Femtosecond laser microfabrication of micro-optic elements in glass

Yan Li (李 焱), Hongbing Jiang (蒋红兵), Hong Yang (杨 宏), and Qihuang Gong (龚旗煌)

State Key Laboratory for Mesoscopic Physics & Department of Physics, Peking University, Beijing 100871

Micro-optic elements have been fabricated in silica and soda-lime glass with femtosecond laser pulses. The dependence of refractive index change on pulse duration, pulse energy and scan passes is investigated and a Fresnel zone plate is induced. A permanent computer-generated hologram encoded by the detour phase method is directly written by microexplosion. The stored image is reconstructed with a collimated He-Ne laser beam. Three-dimensional microchannels are drilled by water-assisted ablation. At low incident pulse energy, only one transverse microhole is observed. At high incident pulse energy, multiple transverse microholes are simultaneously drilled.

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Femtosecond laser microfabrication has attracted much attention due to the advantages such as small heat-affected zones, the versatility to the materials, and the ability of three-dimensional (3D) processing inside the transparent medium. When femtosecond laser pulses are focused into a transparent medium, ultrahigh fluence near the focus can result in nonlinear multiple photon absorption and subsequent avalanche ionization of the material. The modification of material properties, such as refractive index change and cavity generation, is possible on a micrometer scale over a wide range of glass types without the need for linear absorption. When the focus is located at the surface, material ablation and removal will take place. These nonlinear effects have been extensively used for microfabrication and micromachining of various 3D structures in glass, such as waveguides[1], couplers[2], gratings[3], and 3D channels[4]. Optical data storage in nonphotosensitive glass has also been demonstrated[5].

In this paper, several micro-optic elements have been fabricated in silica and soda-lime glass with femtosecond laser pulses. A Fresnel zone plate, a computer-generated hologram and a 3D microchannel were written directly by refractive index change, microexplosion, and ablation, respectively. Multiple transverse microholes were simultaneously drilled.

A regeneratively amplified Ti:sapphire laser system (Spitfire, Spectra Physics) was used, which delivered pulses with a duration of 120 fs, a center wavelength at 800 nm and a repetition rate of 1 kHz. The energy of incident pulse could be continuously varied by rotating a half-wave plate before a Glan-prism. The sample was mounted on a computer-controlled translation stage with 0.1-μm resolution. In order to *in situ* monitor the fabrication process, the sample was optically polished on four sides. A top view and a side view were obtained at the same time by two sets of transilluminated optical microscope system. The experiment was conducted at atmospheric pressure.

The dependence of refractive index change Δn on pulse energy, pulse duration and scan passes was studied. The laser beam was focused by a microscope objective lens with a low numerical aperture (NA) of 0.10. At a fixed scan speed of 10 μm/s, Δn increased with the pulse energy in the range of 0.4–2.2 μJ when the pulse duration was 130 fs. Damage appeared when the pulse energy was over 2.2 μJ. The index change threshold increased with pulse duration between 130 and 230 fs, but the damage threshold decreased obviously, resulting in a triangle region of pulse duration and pulse energy in which only refractive-index-change structures can be obtained[6].

We found Δn could be enhanced by multiple scan passes. At a scan speed of 10 μm/s and pulse energy of 1.2 μJ, Δn was 0.2×10^{-3}, 0.7×10^{-3}, 1.5×10^{-3}, 2.0×10^{-3} for single, 4, 8, and 20 passes. It saturated after 20 passes due to the saturation of defect density. The filament length was almost invariable, which was useful for microfabrication of elements with multiple refractive index changes but with the same thickness.

A Fresnel zone plate was directly written inside silica glass, which consisted of a series of concentric rings. A microscope image of the Fresnel zone plate with 20 zones is shown in Fig. 1. The pulse duration was 130 fs and the writing energy was 1.2 μJ/pulse. The imaging of the logo of Peking University by the zone plate is also demonstrated.

A computer-generated hologram (CGH) was fabricated inside silica glass by microexplosion. An object image of the logo of Peking University was sampled and Fourier transformed by a computer. Then the complex amplitude distribution was encoded by detour phase method to form a binary CGH[7]. The resulted CGH was recorded inside silica glass in a single step by microexplosion.

A long working distance objective lens with a NA of 0.50 was applied to focus the laser pulses. The pulse duration was $\sim$ 300 fs. The incident energy was 0.7 μJ/pulse. The chirped pulses were focused 300 μm beneath the front surface of the sample. The high fluence at focus induced microexplosion to create a void. The void

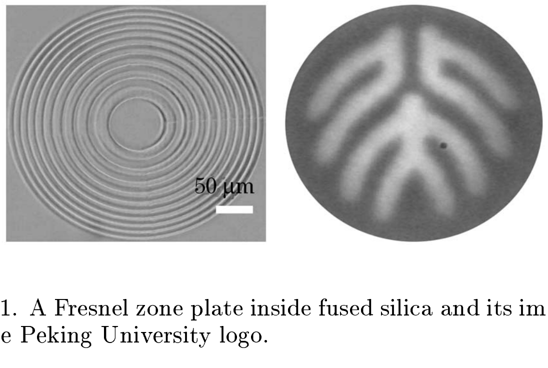

Fig. 1. A Fresnel zone plate inside fused silica and its imaging of the Peking University logo.

damage scattered light strongly, resulting in an opaque spot inside the transparent glass, while the unirradiated dots remained "white".

