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# Femtosecond Micromachining Applications for Optical Devices

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This paper investigates applications of femtosecond lasers for the micromachining of transparent materials and fabrication of optical devices. We show commercial micromachining examples of transparent materials which have been fabricated for various applications. Near infrared femtosecond laser processing is an attractive method to fabricate three-dimensional optical waveguides into various transparent materials. Focused femtosecond laser pulses induce a permanent refractive-index change only near the focal point. We also demonstrate a Y coupler with the splitting ratio of 1:1 written by femtosecond laser pulses into a fused silica glass. The minimum propagation loss of 0.8 dB/cm and the refractive-index change of 0.006-0.01 at the wavelength of 1550 nm were achieved by optimization of the laser fluence.

*OCIS codes :* 140.3390, 220.4610, 230.7370, 230.1360

## I. INTRODUCTION

In recent years, femtosecond laser micromachining has become increasingly important for many fields, including micro-optics, micro-electronics, micro-biology, and micro-chemistry [1-4]. There are a number of advantages in using lasers for micromachining, such as single-step processing, high flexibility, minimal mechanical and thermal deformation and the precise focusing which is possible leading to highly localized treatment of materials. It is now well known that for many of these applications, the femtosecond laser offers advantages over the nanosecond laser pulses [5-8]. These advantages lie in the ability to deposit energy into a material in a very short time period, before thermal diffusion can occur. As a result, the heat-affected zone, where melting and solidification can occur, is significantly reduced. A variety of materials have been demonstrated to be suitable for femtosecond laser micromachining, e.g. metals, semiconductors, polymers, oxide ceramics, silica quartz, optical glasses and crystals. In addition, using infrared femtosecond lasers to induce a change in refractive index by the multi-photon absorption process in transparent materials has been widely investigated in recent years. This technique has been applied to fabricate photonic structures, such as passive optical waveguides in a variety of glasses [9,10], gratings [11], rare earth-doped waveguide amplifiers [12], and couplers [13].

In this paper, we present femtosecond micromachining of transparent materials using a 800 nm Ti:Sapphire laser that emits mode-locked pulses with a duration of 100 fs and a repetition of 1 kHz. We show commercial micromachining examples of transparent materials which have been fabricated for various applications. Further, we report the fabrication of a Y coupler written by femtosecond laser pulses. The refractive-index changes and propagation losses at the wavelength of 1550 nm were estimated.

## II. EXPERIMENTS AND RESULTS

### 1. Applications of femtosecond laser micromachining

Figure 1 shows the schematic of the femtosecond-pulsed laser system. The femtosecond ablation experiments were performed using a Ti:Sapphire laser system, consisting of a Ti:Sapphire oscillator and an amplifier system based on the chirped pulse amplification was used for the ablation with pulse duration of 100 fs, repetition rate of 1 kHz and pulse energy of 1 mJ at $\lambda$ =800 nm. The laser beam was guided into a microscope and focused by a 20× objective (N.A., 0.42). The average power of the laser beam was controlled by neutral density filters inserted between the laser and the microscope objective. The sample under fabrication was translated by a computer-controlled three-dimensional stage at a resolution of 100 nm. The features produced during focused irradiation of femtosecond pulses were observed through a CCD camera mounted upon the microscope. The laser pulses are focused with a 30 mm focal-length quartz lens giving a spot size of 6 ㎛ at the sample. The spatial profile of the laser pulse is nearly Gaussian. The fluence (energy per unit area) varies over the spatial profile of the laser beam. The fluence is controlled by changing the total incident energy with a half-wave plate and a polarizer. The polarization of the laser pulse is controlled by a second half-wave plate.

We machined the U-grooves on the planar-lightwave-circuit (PLC) chip, which has the silica-based waveguides on the Si substrate. Figure 2 represents a schematic of machined U-grooves on the 1x8 PLC splitter. U-grooves were fabricated by using 1 kHz trains of 100-fs laser pulses with a average power of 30 μJ per pulse. The size of the U-groove (126 ㎛×87 ㎛ ×2 ㎜) was designed for a good coupling between optical fiber and waveguide. The sample was mounted on a computer-controlled X-Y-Z-$\theta$ translation stages such that the laser processed-area was free-standing. We translated the sample by approximately 1㎛ between runs. The position, size and center of the optical waveguide on the PLC chip were measured by a vision system. The experiments were carried out in air. We formed U-grooves in one-input and 8-output port on the PLC splitter chip. The height and the width with allowable error margin of ±0.5 ㎛ are determined by laser micro-machining in order to minimize the offset

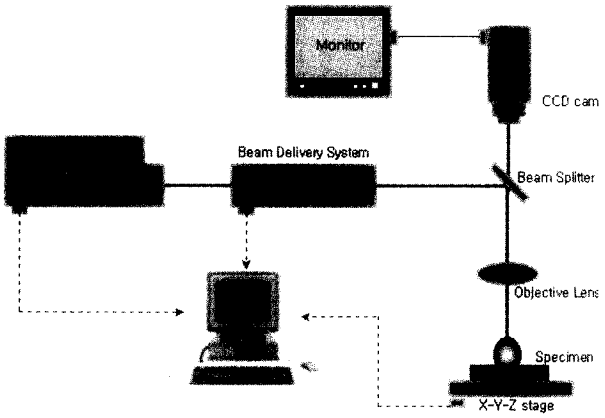


FIG. 1. A schematic of femtosecond-pulsed laser system.

