Femtosecond Laser Application to PLC Optical Devices and Packaging

Ik-Bu Sohn, Man-Seop Lee, and Sang-Man Lee

ABSTRACT—Using tightly focused femtosecond laser pulses, we produce an optical waveguide and 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 present an output field pattern, demonstrating that the splitting ratio of the optical splitter becomes approximately 1:1.

Keywords—Femtosecond laser processing, waveguide writing, PLC optical splitter, passive alignment.

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 have been limited due to the doping with germanium requirement. The femtosecond laser has the ability to sensitize fused silica and chalcogenide glasses, among many others, and in recent years has been used to induce a change in refractive index since the multi-photon absorption process in transparent materials has been widely investigated. The application of the femtosecond laser provides a new technique for making a three-dimensional integrated photonic structure in glasses. This technique was applied to fabricate photonic structures, such as passive optical waveguides, in various glasses [1], [2], gratings [3]-[5], rare earth-doped waveguide amplifiers [6], and couplers [7]-[9].

In this paper, for the first time in the literature to our knowledge, we demonstrate the U-grooved planar lightwave circuit (PLC) optical splitter using a femtosecond laser. The pulse width of the femtosecond laser is 100 fs, the wavelength is 800 nm, and the repetition rate is 1 kHz. The laser beam is guided into a microscope and focused by 20× objective, with a numerical aperture (NA) of 0.42, into the core. The glasses are placed on a computer-controlled stage. The average power of the laser beam is 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 are simultaneously obtained. Finally, the fiber-aligned optical splitter, directly written by femtosecond 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, an output field pattern is presented, demonstrating that the splitting ratio of the optical splitter becomes approximately 1:1.

II. Experiments and Results

When a femtosecond laser pulse is tightly focused inside a transparent material, the laser intensity at the focus may become 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. 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 fabricate an optical splitter in fused silica glass.

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Fig. 1. Optical micrograph of waveguides written inside fused silica glass using a 300 to 500 nJ, 1 kHz, and 100 fs pulse train focused with a 0.42 NA microscope objective.

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 30 μm beneath the surface of the sample with a 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 femtosecond laser beam; the sample resolidifies after being moved away from the laser focus. We observed that the diameter of the cross section increases with the rising pulse energy of the femtosecond 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 an He:Ne laser into the waveguides. The NA of a step-index waveguide is related to the induced index change (Δn) by $\mathrm{NA} = \sqrt{2n\Delta n}$ for a small Δn, where n is the refractive index of the glass. As the pulse energy was 300 to 500 nJ, the refractive-index changes were 0.006 to 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 indexes and core diameters in the waveguides. We measured a waveguide propagation loss of less than 0.86 dB/cm at a wavelength of 1550 nm.

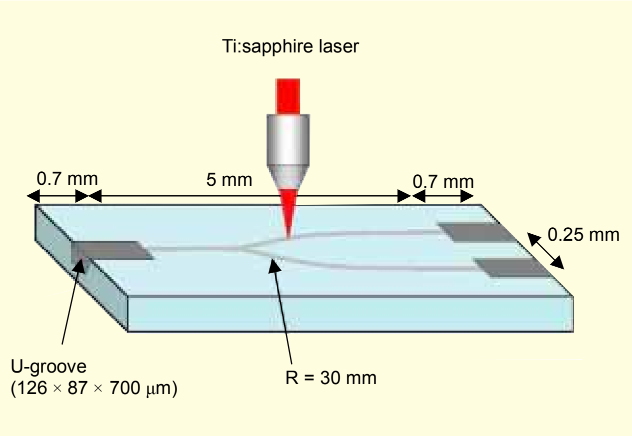
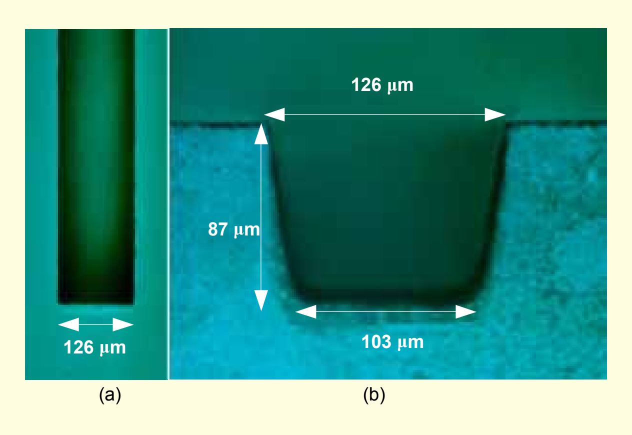


Fig. 2. Schematic diagram of U-grooved optical splitter.



(a) (b)

Fig. 3. Machined U-groove: (a) side and (b)top view.

A schematic diagram of the 1 × 2 optical splitter is presented in Fig. 2. 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 femtosecond 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 30 mm, resulting in equal amounts of light into the two branches. The laser beam was guided into a microscope and focused by a 20 × objective (NA, 0.42) into the core.

The optical interconnection between fibers and optical waveguides is essential for low-cost packaging of multichannel PLC-type optical devices [10]. In the study of optical device technology, passive alignment has become a critical issue. A novel packaging process using femtosecond 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 the one-input and two-output ports of the splitter as shown in Fig. 3. The size of the U-groove is 126 μm × 87 μm × 700 μm and the margin of error was controlled to within ±1 μm. Fiber aligned on the one-input and two-output channels of the U-grooved optical splitter is shown in Fig. 4. 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 femtosecond laser micromachining technique. This packaging technique does not require the use of optical fiber array blocks in the active

ETRI Journal, Volume 27, Number 4, August 2005 Ik-Bu Sohn et al. 447

Fig. 4. Fiber-aligned one-input and two-output channels of U-grooved optical splitter.

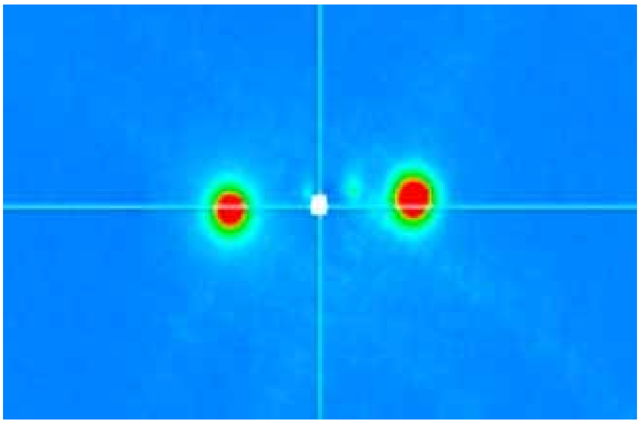


Fig. 5. Far-field pattern of the optical splitter's output with a 1550 nm laser beam coupled into the input waveguide. The splitting ratio is approximately 1:1.

alignment or 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 (0.3 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 the input channel of the optical splitter and imaged the output onto a CCD camera. Figure 5 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 becomes approximately 1:1.

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. 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. In conclusion, the femtosecond laser writing and micromachining technique is a novel means of fabricating PLC optical devices; it is simple and produces accurate passive alignment.

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