Influence of scanning velocity on femtosecond laser direct writing lines on FOTURAN glass

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Received July 16, 2007

Lines are induced on the surface of a photosensitive (FOTURAN) glass by focused femtosecond laser transverse writing with scanning velocity in a wide range of $40-1800$ μm/s. The formed lines are analyzed using scanning electron microscope (SEM) and optical microscope (OM). It is observed that three distinct morphologies of lines are produced depending on the scanning velocity. Lines written in low velocity level ($40-100$ μm/s) and high velocity level ($1000-1800$ μm/s) are uniform and regular, while those written in moderate velocity level ($150-600$ μm/s) are rough. The influence of scanning velocity is explained based on different pulses overlapping or cumulative dose of laser exposure in irradiated area. Fabrication of shallow groove on the surface is also demonstrated.

OCIS codes: 140.3390, 140.7090, 230.4000, 130.3120.

Photosensitive (FOTURAN) glass is a lithium-aluminum-silicate glass doped with small amount of silver (Ag^+) and cerium (Ce^{3+}), which is a photosensitive glass brand of Schott Glass Corporation. Owning to its unique properties in optical transparency, hardness, chemical and thermal resistance, it becomes an attractive fabrication substrate for applications in micro-fluidics, micro-electromechanical systems, micro-optics and bio-photonics. The principle and conventional fabrication process using ultraviolet light has been described in detail[1]. Using pulsed ultraviolet laser as the irradiation source, Helvajian *et al.* have fabricated many patterned components onto this kind of glass for applications like nanosatellites and proposed a hypothesis of critical dose of ultraviolet exposure[2].

Since the nonlinear interaction of focused femtosecond laser with transparent materials is different in mechanism from long pulse laser, femtosecond laser is widely adopted for processing various materials recently[3,4]. Kondo *et al.* demonstrated the fabrication of Y-branched hole employing femtosecnod laser at 400 nm inside similar photosensitive glass[5]. Cheng *et al.* have recently demonstrated a variety of true three-dimensional (3D) micro-fluidic or micro-optical devices inside FOTURAN using near-infrared femtosecond laser[6−8]. The exact photoreaction mechanism of the photosensitive glass with femtosecond laser irradiation is not yet completely understood and needs wide investigation[9−12].

In this paper, we report the lines written on the surface of FOTURAN glass by focused femtosecond laser with transverse writing geometry. Transverse writing and longitudinal writing are two writing modes of femtosecond laser with beam propagation direction perpendicular and parallel to the scanning direction, respectively.

The femtosecond laser writing setup is illustrated in Fig. 1. Near-infrared femtosecond pulses were generated from a commercial mode-locked Ti:sapphire chirped pulse amplification (CPA) laser system (UMW-2110i, Clark-MXR Inc.). The center wavelength, pulse duration, repetition rate and maximum output power were 775 nm, 150 fs, 1 kHz and 1 W, respectively. The incident laser was adjusted by neutral density (ND) attenuator filter to obtain appropriate average power for writing. A 20× objective (NA = 0.40), which was mounted on z axis of a 3D precise translation stage, was employed to focus the incident laser beam with 5-mm diameter on the surface of polished bulk FOTURAN glass (10 × 10 × 3 (mm)). The bulk was placed on x-y plane of the translation stage, which was computer-controlled with a translation resolution of 0.5 μm.

The focus spot diameter was evaluated to be about 9 μm on the bulk. The focusing status on surface was realized through an iterative protocol as follows. The focus spot was initially set above the surface. Several incident pulses with energy above the optical-breakdown threshold of the bulk caused damaged micro-spots on the surface, then the objective lens was moved downward by a small distance and the same procedure was performed. By comparing the diameters of the micro-spots formed in these two steps, one could figure out the relative position

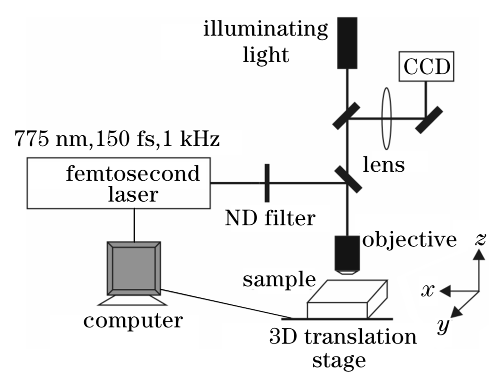

Fig. 1. Experimental setup for femtosecond laser direct writing on FOTURAN.

