Femtosecond fiber laser direct writing of optical waveguide in glasses

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ABSTRACT

There is a great deal of interests and efforts in the area of femtosecond (fs) laser direct writing of transparent materials, which shows promise to be a powerful and flexible technique for rapid fabrication of photonic micro-device, such as gratings, waveguides and optical amplifiers. Waveguide properties depend critically on the sample material properties and writing laser characteristics. In this paper, we present results on the micro-fabrication of waveguide and photonic micro-devices using fs fiber laser direct writing technique. Single line writing of different types of glasses with respect to the focused laser beam at different pulse energies and writing speeds has been investigated at first. Then the waveguide properties were characterized in terms of their shapes and transmission. It was found that specific consideration of the pulse energy, repetition rate and writing speed should be taken into account in order to fabricate low loss positive index guiding waveguide devices in a specific type of glass. Furthermore, a coupler-like guiding structure in glasses has also been demonstrated. The modified regions in both waveguides were checked by scan electron microscope (SEM) to reveal possible cracks and non-refractive structural defects. This technique can be used to produce micro photonic devices and applied to fabricate a single glass chip 3D photonic devices.

Keywords: Femtosecond laser, fiber laser, direct writing, photonic device, waveguide.

1. INTRODUCTION

In recently years, femtosecond (fs) laser direct writing of transparent material has become a powerful micro-fabrication technique for passive and active integrated optical devices [1-7]. When fs laser pulses are tightly focused inside a bulk transparent material, the locally deposited energy in the small volume around the focus can induce local modification of refractive index inside glass network by a variety of mechanisms [8-10]. Combination of nonlinear absorption through photoionization and avalanche ionization allows energy to be deposited in a small volume around the focus [9]. While the process of nonlinear absorption of fs laser pulses in dielectrics is well assessed [11-12], the physical mechanisms for permanent refractive index changes in transparent materials are not yet fully understood. Compared with traditional fabrication technique, fs laser waveguide writing has a number of advantages – simple, cost effective and capability of wide variety of material processing and “at will” structure writing. In addition, traditional techniques can only produce structures in planar geometry, while fs laser pulses give the potential to directly write complex circuits and three-dimensional optical waveguide structures inside transparent materials which are impossible with traditional fabrication methods. Meanwhile, advances in laser technology have produced much more compact and reliable writing lasers and this makes the industrial application of fs transparent material writing possible.

Two different regimes of fs waveguide writing can be classified depending on whether the pulse gap is longer or shorter than the thermal diffusion time. For low repetition rate regime, the material modification is produced by the individual pulses and the processing speed is relatively slow [13]; for high repetition rate regime, the time between successive pulses is shorter than the thermal diffusion time, resulting in a heat accumulation in the focal volume during laser processing [14-15]. As the laser is scanning through the sample, the molten material cools from the outside in, resulting in a smooth permanent refractive index change. This gives faster processing speed and symmetric cross section due to isotropic heat diffusion. Since the thermal diffusion time in the glass is about 1 μs, the transition between the two regimes takes place at repetition rate around 1 MHz. Recently good results in terms of both fabrication speed and waveguide quality have already been claimed by researchers using lasers operating in this intermediate regime [16-18].

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In this paper, different types of optical waveguides written in fused silica and borosilicate glass with a fs fiber laser were demonstrated. A wide range of laser direct writing parameters was examined, giving waveguide processing windows in the heat accumulation regime. The waveguides are characterized for near-field mode profiles and propagation loss for different lasers. The numerical aperture and refractive index change is also estimated. The waveguides in fused silica shows symmetric guiding properties, resembling an optical coupler. The smooth cross section morphology is confirmed by scanning electron microscopy (SEM).

2. METHODS & MATERIALS

2.1 Experimental setup

The laser direct writing experimental setup is shown in Fig.1. The fs laser system is a commercialized mode-locked seed fiber laser (PolarOnyx, Inc. - Uranus Series), generating 750 fs pulses (FWHM) at 1030 nm wavelength with pulse repetition rate tunable between 1 Hz and 1 MHz with an acousto-optic modulator (AOM). The output collimated beam is a nearly symmetric Gaussian with M^2<1.3 and the maximum output pulse energy is 10 μJ. The laser beam is focused into the glass sample by a microscope objective at a depth from the sample surface of about 200 μm. The sample is written in transversal direction which is perpendicular to the laser incident direction, since it allows for writing waveguides with arbitrary length and minimizes the detrimental aberration effects. The focal spot size for the laser beam can be calculated by $1.22\,\lambda/(N.A.)$, where λ is the laser wavelength and N.A. is the numerical aperture of the objective lens. Two focusing objectives are alternatively used – 50x (N.A. = 0.55) and 20x (N.A. = 0.4). Both of the focal spot diameters are less than 5 μm for 1030 nm. An attenuator is used to control the laser pulse energy for fabrication and a mechanical shutter is synchronized with the laser system. The total beam delivery loss is less than 20 percent. A CCD camera is used to obtain a live view for the laser direct writing. The sample is mounted on a motorized translation stage and the linear motion stage is controlled by computer to achieve different sample moving speeds.

