

# Fabrication of Micro-Photonic Component in Silica Glass with Femtosecond Laser Pulses

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(Received December 11, 2003)

When femtosecond laser pulses are focused inside the bulk of transparent materials, the intensity in the focal volume becomes high enough to produce permanent structural modifications. This technique has been applied to fabricate three-dimensional photonic structures such as optical memory, waveguides, gratings, and couplers inside a wide variety of transparent materials. In this paper, we review the fabrication of optical elements in glasses with femtosecond laser pulses, including the fabrication of waveguides, couplers, Bragg gratings, zone plates, holographic memory, and micro holes.

*OCIS codes* : 320.7110, 140.3330, 190.7110, 140.3440, 050.1970, 130.3120

## I. INTRODUCTION

In recent years, micromachining by femtosecond laser pulses in transparent materials has received much attention. When femtosecond laser pulses are focused inside the bulk of a transparent material, the intensity in the focal volume can become high enough to cause nonlinear absorption, which leads to localized modification in the focal volume, while leaving the surface unaffected [1-3]. Direct writing of optical devices using femtosecond laser pulses in glass has potential applications in the telecommunication industry. The induction of permanent refractive-index change at the laser focal point has been reported in the bulk of glasses to the order of  $10^{-2}$  to  $10^{-4}$  [4]. Recent demonstrations of three-dimensional micromachining of glass using femtosecond laser pulses include waveguides [4-11], couplers [9-16], gratings [17-24], and three-dimensional binary data storage [25-28], lenses [29,30], and channels [31-34].

In this paper, we review the fabrication of photonic components in glasses with femtosecond laser pulses. We present the induction of refractive-index change in silica glass by filamentation of laser pulses. The fabrication of 2-mm directional couplers to split the coupled beam into 1:1 at a wavelength of 632.8 nm is demonstrated [16]. The fabrication of three-dimensional optical couplers is demonstrated. We present the fabrication of volume gratings [18]. The maximum diffraction efficiency was 74.8% with the grating that had the period of 3  $\mu\text{m}$  and the thickness of 150  $\mu\text{m}$ . Fresnel

zone plate by embedding voids in silica glass is demonstrated [29]. Holographic data storage on fused silica, soda-lime, and lead glasses with a single laser pulse is presented [23]. Finally, we show the fabrication of three-dimensional holes of several micrometers in diameter in contact with water at the rear surface of silica glass [34].

## II. WAVEGUIDE AND COUPLER

Techniques for fabricating waveguides can be divided into two categories: side writing and parallel writing. Figure 1 (a) and (b) show the schema of fabrication of waveguides embedded in glass by side-writing and parallel writing, respectively. In parallel writing, laser pulses are focused into the sample by a low-numerical-aperture (NA) lens having a long working distance, and the sample is translated parallel to the propagation axis of the laser pulses. The length of the waveguide is then restricted by the working distance of the focusing objective. However, parallel writing can fabricate waveguides having symmetrical cores and can make full use of the three-dimensional volume.

We have reported that filamentation of femtosecond laser pulses induces permanent refractive-index change in silica glass [5]. Filamentation occurs due to a balance between the Kerr self-focusing of the laser pulse and the defocusing effect of the high-intensity plasma generated in the self-focal region. The region of refractive

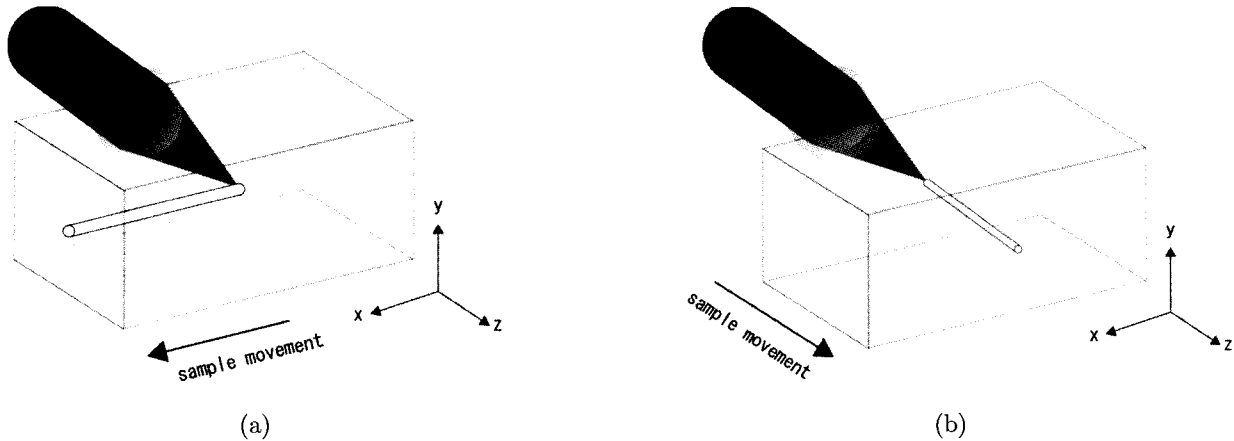


FIG. 1. Fabrication of waveguides embedded in glass. (a) side-writing and (b) parallel writing.

index change was 10 to 500 micrometers long due to the NA of the focusing lens. The refractive-index change was as large as  $0.8 \times 10^{-2}$ . By translation of the sample parallel to the optical axis, the 2-mm straight waveguide was fabricated. In this section, we report the fabrication of three-dimensional couplers by filamentation of femtosecond laser pulses [16].