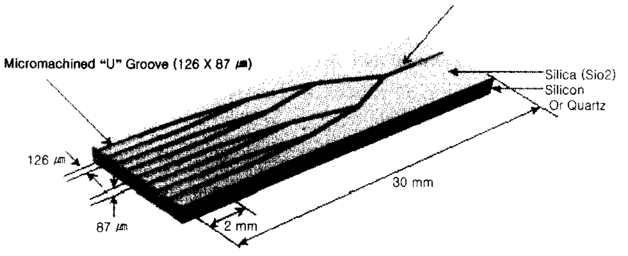
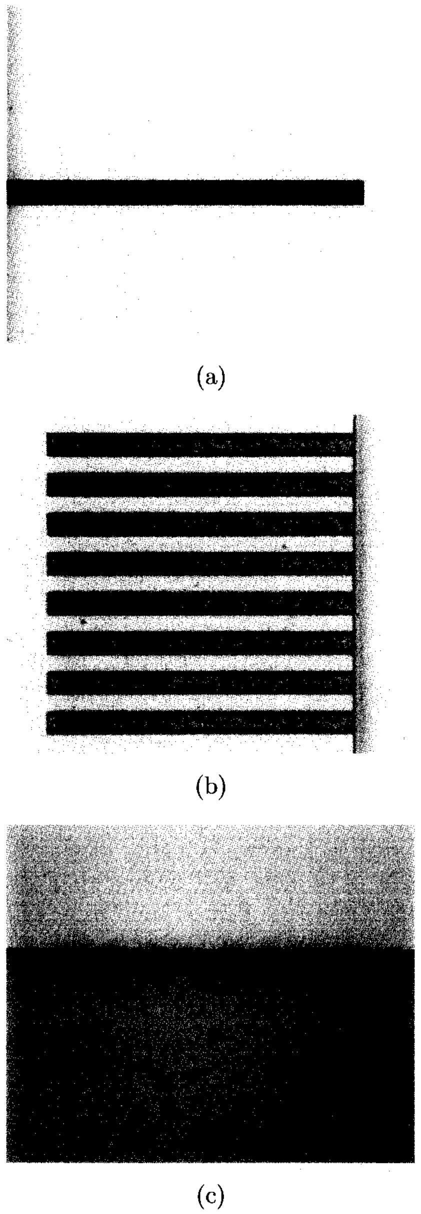


FIG. 2. A schematic of machined U-grooves on the PLC chip.


(a)

(b)

(c)

FIG. 3. U-groove on the PLC chip based in the Si substrate, machined by femtosecond laser pulses; (a) top view of input channel, (b) top view of output channel, and (c) side view of output channel at the surface of U-groove. The size of U-grooves is 126 ㎛×87 ㎛×2 ㎜.

between the core of the waveguide and fiber. It is quite obvious that the U-grooves machined with femtosecond pulses are very clean as shown in Fig. 3. The roughness of the bottom surface on the U-groove was measured around ±0.3 ㎛ with 3D Surface Profiling System (SNU Precision Co., SIS-2000). These results confirm the highly precise alignment of the optical fibers and PLC chip.

Figure 4 shows other applications using femtosecond laser pulses on transparent materials. We fabricated the optical devices, such as the micro-reactor for the mixture of chemical solutions on quartz and the bio chip on glass as shown in Fig. 4 (a, b). Further, we machined a hole for inserting an optical fiber across the dipole antenna made from quartz as demonstrated in Fig. 4 (c). The diameter and thickness of the hole were 150 ㎛ and 700 ㎛, respectively. It was drilled from the rear surface in air.

