Waveguide Fabrication in Yb^{3+} Doped Phosphate Glass by 50 kHz Repetition Rate Ultrafast Laser

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Waveguide (trace guiding type) inscription condition inside Yb^{3+} doped phosphate bulk glass was investigated under irradiating of 50 kHz repetition rate volume ultrafast lasers. We processed single trace and multi-core ones inside the bulk material, the captured near field mode pattern confirmed that both structures perform good guiding properties. Beam shaping technique was adopted during fabrication of the single trace in order to obtain a relative symmetric waveguide cross section. Waveguide lasing was achieved in the single line trace with a linear cavity configuration. The maximum laser output of 11 mW was obtained under mono-directional of 980 nm space light pumping, with ~2% corresponding slope efficiency. Guiding mode could be manipulated in the Expanded-core waveguide (ECW) by extra design freedom in the structure parameter, and ECW generally support larger effective mode area light transporting.

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1. Introduction

Tremendous research works have been reported in microstructure fabrication with the aid of ultrafast laser in the last few decades. In contrast to other traditional techniques (e.g. ion exchange or vapor deposition), ultrafast laser direct writing technique has been proved to be low-cost and rapid way in monolithic photonic devices fabrication, especially demonstrating its superiority and flexibility in 3D photonics structuring [1-5]. When ultrafast laser pulses are focused inside transparent dielectrics, highly localized and permanent modifications could be made in the vicinity of focal volume due to nonlinear optical absorption, thus giving rise to the change of refractive index. The result of modification can be unfathomable. In crystal substrate, normally a negative change of index is formed at the modified area due to the lattice expanding and positive in the surroundings resulting from the stress [6]. While in a glassy material, sign of index modification depends on both material composition [7, 8] and the laser parameters.

Among most glassy substrates, phosphate glasses are attractive because they can incorporate larger concentrations of rare earth ions without the onset of clustering effects appeared in some other glass hosts. This could be beneficial in the fabrication of high gain active waveguide devices such as amplifiers and lasers. However, most phosphate glass compositions have molecular-level structures that expand under the fs-laser irradiation and produce POHC (phosphorus-oxygen hole center) defects, making them less practical for laser-written waveguides. Fletcher et al. put an emphasis on the glass composition and conclude that zinc polyphosphate glass with an oxygen to phosphorus ratio of 3.25 ($60ZnO-40P_2O_5$ glass) produces a positive refractive index change, in low repetition regime under 1 kHz, 180 fs pulse duration, 2-10 J/cm^2 fluencies and in longitudinal focusing geometry [8]. Douglas J. Little at al. revealed that the positive refractive index change in Qx phosphate glass could be attributed to an increase in the proportion of Q^1 P-tetrahedra and the associated increase in the polarizability after exposure of fs-laser [9]. Another aspect is in the heat accumulation regime (laser repetition typically above Megahertz). The interval between successive femtosecond pulses is shorter than the time for thermal diffusion which could cause material melting. This thermal process in combination with multiphoton absorption and plasma formation induces rearrangement of chemical bonds and density variation in the area of several micrometers near the focal volume [10-13]. Under tight focusing, normally there is no need of slit shaping method with a high pulse repetition rate (1-10 MHz) because with a gentle dose of energy, the cross section of waveguide could be automatically uniform and symmetric due to the heat diffusion and annealing. Despite many interpretations proposed, the mechanism of fs-laser induced refractive index change inside glasses can still be partially understood and is continually under investigation.

The sample used in this paper is Ytterbium doped (9% by weight) phosphate glass of Qx series from Kigre. It is exactly the same glass in Douglas J. Little's research however here we employ an ultrafast laser source with an improved pulse repetition fixed at 50 kHz. Thus it remains in the noncumulative-heating regime but we get two merits ahead: firstly it is more applicable for us to precisely scan and optimize the pulse energy since our previous work confirmed that the inscription window is quite narrow that the permitted pulse energy is only between 1.2-1.5 μJ with 1 kHz repetition rate, and this imposes higher requirement on the stability of the long term average power on 1 kHz system. Secondly the fabrication efficiency could be improved

50 times in contrast with 1 kHz supposing we are on the same inscription conditions. Taking advantage of 50 kHz system, the experiment firstly arranged in this paper is to investigate the single trace writing conditions (parameters scan of pulse energy and pulse duration), it is found that under transversal writing with beam shape method, positive index modification can be easily obtained, but in order to maintain good quality with single mode guiding, modest dose should be adjusted. Waveguide laser oscillation was achieved in this single trace. In addition, expanded core waveguide with structure of an array of layer guiding trace is demonstrated. With large mode area (LMA) characterization, it would have the prospect in large power scaling applications. It is noted that the polarization effect usually appear in anisotropic stress-type waveguide, typically in ultrafast laser inscribed double line structure. We report here in our case, no obvious proof of polarization effects are manifested in both single guiding trace and expanded core waveguide (Type I waveguide).