Experiments were performed using a regeneratively amplified Ti:sapphire laser system which produces 130 fs, 800 nm, 1 kHz pulses. The laser pulses propagate along the optical axis (+z direction). The sample was a piece of SiO<sub>2</sub> glass and was mounted on a computer-controlled three-axis motion stage. Focusing laser pulses by a 0.30-NA objective lens formed a single filament with a length of 40  $\mu\text{m}$ .

We fabricated a directional coupler containing a 2-mm-long straight waveguide and a curved waveguide connected to a different straight section. The straight section was parallel to the straight waveguide and was separated by a 4- $\mu\text{m}$  center-to-center distance. The

straight waveguide was fabricated using a translation speed of 0.2  $\mu\text{m}/\text{s}$ . Another straight waveguide was then fabricated parallel to the straight waveguide. The curved waveguide was fabricated from one end of the straight section with arc radii of 17 mm. Several couplers were fabricated by varying the length of the straight sector  $L$ .

Coupling properties were investigated by focusing a He-Ne laser beam having a wavelength of 632.8 nm into the straight waveguide. The splitting ratios of the directional couplers with  $L = 1$  mm and  $L = 0.5$  mm are approximately 1:1 and 1:0.5, respectively. Experimental results show that splitting ratio depends on interaction length  $L$ , and that this behavior is a typical characteristic of directional couplers.

We demonstrate the realization of three-dimensional directional couplers. Figure 2 (a) shows the schema of a three-dimensional directional coupler consisting of three waveguides: a 2-mm-long straight waveguide (waveguide I) and two curved waveguides that are

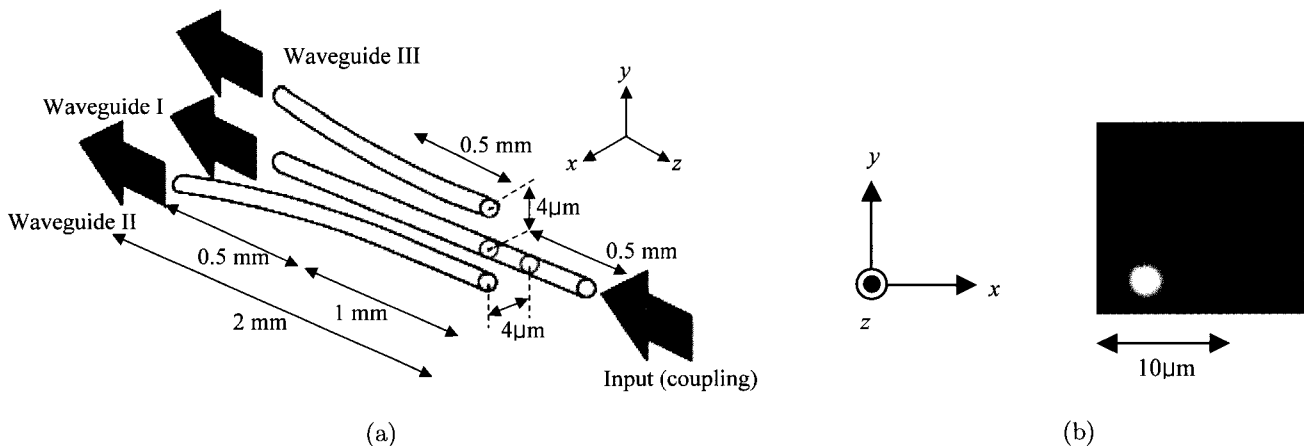


FIG. 2. (a) Schematic of a three-dimensional directional coupler. (b) Near-field patterns of coupler output when coupling to a He-Ne laser at a wavelength of 632.8 nm.

connected to straight sections (waveguide II and III). Lengths of the straight sectors in waveguide II and waveguide III were 0.5 mm and 1.0 mm. The He-Ne laser beam was coupled to the straight waveguide and the near-field patterns (NFP) were monitored using a charge-coupled device (CCD) camera. Figure 2 (b) shows the NFP of beams from the coupler at a wavelength of 632.8 nm. The beam was split amongst the three waveguides at different intensities.

### III. VOLUME GRATING

The volume grating with a fine period is an important device because of its large diffraction angle, high diffraction efficiency, and high wavelength selectivity. There are two methods of fabricating the grating with femtosecond laser pulses inside silica glass. One is the two-beam interference method [20-24]. The grating is created by two-beam interference of a split single pulse. The grating usually has a fine period of less than 1  $\mu\text{m}$  and can be recorded only by a single pulse. However the diffraction efficiency of the grating is very low (1%) and it is difficult to control its thickness and three-dimensional shape. The other is the direct-writing method [17,19]. The fabrication time is longer, however, one can vary the thickness and period of the grating. In this section, we report the fabrication of Bragg gratings by direct-writing with filamentation in silica glass.

