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Femtosecond Laser Induced Optical Waveguides and Micro-mirrors Inside Glasses *

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Optical waveguides and micro-mirrors have been successfully induced inside fused silica glass and k_9 glass, respectively, by focusing a 800 nm femtosecond (fs) pulsed laser with a repetition rate of 1 kHz. The change of refractive index was determined to be 0.001–0.008 in the fused silica glass and 0.006 in the k_9 glass. The refractive index change is dependent on both the dose of irradiation and the power density of the fs pulsed laser. Photoluminescence was observed in the irradiated region, and was attributed to the defects induced by fs laser irradiation. We discuss the relationship between the optical property and the luminescent property of the irradiated region.

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Owing to ultra-short pulses with high peak power density, the interaction of a femtosecond (fs) laser with matter causes many nonlinear physical phenomenon, such as multi-photon absorption,[1] supercontinuum,[2] micro-exploring,[3] photo-darkening, plasma, thermal electron effect[4] and so on. In recent years, using infrared fs lasers to induce a change in refractive index by the multi-photon absorption process in transparent materials has been widely investigated. This technique has been applied to fabricate photonic structures, such as three-dimensional optical storage,[5] waveguides in a variety of glasses,[6−10] gratings,[11] couplers,[12] and photonic crystals.[13] In 1996, Hirao *et al.*[6] reported on the observation of an increase in refractive index induced by a fs laser and the performance of optical waveguides in the irradiated region in various glasses. In the past few years, a change in refractive index induced by ultraviolet (UV) light in glasses[14] has also been investigated, but the UV-photosensitive glasses were limited due to the requirement of doping with germanium. A fs laser can sensitize a wide variety of glasses, such as fused silica glasses, chalcogenide glasses and ZBLAN glasses, etc. Application of the fs laser provides a new technique for making three-dimensional integrated photonic structures in various glasses. In this Letter, we investigate the relationship between fs laser irradiation conditions and refractive index change in silica and k_9 glasses. The increase/decrease of refractive index was induced by controlling the irradiated conditions in the two glasses. We have successfully created permanent stripe optical waveguides in silica glass and micro-mirrors in the k_9 glass. We have observed fluorescence in the irradiated region, and we discuss its mechanism.

In our experiment, we used a regenerative amplified 800nm Ti:sapphire laser that emits mode-locked pulses with a duration of 120 fs and a repetition of 1 kHz. The laser beam was focused into polished plates of various glasses via a 10× microscope objective. The glasses were placed on a computer-controlled X–Y stage. The average power of the laser beam was controlled by neutral density filters inserted between the laser and the microscope objective. Samples could be moved at a speed of 10–100 μm/s either parallel or perpendicular to the axis of the laser beam. The resulting refractive index changes were estimated by coupling light from an He–Ne laser into the waveguides or on to the micro-mirrors. Fluorescence spectra were measured by a UV-Lab Raman infinity under the excitation of a 488 nm argon ion laser focused on to the cross sections of the irradiated regions.

Figure 1 shows a microscope photograph of the cross-section array of the irradiated regions generated with different laser powers (1–50 μW) and moving speeds (10–80 μm/s) of the sample parallel to the axis of the fs laser beam for the silica glass via a microscope objective (NA = 0.3, 10×). It can be observed that the diameter of the cross section increases with the increasing average power of the fs laser beam and is independent of the moving speed of the sample. As the average power of the irradiation light is lower, the cross section is nearly circular with a diameter of 5–15 μm. The corresponding irradiated region acts as a waveguide. As the average power is higher than 20 mW, optical breakdown occurs. The profile of the cross section becomes irregularly circular. In this case, the irradiated region cannot propagate light any longer. Some researchers have investigated this phenomenon[15] and considered that non-bridging

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oxygen hole centres, per-oxy-radicals, colour centres and voids were formed in the irradiated region.

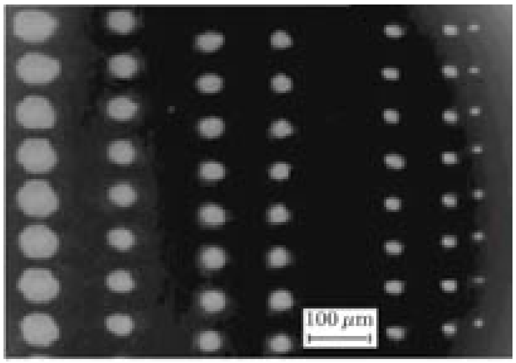

Fig. 1. Microscope photograph of the cross-section array of irradiated regions on fused silica glass under different irradiation conditions. From left to right, the average powers of the fs laser are 50, 30, 20, 15, 10, 5 and 4 mW, respectively. From top to bottom, the moving speeds are 10, 20, 30, 40, 50, 60, 70 and 80 μm/s, respectively.