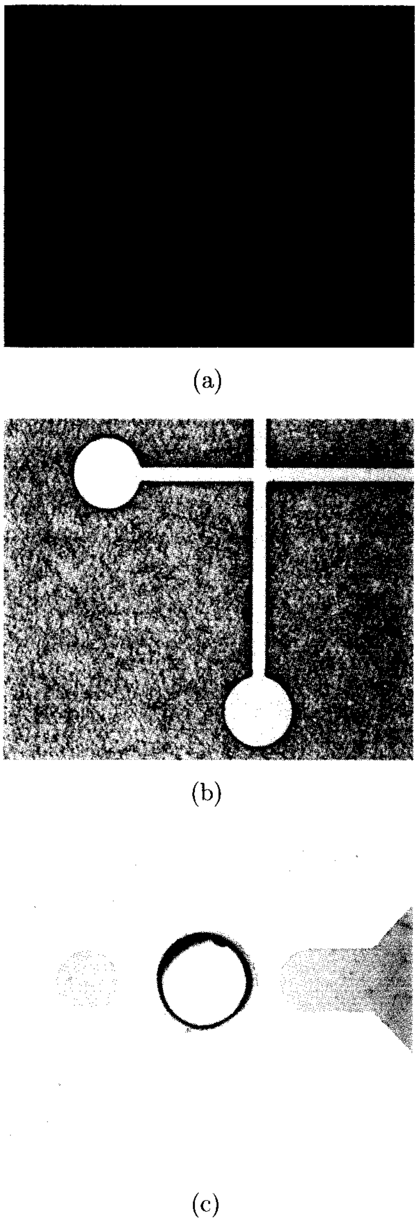


FIG. 4. Applications of femtosecond laser micromachining ; (a) microreactor (quartz) with channel width of 100 ㎛, (b) bio chip (glass) with hole diameter of 500 ㎛, and (c) hole of dipole antenna (quartz) with hole diameter of 150 ㎛.

## 2. Direct writing of waveguides by femtosecond laser pulses

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. 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. The cumulative thermal effects discussed above provide a new tool for micromachining transparent materials. By scanning the laser focus of a continuous 1-kHz 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 optical waveguides and a Y coupler in fused silica glass.

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 waveguide and the measurement of the numerical aperture (NA) of the waveguides. The NA of a step-index waveguide is related to the induced index change $\triangle n$ by $\mathrm{NA}=(2\mathrm{n}\triangle n)^{1/2}$ for small $\triangle n$, where n is the refractive index of the glass. As the average power was 0.3-0.5 mW, the refractive-index changes were 0.006-0.01. Because the refractive-index change $\triangle n$ depends on the pulse peak power and speed of the sample, we can control the irradiation conditions to create different refractive-index change and core diameter of the waveguides.

A schematic of the Y coupler is presented in Fig. 5. The length of the Y coupler is 5 mm, and the separation of the two branches is 0.25 mm. The Y coupler was fabricated by using 1 kHz trains of 100-fs laser pulses with an average power of 0.35 $\mu J$ per pulse. The laser beam was guided into a microscope and focused by a 20× objective (NA, 0.42). 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

FIG. 5. Optical micrograph of the Y coupler written inside fused silica by using a 0.35 $\mu J$, 1 kHz, femtosecond pulse train focused with a 0.42-NA microscope objective.

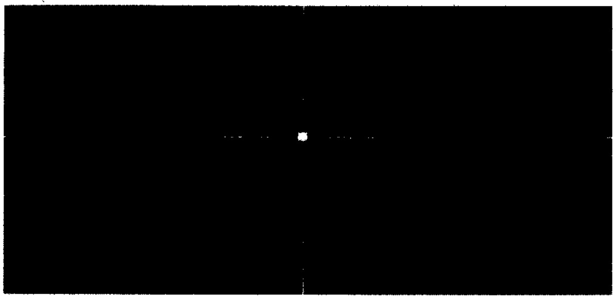


FIG. 6. Far-field pattern of the Y coupler's output with a 633 nm He:Ne laser beam coupled into the input waveguide. The splitting ratio is approximately 1:1.

two branches. The Y coupler was written inside a slab of transparent material about 300 $\mu m$ beneath the surface of the fused silica glass. We translate the sample at a speed of 50 $\mu m$/s in a direction perpendicular to the axis of the femtosecond laser beam. The sample 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 average power of the femtosecond laser beam and is independent of the moving speed of the sample. The minimum propagation loss of 0.8 dB/cm was measured at a wavelength of 1550 nm.

To examine the guiding properties of the waveguides, we coupled light from a He:Ne laser into one end of the waveguide and imaged the output onto a CCD camera. The output image of a He:Ne laser beam (633 nm) coupled into the input guide is shown in Fig. 6. To investigate the guided mode properties, we cut and polished both ends of the waveguides, coupled a He:Ne laser beam at 633-nm wavelength, and monitored the field output patterns with a CCD camera. This demonstrates coupling between the two waveguide branches. The splitting ratio is about 1:1.

## III. CONCLUSION

The drilling of transparent materials by the femtosecond laser pulses was found to be much more controllable and reproducible than nano and picosecond laser pulses. We showed applications of femtosecond lasers on the micromachining of transparent materials and fabrication of optical devices. Finally, we have demonstrated a Y coupler with the splitting ratio of 1:1 written in a fused silica glass by using femtosecond laser pulses. The laser pulse-induced refractive index changes were 0.006-0.01. Waveguide propagation losses at a wavelength of 1550 nm were measured.

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