Figure 3 shows the schema of the fabrication of the volume grating. A 150- $\mu\text{m}$ -long filament was formed by focusing 0.1  $\mu\text{J}$  pulses with a 0.10-NA focusing lens. When the filament was scanned for 300  $\mu\text{m}$  along the  $x$ -axis (perpendicular to optical axis) at the speed of

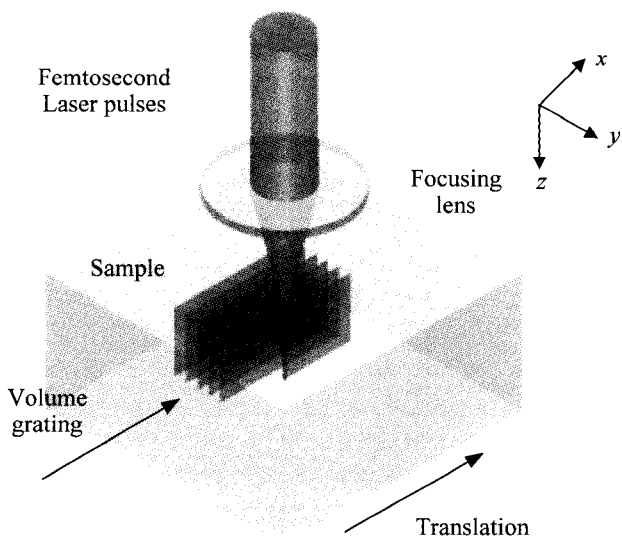


FIG. 3. Fabrication of a volume grating in silica glass.

1  $\mu\text{m/s}$ , a layer of refractive-index change with a thickness of 2  $\mu\text{m}$  was induced. We stacked 60 layers along the  $y$ -axis with a sample displacement of 5  $\mu\text{m}$ . Figure 4 shows optical images of the fabricated gratings. Figure 4 (a) shows the top view of the grating that was observed from the  $z$ -axis. Figures 4 (b) and 4 (c) are the side views that are observed from the  $x$ - and the  $y$ -axes, respectively.

We fabricated several different gratings by varying the thickness and period and measured diffraction efficiency. The diffraction efficiency of the grating was measured with a cw He-Ne laser at the wavelength of 632.8 nm as shown in Fig. 5 (a). The angle of the He-Ne beam with respect to the grating vector was adjusted to achieve the maximum diffraction efficiency. The maximum diffraction efficiency of 74.8% was obtained when the grating has a period of 3  $\mu\text{m}$ . The profile and image of the diffraction pattern are shown in Fig. 5 (b). When the period of the grating was narrowed, the diffraction efficiency increased. We also estimated the refractive-index change of the gratings using the coupled wave theory [40,41]. When the grating satisfies Bragg's law, the diffraction efficiency  $\eta$  is given by

$$\eta = \sin^2\left(\frac{\pi n_1 t}{\lambda \cos\theta}\right) \quad (1)$$

where  $n_1$  denotes the refractive-index change,  $t$  is the thickness of the grating,  $\lambda$  is the wavelength of the

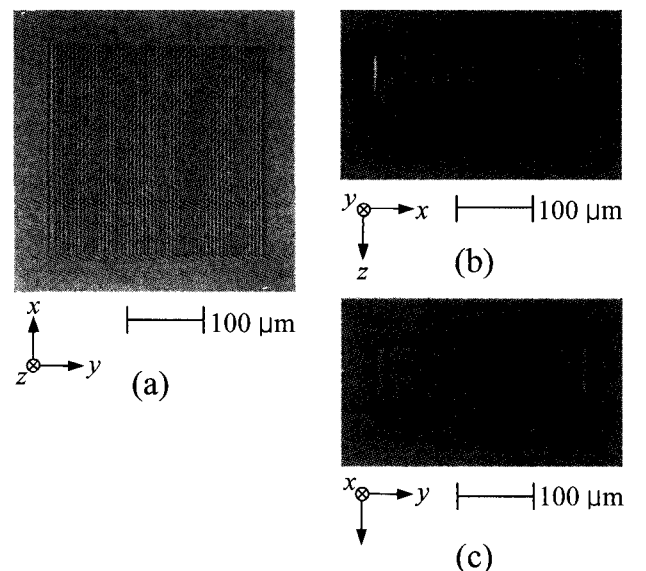


FIG. 4. Optical images of the fabricated grating with the period of 5  $\mu\text{m}$  and thickness of 150  $\mu\text{m}$ . The fabrication energy was 1.0  $\mu\text{J}$  and the translation speed of the filament was 1  $\mu\text{m/s}$ . (a) Top view. (b) Side view ( $xz$ -plane). (c) Side view ( $yz$ -plane).

