Waveguide fabrication in Bismuthate glasses using femtosecond laser pulses

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Abstract: Femtosecond direct written waveguides in bismuthate glasses are reported. This is the first demonstration of direct written guiding channels in bismuthate glass which show an index of refractive change as high as 3×10^{-3}.

1 Introduction

The availability of femtosecond laser pulses has recently stimulated much interest in making new optical devices. Femtosecond lasers can create high peak intensity with only moderate energies at the focal point. This characteristic has made femtosecond laser a powerful tool for micromachining transparent materials hence allowing three-dimensional embedded devices to be written in one step fabrication process. The writing of waveguides in different glasses (for example, silica, chalcogenide, phosphate glasses) using femtosecond laser pulses has already been demonstrated [1-3].

Bismuthate glasses are promising optical materials for use as broadband amplifiers because of high refractive index (>2) and high rare-earth doping level (>30000ppm, in silica it is only 1000-2000ppm) and high emission spectra. Waveguides fabricated in bismuthate glasses by UV-writing have been reported [4], where light was guided outside the direct written channel. This paper reports the first waveguides written in the bismuthate glasses by femtosecond laser pulses. The fabricated channels show an index of refractive change up to 3×10^{-3} and the guiding of light was proved to be inside the written channels.

2 Experiment

The fabrication of waveguides was performed with a regeneratively amplified Ti:sapphire laser operating at 100 kHz (pulse duration $\tau \approx$ 150fs, wavelength λ =800nm). The laser beam was tightly focused into the bulk of the sample by a 50$\times$(NA=0.55) microscope objective down to a focal spot of ~1.5µm. The sample was moved perpendicularly to the direction of the beam propagation by a computer –controlled stage (see Fig.1). Using this setup, six groups of waveguides were direct-written within the bulk of bismuthate samples. Each group was realized by writing four waveguides with different speed (40µm/s, 80µm/s, 120µm/s, and 160µm/s) spaced of 100µm between them and constant average power. (P1=272mW, P2=200mW, P3=150mW, P4=100mW, P5=50mW and P6=10mW) The waveguides were written 200-300µm under the surface and the end faces of the sample were polished after writing process.

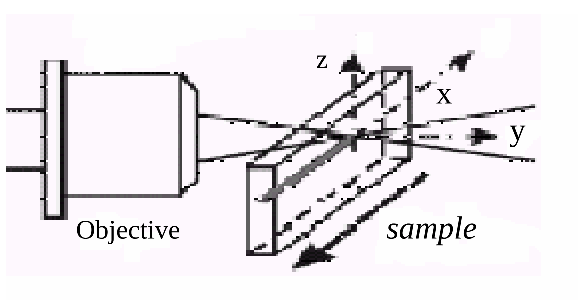

Fig.1. Schematic diagram showing the waveguide writing geometry.

3 Result and discuss

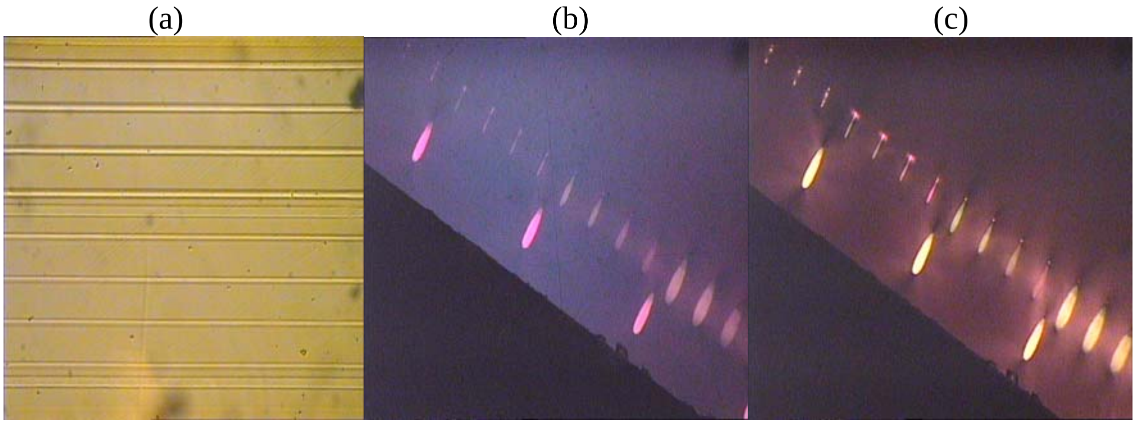

Fig.2. Microscope pictures of the waveguidess:

(a) Picture of part of the sample (P3, P4) on zx plane with white light illuminating from below.
(b) Picture of the end-face of the sample (zy plane) between cross polarizers with white light illuminating from above.