2.2 Materials

In this study, fused silica and borosilicate glass were used for laser direct writing. Both samples are pre-polished for the main surfaces with original dimensions of 20 mm x 20 mm x 2 mm and 25 mm x 25 mm x 9 mm, respectively. Before experiments, the sample was carefully cleaned. After writing, the samples were cut to different widths and polished for the edge surfaces for waveguide characterization.

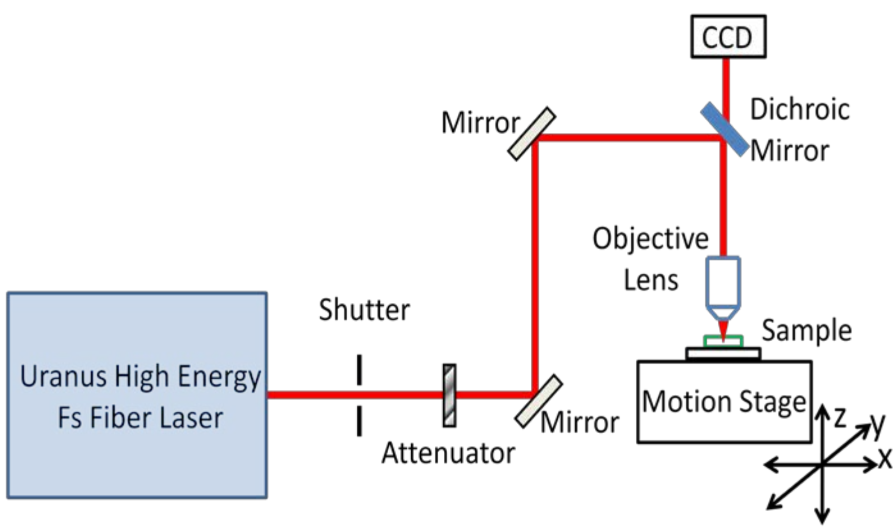


Figure 1. Experimental set up of fs laser direct writing of waveguide.

2.3 Microscopy & measurements

After laser processing and polishing, the top view and cross section view of the laser written structures were captured and characterized by optical transmission microscopy at first. Then SEM was used to reveal possible cracks and non-refractive structural defects. The waveguides were further characterized by launching 650 nm red laser or 532 nm green laser with propagation loss and insertion loss measured using microscope objective or butt-coupled single-mode optical fiber. Near-field mode profiles were also captured using CCD camera.

3. RESULTS & DISCUSSION

3.1 Parametric study of laser direct writing

To systematically study the fs laser waveguide direct writing, the laser beam light was applied at writing speeds from 0.05 to 100 mm/s, incident pulse energies from 100 nJ to 5 μJ, and focal NAs of 0.40, 0.55 at repetition rates of 1 MHz.

For all the fs laser writing lines with different laser parameters, each line was scanned only once. The samples were firstly checked by the optical microscope and then checked by SEM to confirm no ablation or crack generation for the modified volume (Figure not shown here).

Since the repetition rate is high and there are hundreds of thousands of pulses hitting at the same spot, a useful measurement of exposure is the average fluence along the writing path:

$$F_{ave} = \frac{E*R}{2r*v} \tag{1}$$

Where E is the single pulse energy, R is the repetition rate, r is the focal spot size and v is the laser writing speed.

The written borosilicate sample cross section view and top view are presented in Fig. 2 with respect to different pulse energies and the same writing speed. The cross sections are asymmetric because of the transverse writing method. This can be improved by methods such as beam shaping method [19-20]. The laser modified areas clearly show a double structure, a center core with a droplet-like surrounding volume. This kind of structure is typical for this irradiation conditions and can be interpreted by considering the inner core as the directly irradiated focal region and the outer structure as the region modified by thermal diffusion of the energy stored in the inner core.