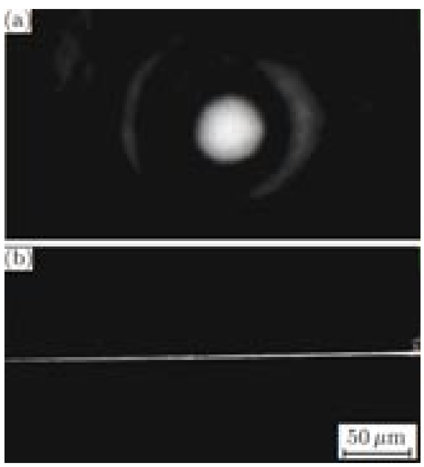

Fig. 2. Waveguide formed in the fused silica glass using 800 nm, 120 fs and 1 kHz mode-locked pulses with an average power of 6 mW through a microscope objective (NA = 0.3, 10×) by moving the sample at 30 μm/s. For this case, Δn has the maximum of 0.008. (a) Far-field mode pattern at 632.8 nm output of induced waveguide in fused silica glass. (b) Image of a waveguide line guiding 632.8 nm light in fused silica glass.

Figure 2(a) shows the far-field mode pattern image of the 632.8 nm laser output of the waveguide induced by the fs laser in the fused silica glass. The profile of the waveguide line is shown in Fig. 2(b). By changing the average power of the fs laser, we have obtained that the optical threshold of the fused silica glass is about 4 mW. Below 4 mW, we cannot observe any optical effect in the glass. Above 4 mW, the waveguide effect appears and becomes significant with the increasing power. As the power increases further, the waveguide effect decreases. At 20 mW, optical breakdown occurs. The resulting refractive-index changes were estimated by the coupling of an He–Ne laser into the waveguide and the measurement of the NA of cone of light that merged. The NA of a step-index waveguide is related to the induced index change Δn by $\mathrm{NA} = (2n\Delta n)^{1/2}$ for small Δn, where n is the refractive index of the glass. The refractive index change Δn was determined to be 0.001–0.008 in the fused silica glass under the irradiation with powers of 5–20 mW and speeds of 10–100 μm/s. The maximum of the refractive index change is 0.008, which occurs under the laser power of 6 mW and the speed of 30–40 μm/s. By changing the moving speed of the sample from 10 μm/s to 100 μm/s at fixed power of exposure, we observed that the maximum Δn occurs with a speed of 30–40 μm/s. When the speed is 10 μm/s, it is easy to meet optical breakdown in the glass. When the speed is within 80–100 μm/s, Δn is smaller than 0.001. The above results indicate that two main factors influence the change of refractive index. The first factor is the pulse peak power, which dominates for nonlinear processes. The diameter of the cross section is only dependent on the power. The second factor is the moving speed of the sample, which influence the exposure dose. Because the refractive-index change Δn depends on the above two factors, we can control the irradiation conditions to create different refractive-index change and core diameter of waveguides.

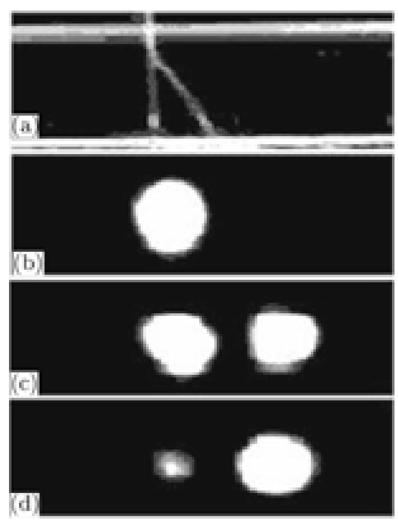

Fig. 3. Reflection of the 632.8 nm incident light by a micro-mirror induced by the fs laser in k_9 glass with Δn being decreased about 0.006 under the average power 10 mW of fs pulses through a microscope objective (NA = 0.12, 10×) by the moving speed of the sample at 30 μm/s. (a) The image of incident (left), transmitted (left) and reflective (right) light beams at the irradiated region (micro-mirror) in k_9 glass; (b) spot of transmitted light without reflection; (c) spots of transmitted (left) and partly reflective (right) light; and (d) spots of transmitted (left) and reflective (right) light in the case of nearly total reflection.