of focused spot to the surface. After several same steps, one could focus the laser spot on the surface. Due to the short Rayleigh distance, the focusing status was not difficult to achieve with a focusing deviation no more than 5 μm. In the experiment, FOTURAN glass was translated at a velocity range of $40-1800$ μm/s. The writing process was displayed on computer with a charge-coupled device (CCD) monitoring system.

The threshold damage energy of FOTURAN glass with single pulse was determined to be about 800 nJ in our experiment, corresponding to incident laser average power of 0.8 mW. By holding constant incident average power at 1.20 mW (slightly above the threshold) and varying scanning velocities in a wide range of $40-1800$ μm/s, parallel lines were written on the surface employing transverse writing geometry with only once scanning.

The formed lines are shown in Fig. 2(a) with velocities increasing from top to bottom. Figures 2(b), (c) and (d) show magnified optical microscopic (OM) images of lines written at three scanning velocity levels of $40-100$, $150-600$, and $1000-1800$ μm/s, respectively. It can be observed from Fig. 2 that there are three distinctly different morphologies, corresponding to three levels of scanning velocity: low velocities, moderate velocities and high velocities, respectively. Lines in Figs. 2(b) and (d) are regular and uniform, while lines in (c) are rough. These two regular regions of lines were further observed with scanning electron microscope (SEM) as shown in Fig. 3. Comparing Figs. 3(a) and (b), it can be found that lines written at low velocity level are violently ablated and accompanied by much debris around the irradiated area, while lines at high velocity level are weakly induced clean trace. Figure 4 shows typical morphology of the line written at moderate velocity level of 600 μm/s and it exhibits nonuniform edge again, as the OM observation had previously indicated in Fig. 2(c). Although the tiny vibration of translation stage during scanning may effect the writing to some extent, the evident nonuniformity of lines written at moderate velocity level can not only be attributed to the vibration, due to high stabilization of the stage and the same experimental conditions for the three velocity levels.

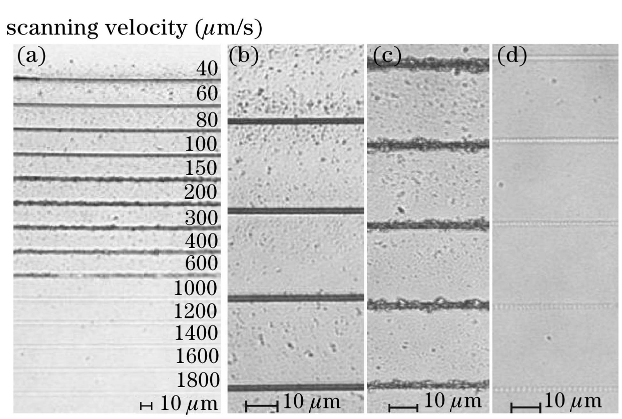

Fig. 2. (a) Transmission optical microscopic images of all lines written at a scanning velocity range of $40-1800$ μm/s. Magnified optical microscopic images of lines written at scanning velocity levels of (b) $40-100$ μm/s, (c) $150-600$ μm/s and (d) $1000-1800$ μm/s, respectively.

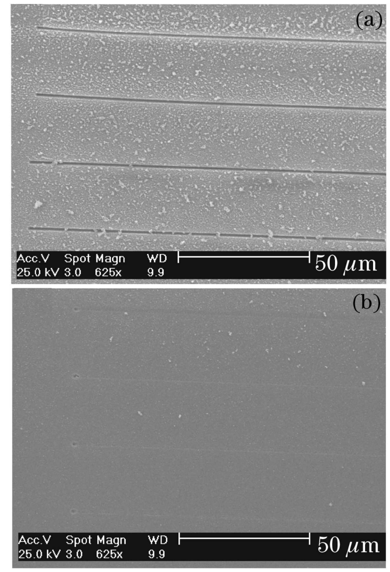

Fig. 3. SEM images of lines written at velocity levels of (a) $40-100$ μm/s and (b) $1000-1800$ μm/s.