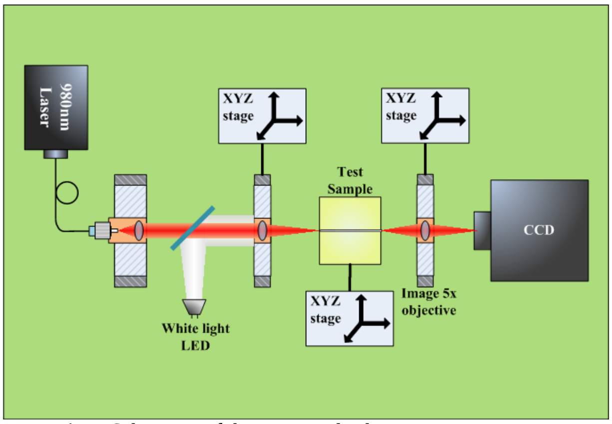

Fig. 1 Schematic of the waveguide characterization system

2. Experimental details

The schematic for the waveguide fabrication experiment is the same as indicated in our previous works [14]. A regeneratively amplified Ti:Sapphire ultrafast laser system (Phidia, Uptek solutions) with repetition rate tuneable from 25 kHz~100 kHz is used as the source, able to deliver ~1000 mW average power (repetition depended) train of pulses with a center wavelength of 800 nm. In this paper however, the repetition rate has been fixed at 50 kHz rate and then optimized since we are looking forward to possessing a relatively high signal-noise ratio and minimum pulse duration (down to 120 fs). To obtain a moderate dose of photon energy, the pulse energy is adjusted by a half wave plate combining with a thin film polarizer (TFP). The amplified pulse is linearly polarized in the horizontal direction after the TFP. An electromechanical shutter is used to control the exposure time during photo-inscription. We use the transverse geometry for the waveguide fabrication which has the privilege in preserving the uniformity of modification along the trace. As to the beam shaping, in order to conserve more laser energy, a pair of cylindrical lens arranged as a 3 times demagnify telescope and subsequently a 500 μm width slit are settled. After that a 20× Mitutoyo microscope objective with numerical aperture of NA=0.42 (working distance 30.8 mm) is chosen to focus the pulsed laser inside the bulk sample. The sample with size of 12×9.7×3.5 mm^3 is mounted on the XYZ precision motion stages (Physik Instrumente) that allow translation parallel or perpendicular to the laser propagation axis. Both the shutter and the 3D translation stage are computer controlled by Labview software. After the laser inscription, an optical image system is utilized to characterize the guiding properties of fabricated waveguide via inspecting the cross section and the corresponding near field mode. The collimated 980 nm diode laser (fibre coupled output with elliptical polarization) is for injection and the white LED light is illuminating for imaging, as shown in Figure 1. Note that for all the images containing the cross section of the waveguide, inscription laser come from the bottom throughout this paper.

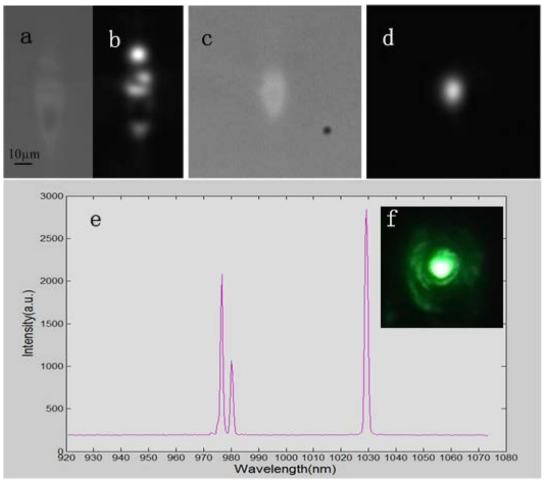

Fig. 2 Single trace cross section and waveguide lasing. The photo-inscribing laser pulses are from the bottom of the image (a) Cross section of over irradiated single trace by 3.9 μJ, 50 kHz, 120 fs ultrafast laser at translating speed of 150 μm/s and (b) the multimode guiding feature, (c) cross section with moderate dose of 1.6 μJ pulse energy inscription and (d) the single mode guiding near field image, (e) spectrum of waveguide lasing at ~1029 nm from waveguide in (c), (f) the inset indicates the far field image of the laser. (a)-(d) are sharing the same scale bar.