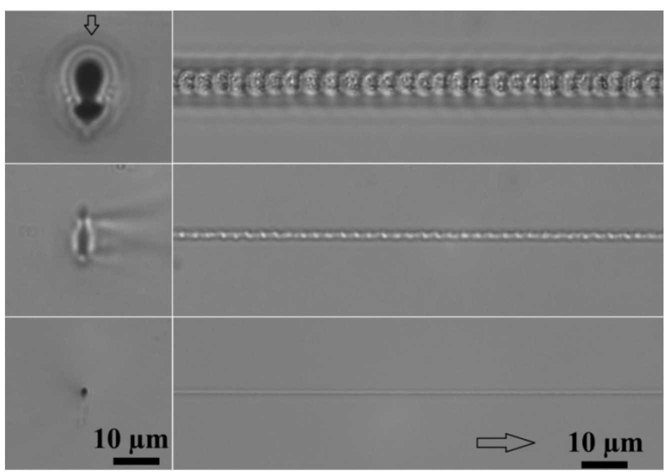


Figure 2. Optical microscope images of cross sections (left) and top views (right) of the borosilicate glass waveguides written with different pulse energies and constant writing speed of 0.1 mm/s (F_{ave} is 56.5 kJ/cm^2, 47.8 kJ/cm^2 and 39.1 kJ/cm^2 from top to bottom). Arrows indicate the laser beam incident direction or writing direction.

From the comparison result as shown in Fig.2, it is worth noting that by increasing the pulse energy at a constant translation speed the overall modified volume width change dramatically from 3 µm to 22 µm, while the total modified volume depth changes from 10 µm to 24 µm.

For fused silica direct writing, it is found that the modification threshold is relatively higher than borosilicate glass since there is no strong evidence of heat buildup with the same laser writing conditions. This can be partially attributed to the relatively higher band gap of fused silica. As shown in Fig. 3, by increasing the pulse energy at a constant translation speed the overall modified volume width and depth is increasing, but is not apparent as borosilicate glass.

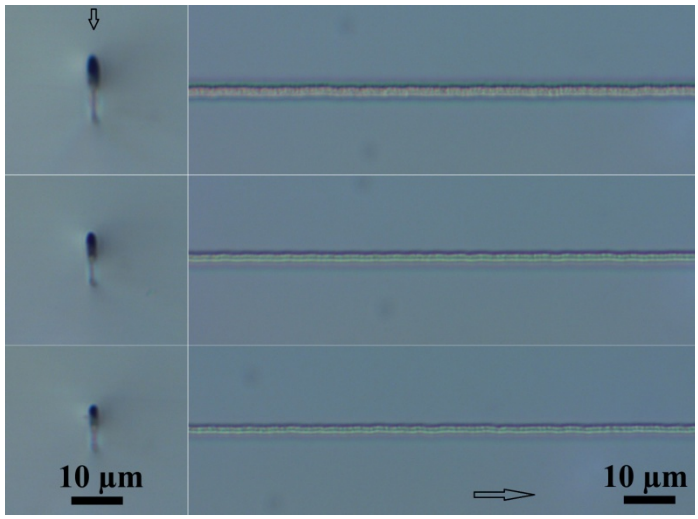


Figure 3. Optical microscope images of cross sections (left) and top views (right) of the fused silica waveguides written with different pulse energies (F_{ave} is 80.4 kJ/cm^2,54.3 kJ/cm^2 and 45.7 kJ/cm^2 from top to bottom) and constant writing speed of 0.5 mm/s. Arrows indicate the laser beam incident direction or writing direction.

As shown in Fig.4, while increasing the translation speed with the same pulse energy, both the modified volume width and depth maintain almost the same size, but the inner core tends to vanish. This shows that for smaller pulse energy, the thermal accumulation effect does not increase the modified volume size notably even changing the writing speeds from 0.1 to 10 mm/s.

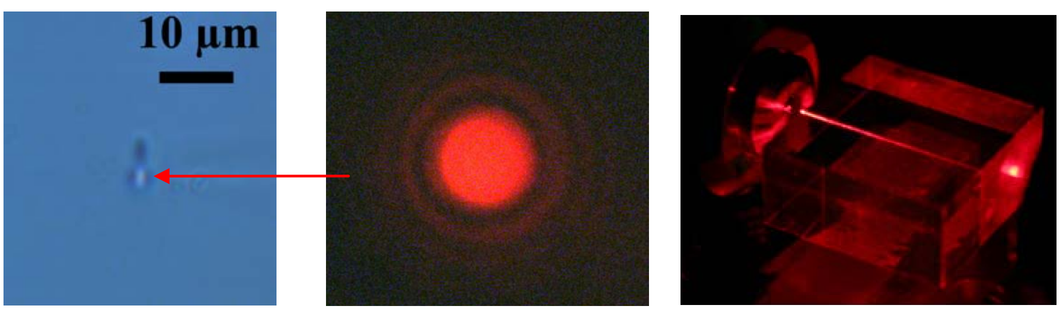
For the 1 MHz repetition rate used in the processing, it is an intermediate situation between single pulse and cumulative regimes since the general thermal diffusion time is 1 µs. In fact, the outer structure can be attributed to thermal diffusion of the single pulse and is thus affected by the pulse energy but not by the writing speed.