To record the desired CGH, the sample was moved step by step and irradiated by the focused pulses according to the hologram pattern. The translation speed was 40 μm/s. The lateral size of the void was about 3 μm so that the translation step was set to be 3μm. The cell width was 24 μm and the final CGH was $\sim 1.54 \times 1.54$ mm^2.

To reconstruct the object image from the fabricated CGH, a collimated He-Ne laser beam was normally incident on the CGH and the diffraction pattern was collected by a lens onto a screen. Then the output image was taken by a digital camera. There were high order images as well as their conjugate images as demonstrated in Fig. 2.

Straight holes and 3D microchannels are drilled in soda-lime galss by water-assisted ablation[8]. A 3D microchannel is demonstrated in Fig. 3. We first situated the focus at the rear surface of the sample and then moved the sample along the $+z$ direction step by step. The translation step of the microstage was 1 μm and about 50 pulses irradiated on each pausing spot. The incident energy was 1.4 μJ/pulse. The NA of the focusing objective was 0.50. Accompanied by the inflow of water, the longitudinal microhole elongated continuously. The diameter of the microhole was ~ 3 μm. When the hole (AB in Fig. 3(a)) reached a length of ~ 35 μm, we changed the translation direction to $-x$ and a ~ 20 μm transverse microhole (BC) was produced. After that, the translation direction was altered to $-y$, another ~ 20 μm microhole (CD) was fabricated. As a result, a true 3D microchannel consisting of a longitudinal and two transverse holes was drilled. The three micoholes were perpendicular to each other and their diameters were approximately equal.

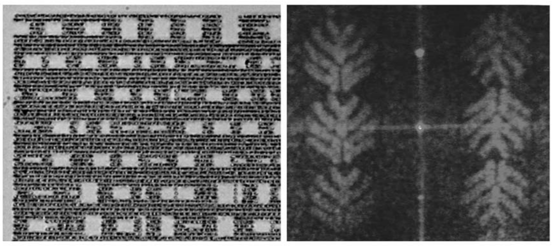

Fig. 2. Part of an embedded computer-generated hologram inside fused silica and its reconstruction of the Peking University logo.

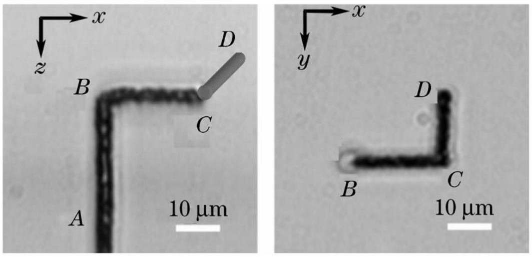

Fig. 3. A 3D microchannel in soda-lime glass observed from x-z plane with the schematic hole CD (a) and observed from x-y plane (b).

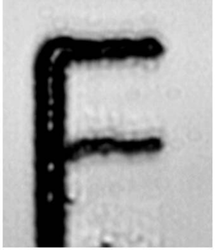

Fig. 4. Two transverse microholes simultaneously drilled in soda-lime glass at the energy of 3.2 μJ/pulse.

Increasing the incident pulse energy, we could obtain a longer longitudinal microhole with a wider diameter. When we altered the translation direction to drill a transverse microhole step by step, we actually got multiple transverse microholes at the same time as shown in Fig. 4. At incident pulse energy of 3.2 μJ, two transverse microholes were obtained. The underlying mechanism might be the refocusing of an intense femtosecond laser pulse in a transparent material.

When the pulse energy was high enough, multiple foci and a filament appeared due to the dynamics competition between self-focusing by Kerr effect and defocusing by the plasma[9]. In addition, the spherical aberration due to air-glass interface might elongate the focus along the propagation direction and also result in multiple foci[10]. As the energy increased, besides the main focus, other foci had sufficient energy to ablate the material in the vicinities of these foci so that multiple transverse microholes could be simultaneously drilled. Because the number and diameters of microholes can be selected by adjusting the pulse energy, it is possible to drill more complicated 3D microchannels at high speed.

In conclusion, a Fresnel zone plate, a computer-generated hologram, and a 3D microchannel have been fabricated in silica and soda-lime glass with femtosecond laser pulses by refractive index change, microexplosion, and ablation, respectively. At high incident pulse energy, multiple transverse microholes were simultaneously drilled. These techniques can be also applied to microfabrication of other diffractive optical elements for microoptics.

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