accurate passive alignment. It will also investigate to fabricate photonic structures, such as three-dimensional optical storage and photonic crystals.

Ⅳ. References

[1] Miura, J. Qiu, H. Inouye, T. Mitsuyu, and K. Hirao, "Photowritten optical waveguides in various glasses with ultrashort pulse laser" Appl. Phys. Lett., vol. 71, pp. 3329-3331, 1997.

[2] K. Hirao and K. Miura, "Writing waveguides and gratings in silica and related materials by a femtosecond laser" J. Non-Cryst. Solids., vol. 239, pp. 91-95, 1998.

[3] K. Kawamura, N. Sarukura, and K. Hirao, "Holographic encoding of fine-pitched micrograting structures in amorphous SiO2 thin films on silicon by a single femtosecond laser pulses" Appl. Phys. Lett., vol. 78, pp. 1038-1040, 2001.

[4] M. Li, M. Ishizuka, X. Liu, Y. Sugimoto, N. Ikeda, and K. Asakawa, "Nanostructuring in submicron-level waveguides with femtosecond laser pulses," Opt. Commun., vol. 212, pp. 159-163, 2002.

[5] D. Grobnic, C. W. Smelser, S. J. Mihilov, R. B. Walker, and P. Lu, "Fiber Bragg gratings with suppressed cladding modes made in SMF-28 with a femtosecond IR laser and a phase mask," IEEE Photon. Technol. Lett., vol. 16, pp. 1864-1866, 2004.

[6] Y. Sikorski, A. A. Said, P. Bado, R. Maynard, C. Florea, and D. K. Killinger, "Optical waveguide amplifier in Nd-doped glass written with near-IR femtosecond laser pulses" Electron. Lett., vol. 36, pp. 396-398, 2000.

[7] A. M. Streltsov and N. F. Borrelli, "Fabrication and analysis of a directional coupler written in glass by nanojoule femtosecond laser pulses" Opt. Lett., vol. 26, pp. 42-43, 2001.

[8] L. Gui, B. Xu, and T. C. Chong, "Microstructure in Lithium Niobate by use of focused femtosecond laser pulses," IEEE Photon. Technol. Lett., vol. 16, pp. 1337-1339, 2004.

[9] C. Florea and K. A. Winick, "Fabrication and characterization of photonic devices directly written in glass using femtosecond laser pulses," J. Lightwave Technol., vol. 21, pp. 246-253, 2003.

[10] M. Takahashi, T. Ido, and T. Nagara, "A polymer PLC platform with a fiber-alignment V-groove for a low-cost 10-GbE WWDM transmitter" J. Lightwave Technol., vol. 16, pp. 266-268, 2004.