(c) Picture of the end-face of the sample (zy plane) between cross polarizers with white light illuminating from below.

After writing, the sample was inspected under an optical microscope (see Fig.2). Waveguides written with a power over 10mW are all visible under the microscope which indicates that the threshold average power of damage for this sample is around 10mW. Moreover it was observed that the channel size increases with the power (Fig.3) and instead decreases with speed (Fig.2 (a)). This kind of melting behavior is normally observed in long pulse irradiation regimes [5] where it is due to the thermal diffusion of the heat from the focal point to the surrounding material. This is probably due to the low melting temperature of the bismuthate glass (between 900-1200°C, while the melting temperature of silica glass is higher than 2000°C.). The heat diffusion between two pulses interaction makes the focal volume start to melt.

Our group has already reported formation of birefringence in silica glass after femtosecond direct writing [6]. So we check the birefringence phenomenon in bismuthate glass after writing. We do not observe birefringence if we put the zx plane between cross polarizers like reported in [6]. Instead we do find birefringence if we put the zy plane between cross polarizers with white light transmit or reflect from the end faces (see Fig.2 (b), (c)). We concluded it by proving that with the white light illuminating from above the visible structure on the top end face came from the light reflected by the bottom end face. Because the birefringence structure between two cross polarizers became weaker if we put phase matching liquid under the bottom end face. This kind of birefringence may arise from elliptical beam shape.

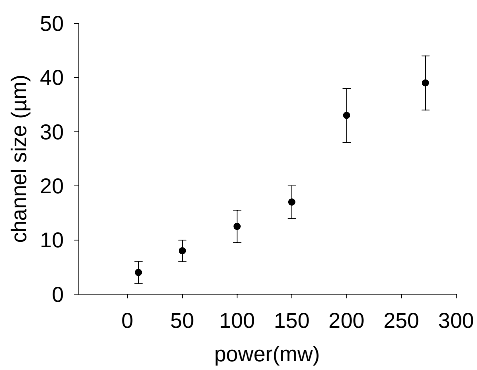

Fig.3. Plot of channel size versus power (processing speed v=40 µm/s)

In order to enable the measurement of the refractive index change of each waveguide with respect to the unprocessed bulk, an interferometric phase-stepping technique was utilized (more experimental details on the interferometric set-up can be found in [6]). The results of those measurements represent the difference of phase $\Delta\phi$ between the light traveling into the irradiated structures and into pure bismuthate, which is related to the average index change through the following equation:

$$\Delta n = [\lambda/(t2\pi)]\Delta\phi, \quad (1)$$

where Δn is the average index change, t the thickness of the structure, and λ the wavelength of light.

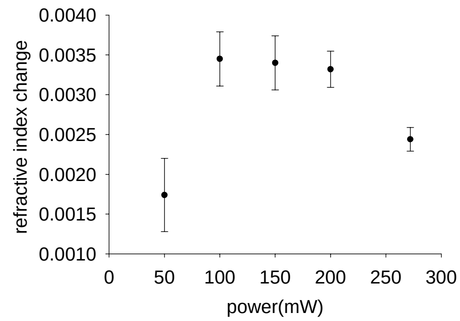

Fig.4.Plot of the refractive index change versus power (speed v=40µm/s)

Figure 5 shows the measured index change of the channels written at 40µm/s versus the average power. The maximum refractive index change is ~3×10^{-3} which is one order of magnitude higher than the index achieved with UV-Writing (4×10^{-4}) [4].

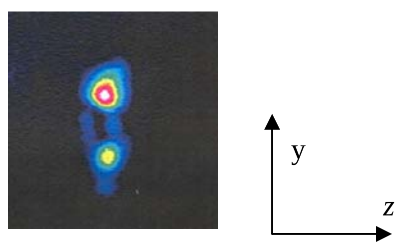

Fig.5. Near-field mode profile at wavelength of 1.5 µm

The mode profile at 1.5 µm is shown in Fig.5. It reveals that the light is transmitting in the core as opposed to the results reported using UV irradiation where the light was guided in the region surrounding the core [4]. Although it is multimode profile, we can still get single-mode profile if it is possible to reduce the beam diameter in y direction using astigmatic beam shaping method [7] or other methods.

4. Conclusion

We reported the first experiment of writing waveguides in bismuthate glasses by femtosecond laser pulses. The index change achieved is the highest ever reported for direct writing technique opens new possibilities in the three dimensional optical devices, especially for all-solid –state lasers and amplifiers.

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