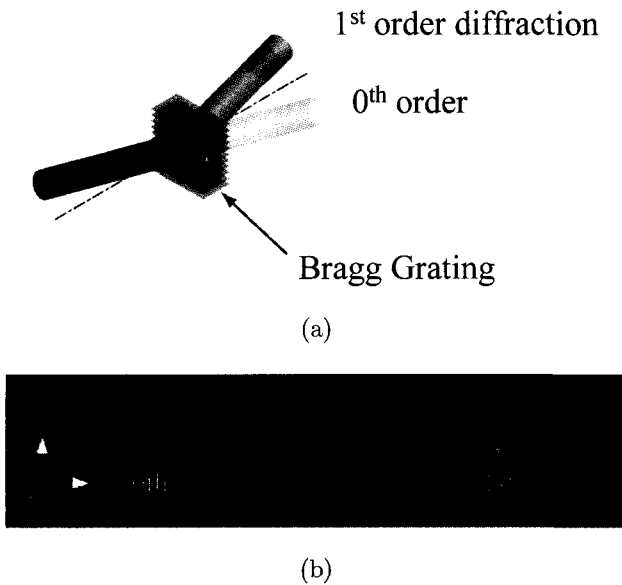


FIG. 5. (a) Schematic of the Bragg grating embedded in silica glass and its diffraction. (b) Diffraction pattern of the fabricated grating with the period of  $3\ \mu\text{m}$  and thickness of  $150\ \mu\text{m}$ . The fabrication energy was  $1.0\ \mu\text{J}$  and translation speed of the filament was  $1\ \text{mm/s}$ .

reading beam, and  $\theta$  is the Bragg angle. Here, we assumed that the distribution of the refractive-index change parallel to the grating vector was sinusoidal and the distribution perpendicular to the grating vector was uniform within the grating. In the case of the grating that has a period of  $3\ \mu\text{m}$  and the thickness of  $30\ \mu\text{m}$ , the refractive-index change was estimated to be  $2.0 \times 10^{-3}$ . By increasing the thickness of the gratings, the efficiency increases from the Bragg's law.

#### IV. FRESNEL LENS

Tightly focusing femtosecond laser pulses with high NA lenses produce submicron-damage inside a wide variety of transparent materials [25-28]. The damage appears as cavities or voids with diameters of only  $200\ \text{nm}$  to  $1\ \mu\text{m}$ , surrounded by densified material. An important feature of the void is the large difference of refractive-index change between a cavity and the surrounding region. We present in this section the report of the fabrication of a lens by embedding voids inside silica glass [29].

Figure 6 shows the schematic of the designed Fresnel lens. Our designed Fresnel lens has the primary focal length of  $3\ \text{mm}$  at the wavelength of  $632.8\ \text{nm}$ . The radius of the first odd zone  $s_1$  was designed to be  $43.5\ \mu\text{m}$ . The size of the zone plate was  $400\ \mu\text{m} \times 400\ \mu\text{m}$ . In this condition, the radius of the outer zone is  $200\ \mu\text{m}$ , which corresponds to the included number of the odd

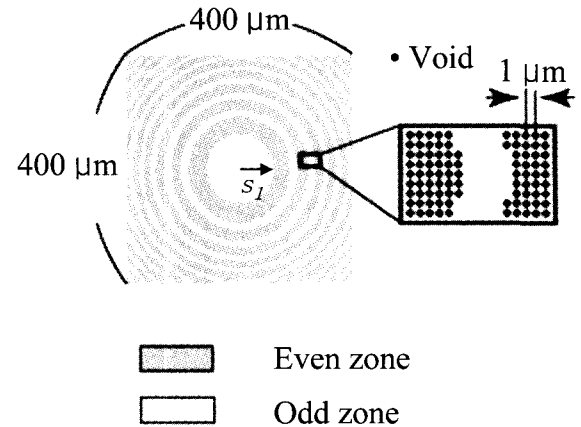


FIG. 6. Schematic of the fabrication of Fresnel zone plate. We constructed the zone plate that passes only the odd zones and obstructs the even zones. Even zones are fabricated by embedding the array of the voids with steps of  $1\ \mu\text{m}$ .

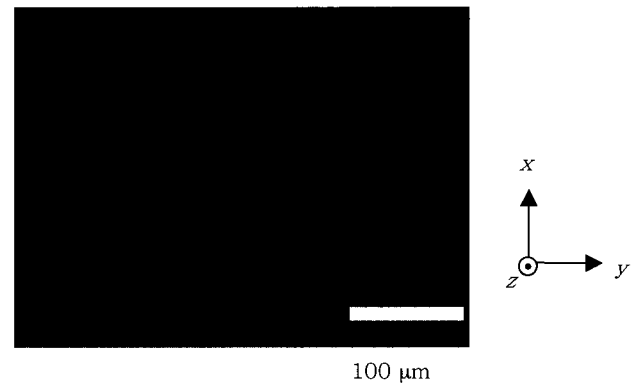


FIG. 7. Optical image of the fabricated Fresnel zone plate by embedding the two-dimensional array of voids. The image was observed under illumination by halogen lamp.

zone plate is eleven.