In k_9 glass, a plate with a width of 20 μm can be created when we focus the fs laser pulse through (NA = 0.12, 10×) microscope objective into the sample with a power of 5–10 mW and a speed of 10–50 μm/s perpendicular to the axis of the fs laser beam. When the 632.8 nm beam was incident on the micro-plate at a certain input angle, we observed the nearly total reflection, as shown in Fig. 3(d). Figure 3(a) shows the image of light split into two beams by a micro-plate induced by the fs laser. In Fig. 3(c), the left spot exhibits the transmitted light, the right shows the reflected light. According to the equation $n_1 \sin\theta = n$ (θ is the angle of reflection and n_1 is the refractive index of the irrigated region in k_9 glass), we can determine that the refractive index decreased about 0.006 under a power of 10 mW and a moving speed of 30 μm/s. In this case, the density of the fs laser light in the region of focus is up to 10^{14} mW/cm^2, which is larger than the photo-darkening threshold of the k_9 glass, 10^{12} W/cm^2.[16] Under such a high power density irradiation, optical breakdown occurs and some voids form in the k_9 glass, leading the refractive index to decrease and the plates (with a width of 20 μm, height of 3 μm, and length of 1.5 cm) to become a micro-mirror. To our knowledge, there have been no reports on this phenomenon so far. This effect can make micro-splitters and micro-mirrors in the glasses.

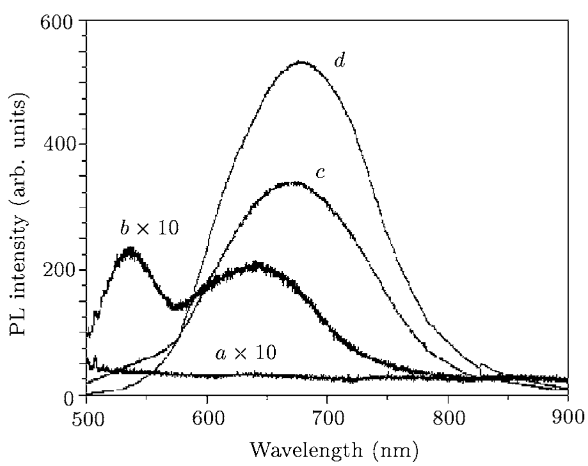

Fig. 4. Fluorescence spectra in irradiated regions under the excitation of the 488 nm Ar^+ laser beam at room temperature. The irradiation powers of the fs laser are (a) 0 mW, (b) 5 mW, (c) 20 mW, and (d) 30 mW.

To investigate the structure of the irradiated region, we measured fluorescence spectra under the 488 nm excitation, as shown in Fig. 4. It is obvious that no luminescence occurs in the region without irradiation. Two bands appear in the spectrum b of a waveguide: one is located at 530 nm, the other is at 680 nm. When the power of the irradiation light increases, the intensity of the 680 nm band grows rapidly, while that of the 530 nm band changes slowly. Spectra c and d show the fluorescence of breakdown lines. The 680 nm peak is dominant in these two spectra. The above spectra indicate that there are at least two kinds of defect formed by the fs laser in the irradiated region. The formation rates of the two defects are different. The lifetime of the 680 nm band was determined to be 16 μs, which was consistent with the result of Ref. [17]. Thus we consider that the 680 nm band has the same origin as Ref. [17]. This is attributed to non-bridging oxygen hole centres generated by the fs laser. The above results indicate that there is a relationship between the optical property and the fluorescence property for waveguide or optical breakdown lines. The luminescence of the irradiated region is currently under investigation.

In conclusion, we have successfully created optical waveguides in a fused silica glass and micro-mirrors in k_9 glass. Under irradiation conditions with a power of 5–10 mW and a speed of 30–40 μm/s via (NA = 0.3, 10×) microscope objective, the effect of the waveguide is significant in the fused silica glass. The range of refractive-index change was 0.001–0.008. In k_9 glass, a plate (with a width of 20 μm and a length of 1.5 cm) was created with a power of 10 mW and a speed of 30 μm/s via (NA = 0.12, 10×) microscope objective. The refractive index of the plate decreased about 0.006. The plate can act as a micro-mirror. Photoluminescence spectra of the irradiated region were measured. We suggest that non-bridging oxygen hole centres and other defects were formed by irradiation. The study of fluorescence spectra is helpful to understand the mechanics of change in structure and refractive index induced by an fs laser in glasses. This work is also useful to fabricate optical communication devices such as micro-mirrors and waveguides in bulk samples by femtosecond laser pulses.

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