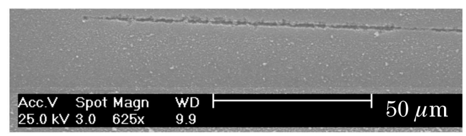

Fig. 4. SEM analysis of the typical morphology of the line written at moderate velocity level of 600 μm/s with average power of 1.2 mW.

Lines written at high velocity level (Fig. 2(d)) still remain transparent in irradiated area and exhibit a little optical contrast with unirradiated area. These lines are similar to the femtosecond-laser-induced refractive-index-change structure in fused silica[3]. The influence of scanning velocity on induced distinct morphologies may be attributed to pulse overlapping or cumulative dose of exposure in irradiated area. High velocity level corresponds to less overlapping and dose, therefore, it only induces slight structural change. On the contrary, in the case of low velocity level, large overlapping is achieved, which results in intensive ablation of FOTURAN glass. The pulse overlap may approximately be evaluated by RD/V, where R, D and V denote pulse repetition rate, focus spot diameter and scanning velocity, respectively. With the 1-kHz repetition rate and 9-μm focus diameter, three velocity levels of $40-100$, $150-600$, and $1000-1800$ μm/s correspond to decreasing focused pulses of $90-225$, $15-60$, and $5-9$ shots at the same position, respectively. Hence, appropriate scanning velocities should be selected at micromachining of different components.

Hereby, femtosecond laser induced refractive-index-change structures can be directly written onto FOTURAN without annealing, which enables fabrication of micro-optical devices such as optical waveguides and gratings. Currently, there are already a few studies concentrated on waveguide writing inside FOTURAN glass[13,14]. However, the propagation loss of waveguide is still high and needs to be largely reduced for practical applications.

After the same heat treatment as Cheng adopted[6] and a subsequent chemical etching in 8% ultrasonic solution

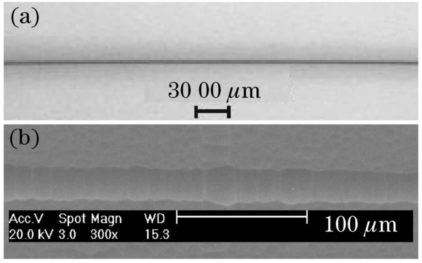

Fig. 5. (a) Optical microscope image of a line written at a scanning velocity of 100 μm/s and incident average power of 1.7 mW; (b) SEM image of the shallow groove formed by etching the line in (a). The width and depth of the groove are 26.5 μm and 1760 nm, respectively.

of hydrofluoric (HF) acid for 50 min at room temperature, a violently ablated line written at 100 μm/s with average power of 1.7 mW, became a shallow groove with width of 26.5 μm and depth of 1760 nm (measured with scanning probe microscope, Digital Instruments Inc., NanoScope III), as shown in Fig. 5. Due to the insufficient exposure of lines written at high velocities, it is difficult to obtain micro-groove after etching.

Parallel lines have been fabricated on the surface of FOTURAN glass using femtosecond laser direct writing with variable scanning velocities from 40 to 1800 μm/s. Their morphologies are analyzed using OM and SEM. Three distinct morphologies of lines are produced depending on three levels of scanning velocity. Lines written in low velocity level ($40 - 100$ μm/s) and high velocity level ($1000 - 1800$ μm/s) are uniform and regular, while those written in moderate velocity level ($150 - 600$ μm/s) are rough. This may be due to different pulse overlapping or cumulative dose of exposure in irradiated area at different scanning velocity levels. High velocity level is suitable for femtosecond laser direct writing of refractive-index-change structures, while low velocity is suitable for fabricating micro-fluidic components after heat treatment and chemical etching.

The authors would like to thank Dongxu Zhang from Tianjin University for heat treatment of sample. This work was supported by the Key Grant Project of the Ministry of Education, P. R. China (No. 10410), the Science and Technology Development Project of Tianjin City (No. 043103911), and the National Natural Science Fundation of China (No. 60608004). Y. Wu's e-mail address is yzhongwu@tju.edu.cn.

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