The laser pulses were tightly focused by an objective lens with a NA of 0.55. We fabricated the Fresnel zone plate by embedding voids at the depth of  $300\ \mu\text{m}$  beneath the sample of silica glass. The sample was displaced dot by dot in the  $xy$ -plane perpendicular to the laser propagation axis by steps of  $1\ \mu\text{m}$ . Figure 7 shows an optical image of the fabricated Fresnel zone plate by embedding the two-dimensional array of voids. The voids were embedded only in the even zones.

We investigated the focusing properties of the fabricated Fresnel zone plate. The beam incident on the lens is diffracted and converges in on the primary focal spot on the optical axis. Figure 8 shows an intensity distribution in the primary focal point when a He-Ne laser beam was incident on the zone plate. The primary

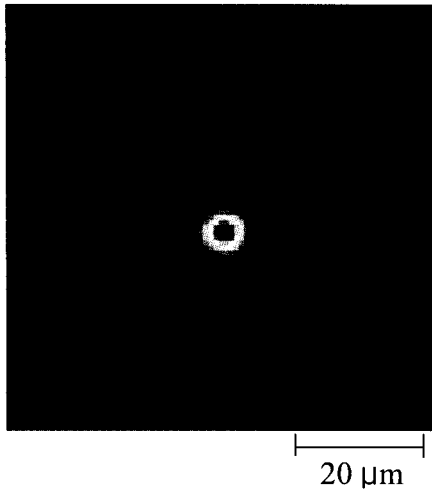


FIG. 8. Intensity distribution in the primary focal point when a cw-He-Ne laser beam at the wavelength of 632.8 nm transmitted through the zone plate. The spot size was  $7.0 \mu\text{m}$  and agree well with the theoretical value of  $6.1 \mu\text{m}$ . The diffraction efficiency was 2%.

focal point was located in air. The measured spot size was  $7.0 \mu\text{m}$  and agreed with the theoretical value of  $6.1 \mu\text{m}$ . The measured diffraction efficiency was 2.0%.

## V. HOLOGRAM

A holographic grating can be encoded on the surface or inside nonphotosensitive glasses by two beam interference of a single near infrared femtosecond laser pulse [21]. The diffraction efficiency of a surface relief grating can reach 20%. These experiments suggest the potential of holographic optical storage in nonphotosensitive glasses, however, no storage of actual data image has been realized. In this section, we present experimental results of holographic data storage on the surface of fused silica, soda-lime, and lead glasses by two-beam interference of a single femtosecond laser pulse [23].

A top view of the experimental schematics for recording of a data image is shown in Fig. 9 (a). A laser pulse is split into the reference and object beams. The two beams are incident onto the sample at approximately equal angles of  $33^\circ$ . The Fourier transform configuration is used to record the information. The reference beam is focused by a lens  $L_R$  of 500 mm focal length. The object beam is expanded by a Galileo telescope and transmitted through a data mask. The data bearing object beam is focused or Fourier transformed by the lens  $L_O$  of 50 mm focal length. A hologram is written when the reference beam intersects with the object beam and their interference fringes are recorded in the sample. When the optical paths are adjusted to give a perfect spatial and temporal overlap of the reference and object beams on the surface of the

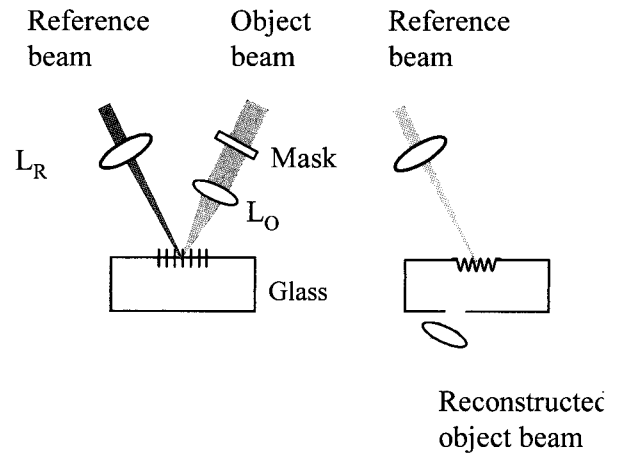


FIG. 9. Top view of experimental schematics for (a) hologram recording and (b) reconstruction of data.