3.2 Waveguide properties

To investigate the guiding properties, all the waveguides were characterized by focusing the 650 nm red laser or 532 nm green lasers onto the input facet of the fs-laser written waveguides through microscope objective or fiber butt-coupling. For both cases, two five-axis micro-positioning stages were used to launch the light into the waveguide and optimize the coupling process. This coupling alignment was achieved by viewing the sample input and output facets by microscope objective. The output guiding mode can be checked by imaging the output surface to CCD camera through an objective. Also an optical power meter is used to check and measure the guided light with an aperture to block the scattered light. Only the waveguides fabricated at small range of pulse energy and writing speed using N.A. = 0.55 microscope objective exhibited good confinement.

Figure 5(a) shows the optical microscope cross section image of borosilicate glass waveguide written with 39.1 kJ/cm^2 average fluence and 10 mm/s writing speed. The arrow indicated brighter region is the guiding region. Figure 5(b) shows the near-field mode profile of output facet when using red laser coupling for the same waveguide. An almost circularly symmetric transverse mode was obtained. When changing the alignment of the coupling fiber or objective, it is observed that the near field of the waveguide mode maintained its shape while varying its amplitude. This indicates that the waveguide is single mode at this wavelength. The mode field diameter is about 2 µm. Figure 5(c) shows the camera view of a red laser coupling with microscope objective of fs written borosilicate glass waveguide and the waveguide is 20 mm long.

Figure 4. Optical microscope images of cross-sections (left) and top views (right) of the borosilicate glass waveguides written with different writing speeds (0.1, 0.5, 1.0, 5.0, 10.0 mm/s from top to bottom) and constant pulse energy. Arrows indicate the laser beam incident direction or writing direction.

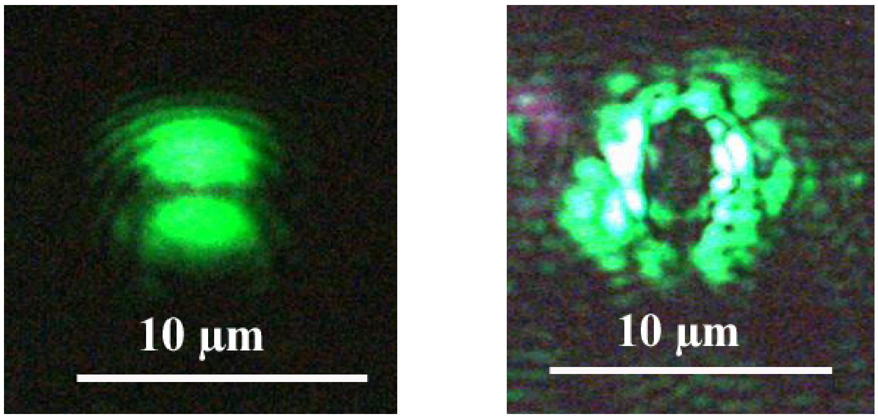


(a) (b) (c)

Figure 5. (a) Optical microscope view of cross section fs-written borosilicate glass waveguide (F_{ave}=478 J/cm^2 with 10 mm/s); (b) Near-field mode profile of 650 nm red laser beam of the same waveguide as (a); (c) Camera view of red laser beam coupling of fs written waveguide (F_{ave}=56.5 kJ/cm^2 with 0.1 mm/s).

As shown in Fig. 6(a), multi-mode profile can be obtained with green laser coupling for waveguide written with 39.1 kJ/cm^2 average fluence and 0.1 mm/s writing speed, since the modified mode field diameter is larger due to slower writing speed and more pulse overlap. This shows the possibility of by changing only one parameter - the writing speed one can produce waveguides with a controllable mode number. While for other borosilicate glass waveguides written with higher pulse energies or slower writing speeds, the guiding mode is not single mode or the mode is not well-formed, which is indicative of small positive or negative refractive index modification resulting in larger loss. Furthermore, for higher pulse energy, the guiding region is located in a ring like structure centered at the fs-laser focusing location, as shown in Fig. 6(b).