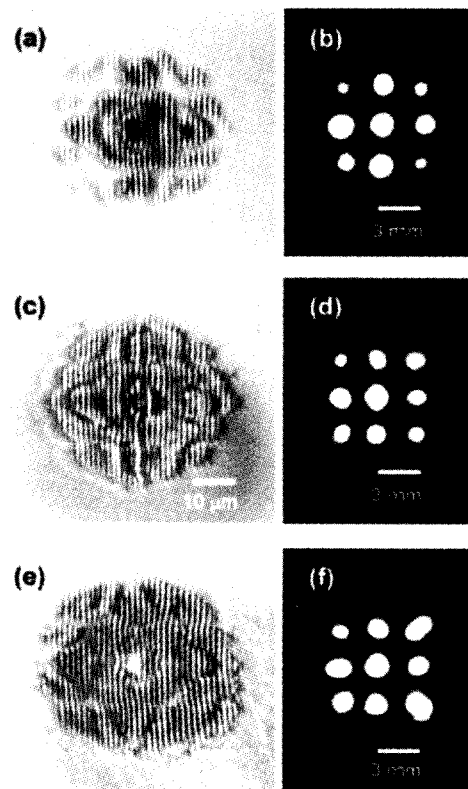


FIG. 10. Holograms recorded on fused silica, soda-lime, and lead glasses and their corresponding reconstructed images. (a) A hologram on fused silica glass and (b) the corresponding reconstruction data; (c) a hologram on sodalime glass and (d) the corresponding reconstruction data; (e) a hologram on lead glass plate and (f) the corresponding reconstruction data.

sample, we can observe a clear fringe pattern. The data image can then be reconstructed by illumination of the hologram with the reference beam (Fig. 9 (b)). By use

of a second lens behind the sample to perform a second Fourier transformation, the data information can be retrieved by a CCD camera. The experimental results are shown in Fig. 10. The energies of the reference beam and object beam are 130 and 110  $\mu\text{J}$  per pulse, respectively for silica glass. Under these energies, only part of the fringes whose intensities are above the ablation threshold are recorded in the hologram. When the soda-lime glass with a lower threshold is used, more fringes can be recorded. Figure 10 (c) illustrates a hologram on a soda-lime glass plate under the same experimental conditions. The reconstructed image shown in Fig. 10 (d) is better than that in Fig. 10 (b) on fused silica compared with dimmer spots at the four corners of the reconstructed image. Because the lead glass has a much lower threshold, we can record a hologram with weaker energy. Figure 10 (e) shows a typical micro hologram on lead glass. The reconstructed data image is shown in Fig. 10 (f). All nine spots are clearly retrieved.

## VI. MICRO-HOLE

In order to obtain a three-dimensional hole, Kondo *et al.* produced a Y-branched hole by translating the photomachinable glass perpendicular to the incident femtosecond laser beam, followed by heat treatment and subsequent etching in dilute aqueous hydrofluoric (HF) solution [31]. Marcinkevicius *et al.* demonstrated femtosecond laser-assisted three-dimensional microfabri-

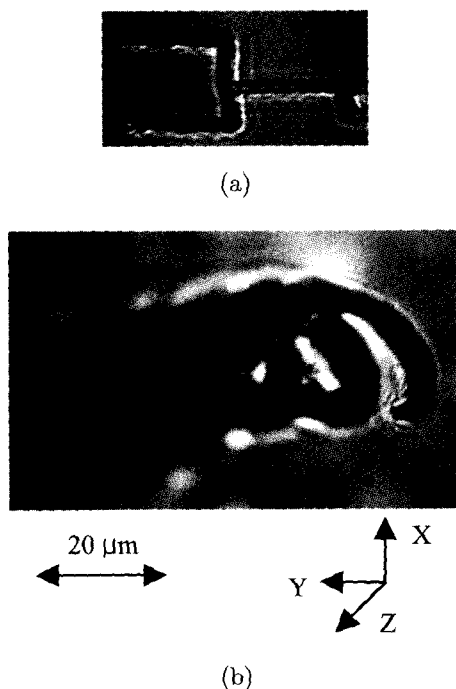


FIG. 11. Microholes in (a) a 2D plane and (b) a 3D space.

cation of an H-shaped channel in silica glass that was carried out in two steps: writing a preprogrammed pattern to the silica volume by producing uniformly distributed damage spots by laser pulses and then etching in a 5% aqueous solution of HF acid [32].

Li *et al.* have demonstrated microchannel-drilling inside silica glass in a single step with femtosecond laser pulses [34]. No postfabrication such as heat treatment or wet etching was needed. It should be noted that its rear surface was in contact with distilled water. We show complex structures of the microholes by using Li's method. The fabricated hole in the two-dimensional plane is shown in Fig. 11 (a). The top of a spiral structure in three-dimensional space is shown in Fig. 11 (b). This technique can be applied to the fields of micro-optics, microelectronics and microchemistry.

## VII. CONCLUSION

In conclusion, the fabrication of 2 mm directional couplers to split a beam into 1:1 at a wavelength of 632.8 nm was demonstrated. Realization of three-dimensional directional couplers was also demonstrated. We demonstrated the fabrication of volume gratings. The maximum diffraction efficiency of the fabricated grating was 74.8%. We fabricated a Fresnel zone plate having a size of 400  $\mu\text{m} \times 400 \mu\text{m}$  by embedding voids in silica glass. Holographic data storage on the surface of fused silica, soda-lime, and lead glasses is presented. The relief microhologram is recorded on a nonphotosensitive glass plate after the sample is exposed to the interference fringe of object beam and reference beam that are split from a single femtosecond pulse. Femtosecond laser pulses open a new door to the fabrication of photonic devices in transparent materials.

## REFERENCES

- [1] M. E. Fermann, A. Galvanauskas, G. Sucha, *Ultrafast Lasers* (Marcel Dekker, New York, 2003).
- [2] K. Hirao, T. Mitsuyu, J. Si, and J. Qiu, *Active Glass for Photonic Devices* (Springer-Verlag, Berlin, 2001)
- [3] K. Itoh and W. Watanabe, "Toward nano- and micro-processing in glass with femtosecond laser pulses," *RIKEN Review*, vol. 50, pp. 90-94, 2003.
- [4] K. M. Davis, K. Miura, N. Sugimoto, and K. Hirao, "Writing waveguides in glass with a femtosecond laser," *Opt. Lett.* vol. 21, 1729, 1996.
- [5] K. Yamada, W. Watanabe, T. Toma, J. Nishii, and K. Itoh, "In situ observation of photoinduced refractive index changes in filaments formed in glasses by femtosecond laser pulses," *Opt. Lett.* vol. 26, 19, 2001.
- [6] C. B. Schaffer, A. Brodeur, J. F. Garcia, and E. Mazur, "Micromachining bulk glass by use of femtosecond laser pulses with nanojoule energy," *Opt. Lett.* vol. 26, 93, 2001.

- [7] M. Will, S. Nolte, B. N. Chichkov, and A. Tuennermann, "Optical properties of waveguides fabricated in fused silica by femtosecond laser pulses," *Appl. Opt.* vol. 41, 4360, 2002.
- [8] S. Nolte, M. Will, J. Burghoff, and A. Tuennermann, "Femtosecond waveguide writing: a new avenue to three-dimensional integrated optics," *Appl. Phys. A* vol. 77, 109, 2003.
- [9] A. Salimonia, N. T. Nguyen, M. -C. Nadeau, S. Petit, S. L. Chin, and R. Vallée, "Writing optical waveguides in fused silica using 1 kHz femtosecond infrared pulses," *J. Appl. Phys.* vol. 93, 3724, 2003.
- [10] G. Cerullo, R. Osellame, S. Taccheo, M. Marangoni, D. Polli, R. Ramponi, P. Laporta and S. De Silvestri, "Femtosecond micromachining of symmetric waveguides at 1.5 mm by astigmatic beam focusing," *Opt. Lett.* vol. 27, 1938, 2002.
- [11] Y. Tokuda, M. Saito, M. Takahashi, K. Yamada, W. Watanabe, K. Itoh, and T. Yoko, "Waveguide formation in niobium tellurite glasses by pico- and femtosecond laser pulses," *J. Non-Cryst. Solids* vol. 326&327, 472, 2003.
- [12] D. Homoelle, W. Wielandy, A. L. Gaeta, E. F. Borrelli, and C. Smith, "Infrared photosensitivity in silica glasses exposed to femtosecond laser pulses," *Opt. Lett.* vol. 24, 1311, 1999.
- [13] 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. 42-44, 2001.
- [14] K. Minoshima, A. M. Kowalevich, I. Hartl, E. P. Ippen, and J. G. Fujimoto, "Photonic device fabrication in glass by use of nonlinear materials processing with a femtosecond laser oscillator," *Opt. Lett.* vol. 26, 1516, 2001.
- [15] K. Minoshima, A. M. Kowalevich, E. P. Ippen, and J. G. Fujimoto, "Fabrication of coupled mode photonic devices in glass by nonlinear femtosecond laser materials processing," *Opt. Express* vol. 10, 645, 2002.
- [16] W. Watanabe, T. Asano, K. Yamada, K. Itoh, J. Nishii, "Wavelength division using three-dimensional couplers fabricated by filamentation of femtosecond laser pulses," *Opt. Lett.* vol. 28, 2491, 2003.
- [17] K. Yamada, W. Watanabe, J. Nishii, and K. Itoh, "Anisotropic refractive-index change in silica glass induced by self-trapped filament of linearly polarized femtosecond laser pulses," *J. Appl. Phys.* vol. 93, 1889, 2003.
- [18] K. Yamada, W. Watanabe, K. Kintaka, J. Nishii, and K. Itoh, "Volume grating induced by a self-trapped long filament of femtosecond laser pulses in silica glass," *Jpn. J. Appl. Phys.* vol. 42, 6916, 2003.
- [19] L. Sudrie, M. Franco, B. Prade, and A. Mysyrowicz, "Writing of permanent birefringent microlayers in bulk fused silica with femtosecond laser pulses," *Opt. Commun.* vol. 171, 279, 1999.
- [20] Y. Li, W. Watanabe, K. Yamada, T. Shinagawa, and K. Itoh, J. Nishii, and Y. Jiang, "Holographic fabrication of multiple layers of grating inside soda-lime glass with femtosecond laser pulses," *Appl. Phys. Lett.* vol. 80, 1508, 2002.