Unlike borosilicate glass, it is found that the fs written fused silica waveguide region is not in the center core of the focal volume. Two symmetric guiding regions were found on both sides of the center region, which shows a very interesting coupler-like structure (as shown in Fig. 7). Further coupling characterization is still needed to study the split ratio and insertion loss. This shows great potential for direct coupler device fabrication with fs laser single line writing of glass sample.



(a) (b)

Figure 6. Near-field mode profile of 532 nm green laser beam of fs-written borosilicate glass waveguide: (a) F_{ave}=39.1 kJ/cm^2 with 0.1 mm/s; (b) F_{ave}=50.0 kJ/cm^2 with 0.2 mm/s.

3.3 Refractive index change and waveguide loss

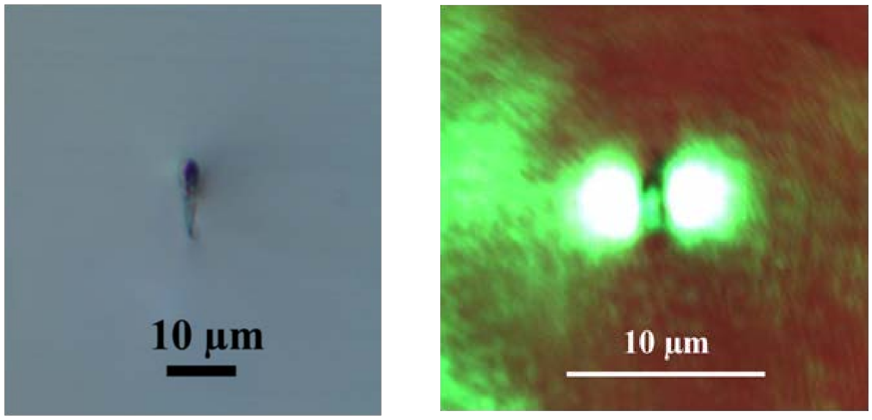
To estimate the refractive index change for the fs laser direct written borosilicate glass waveguide, the mode diameter was measured at a certain distance and the numerical aperture of the waveguide can be obtained by dividing the distance by the mode radius. The largest numerical aperture among all the written borosilicate glass waveguides was measured as 2.41×10^{-2}. The refractive index change can be estimated by the measured N.A. of the waveguide. Assuming a square index profile,

$$N.A. = \sqrt{n_1^2 - n_2^2} \approx \sqrt{2n_2\Delta n} \tag{2}$$

where n_1 is the index of the waveguide, and n_2 is the index of the substrate material. For borosilicate glass sample, $n_2 = 1.46$, so the estimated largest refractive index change at 650 nm is $\Delta n = 1.99 \times 10^{-4}$.

To measure the propagation loss, two samples was prepared with the same writing conditions and different lengths, and each facet was highly polished. The transmitted laser light intensity was measured for both samples and the propagation loss is determined from the ratio of the transmission of the longer waveguide to that of the shorter waveguide. The coupling loss is calculated by the difference between total insertion loss and propagation loss.

The minimum propagation loss is about 2.89 dB/cm for laser writing conditions of F_{ave}=478 J/cm^2 and 10 mm/s writing speed. And the coupling loss is obtained as 4.34 dB/cm. The propagation loss is in the range of 2-4 dB/cm for the observed waveguides. Possible reasons contributing to the large loss of the waveguide include the translation stage quality and the sample glass inhomogeneity. Further work is needed to improve the propagation and coupling loss of the waveguides written by the fs laser.



(a) (b)

Figure 7. Fs-written fused silica waveguide: (a) microscope view of cross section; (b) camera view of output facet coupling with green laser (laser modified area is located between two guiding region).

4. SUMMARY

Femtosecond fiber laser direct writing fabrication, investigated in this paper, is capable of producing optical waveguide and coupler-like device inside bulk transparent materials without the need for lithography, etching and a controlled environment, and hence offers remarkable technological flexibility. Using this fs direct writing process, we have manufactured various waveguides with different laser writing parameters and the waveguides properties have been scrutinized. This fs fiber laser based process is inherently simple, direct, reliable and reasonably inexpensive. This commercial laser system is more attractive as compared with fs solid state lasers. The devices fabricated in both glass types outlined in this paper raise the prospects of creating optical devices and micro-optics for photonic and biochemical applications.

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