- [21] K. Kawamura, T. Ogawa, N. Sarukura, M. Hirano, and H. Hosono, "Fabrication of surface relief gratings on transparent dielectric materials by two-beam holographic method using infrared femtosecond laser pulses," *Appl. Phys. B: Lasers Opt.* vol. 71, 119, 2000.
- [22] K. Kawamura, M. Hirano, T. Kamiya, and H. Hosono, "Holographic writing of volume-type microgratings in silica glass by a single chirped laser pulse," *Appl. Phys. Lett.* vol. 81, 1137, 2002.
- [23] Y. Li, W. Watanabe, K. Itoh, and X. Sun, "Holographic data storage on nonsensitive glass with a single femtosecond laser pulse", *Appl. Phys. Lett.* vol. 81, 1952, 2002.
- [24] Y. Li, K. Yamada, T. Ishizuka, W. Watanabe, K. Itoh, and Z. Zhou, "Single femtosecond pulse holography using polymethyl methacrylate," *Opt. Express* vol. 10, 1173, 2002.
- [25] E. N. Glezer, M. Milosavljevic, L. Huang, R. J. Finlay, T.-H. Her, J. P. Callan, and E. Mazur, "Three-dimensional optical storage inside transparent materials," *Opt. Lett.* vol. 21, 2023, 1996.
- [26] E. N. Glezer and E. Mazur, "Ultrafast-laser driven micro-explosions in transparent materials," *Appl. Phys. Lett.* vol. 71, 882, 1997.
- [27] W. Watanabe, T. Toma, K. Yamada, J. Nishii, K. Hayashi, and K. Itoh, "Optical seizing and merging of voids in silica glass with infrared femtosecond laser pulses," *Opt. Lett.* vol. 25, 1669, 2000.
- [28] W. Watanabe and K. Itoh, "Motion of bubble in solid by femtosecond laser pulses," *Opt. Express* vol. 10, 603, 2002.
- [29] W. Watanabe, D. Kuroda, K. Itoh, and J. Nishii, "Fabrication of Fresnel zone plate embedded in silica glass by femtosecond laser pulses," *Opt. Express* vol. 10, 978, 2002.
- [30] E. Bricchi, J. D. Mills, P. G. Kazansky, B. G. Klappauf, and J. J. Baumberg, "Birefringent Fresnel zone plates in silica fabricated by femtosecond laser machining," *Opt. Lett.* vol. 27, 2200, 2002.
- [31] Y. Kondo, J. Qiu, T. Mitsuyu, K. Hirao, and T. Yoko, "Three-dimensional microdrilling of glass by multiphoton process and chemical etching," *Jpn. J. Appl. Phys.* vol. 38, L1146, 1999.
- [32] A. Marcinkevicius, S. Juodkazis, M. Watanabe, M. Miwa, S. Matsuo, H. Misawa, and J. Nishii, "Femtosecond laser-assisted three-dimensional microfabrication in silica," *Opt. Lett.* vol. 26, 277, 2001.
- [33] M. Masuda, K. Sugioka, Y. Cheng, N. Aoki, M. Kawachi, K. Shihoyama, K. Toyoda, A. Helvajian, and K. Midorikawa, "3-D microstructuring inside photosensitive glass by femtosecond laser excitation," *Appl. Phys. A* vol. 76, 857, 2003.
- [34] Y. Li, K. Itoh, W. Watanabe, K. Yamada, D. Kuroda, J. Nishii, and Y. Jiang, "Three-dimensional hole drilling of silica glass from rear surface with femtosecond laser pulses," *Opt. Lett.* vol. 26, 1912, 2001.
- [35] S.-H. Cho, H. Kumagai, I. Yokota, K. Midorikawa and M. Obara, "Observation of self-channeled plasma formation and bulk modification in optical fibers using high-intensity femtosecond laser," *Jpn. J. Appl. Phys.* vol. 37, L737, 1998.

- [36] W. Liu, O. Kosareva, I. S. Golubutsov, A. Iwasaki, A. Becker, V. P. Kandidov, and S. L. Chin, "Random deflection of the white light beam during self-focusing and filamentation of femtosecond laser pulses in water," *Appl. Phys. B* vol. 75, 595, 2002.
- [37] K. Okamoto, *Fundamentals of optical waveguides* (Academic Press, San Diego, 2000) Chapter 4.
- [38] D. Marcuse, *Light transmission optics* (Van Nostrand Reinhold, New York, 1972).
- [39] R. S. Taylor, C. Hnarovsky, E. Simova, D. M. Rayner, M. Mehandale, V. R. Bhardwaj, and P. B. Corkum, "Ultra-high resolution index of refraction profiles of femtosecond laser modified silica glass," *Opt. Express* vol. 11, 775, 2003.
- [40] E. Hecht: *Optics* (Addison Wesley, San Francisco, 2002) 4th ed., Chap. 10, p. 443.
- [41] H. Kogelnik, "Coupled wave theory for thick hologram gratings," *Bell Sys. Tech. J.* vol. 48, 1969, 2909.