3. Results and discussion

3.1 Single trace waveguide inscription

It was already confirmed by Douglas J. Little that trace guiding waveguide could be produced in Qx phosphate glass with 120 fs pulses. Hence firstly we keep the shortest pulse duration of 120 fs as well. Taking the measure after the slit (~70% laser power will be blocked by the 500 μm width slit), the experiment is firstly carried out by scanning pulse energy from 3.9 μJ to 1.0 μJ, and the stage translation velocity from 600 μm/s to 40 μm/s. The total length of the waveguide is 9.7 mm throughout the sample. The top line of Figure 2 shows the white-light illuminated transmission microscopy and the near field mode of the laser generated structures processed by 3.9 μJ and 1.6 μJ pulse energy at translation speed of 150 μm/s. Under intensive irradiation of 3.9 μJ pulse energy, the affected region can be extended, especially along the laser propagation direction, and void began to form near the entrance of the laser focus. Light guiding can be highly multimode with several guiding regions as shown in Figure 2(a) and (b). As the dose decreasing the affected zone begins to shrink and nearly symmetric, and the void gradually disappeared. It is shown in Figure 2(c) and (d) that finally a single mode waveguide can be achieved with 1.6 µJ pulse energy and it is the same level as reported in 1 kHz system. The size of the mode field diameter (MFD) is around 12 µm. Mode confinement begin to degrade and eventually result in guiding collapse when the pulse energy down below 1.0 µJ. Waveguide lasing was achieved in the latter waveguide with a linear cavity configuration (as shown in Figure 1, in addition clinging a dichroic mirror to the left facet of the sample and a coupler mirror to the right). Maximum laser output of 11 mW was obtained with a 5% output coupler (residual pumping is removed by an 45 ° dichroic mirror), under monodirectional 980 nm light pumping. The lasing threshold is ~95 mW for the pumping. The maximum power of 980 nm pumping is 650 mW. Therefore the corresponding slope efficiency is measured to be approximately 2%. Figure 2(e) demonstrates the laser emission spectrum. The peaks around 980 nm are from the pumping. With central wavelength of ~1029 nm, the FWHM line width of the emission laser is approximately 3 nm. The inset of (f) shows the far field image of the laser spot from infrared viewer.

In this article we didn't put an emphasis on optimizing the performance of the lasing since only to verify the quality of the waveguide we inscribed, but still several means could be implemented to improve the lasing performance:

(1) Elaborately adjust different writing parameters (dose of energy and pulse duration etc.) to get a waveguide with better confinement of light and lower transmission loss.

(2) The focal diameter of the pumping should match better the MFD (Mode Field Diameter) of the waveguide in order to enhance the pumping efficiency. Also, bidirectional pumping configuration is preferred to improve performance in waveguide lasing experiment.

(3) The air gap and the angle between surface of mirrors and the facet of testing sample would bring in great intra-cavity attenuation as well as lasing instability. In bulk-glass waveguide laser devices have been demonstrated in other's works by using external-fiber Bragg gratings or direct writing distributed-feedback (DFB) structures [14, 15] to complete a cavity around a rare-earth-doped waveguide. In our case one simple way for improvement is to coating films on both end face of the waveguide (with corresponding filtering function as the two mirrors).

(4) Substitute with a different output coupling mirror would have a chance to optimize the lasing performance.

Previous work in fused silica indicated that shorter pulse duration favors the positive index [16] and we investigate whether it is the same trend in Qx phosphate glass. By adjusting the position of grating in the compressor, pulse duration was expanded to 450 fs, 670 fs and 890 fs. The translation velocity is fixed at 150 µm/s and energy is scanned from 3.0 µJ to 1.0 µJ. Finally positive index modification also could be achieved with longer pulse duration as long as the dose of the pulse is strong enough above a certain threshold. Figure 3(a) indicates the guiding feature (white light illuminating at the same time) of the waveguide fabricated by 450 fs ultra short pulse, and the Figure 3(b) and 3(c) corresponding to 670 fs and 890 fs. Column 1-4 refer to the pulse energy of 2.4 µJ, 1.8 µJ, 1.5 µJ and 1.2 µJ. Red crosses on the right bottom of the picture reveal that guiding is no longer supported. It can be concluded that the threshold value for guiding rises according to the increasement of pulse duration. A Spanish group [17, 18] report that the peak power of incident ultrafast laser (by variation of pulse duration) can be critical for controlling nonlinear beam propagation and pre-focal depletion and therefore can be important in energy deposition for waveguide fabrication, which impose an upper limit for eliminating the undesired nonlinear effects. In comparison with our case, despite we are under different inscription condition (focusing condition, energy dose, dopants in substrate etc.), the trends and results can be consistent. It is certain that the window for waveguide inscription in phosphate glass could be enlarged (with different focusing condition, different pulse duration and pulse energy etc). The problem is where the optimum point is inside bulk phosphate glass for waveguide writing (with better light confinement and minimum propagation loss). Further investigation is ongoing to clarify this problem.

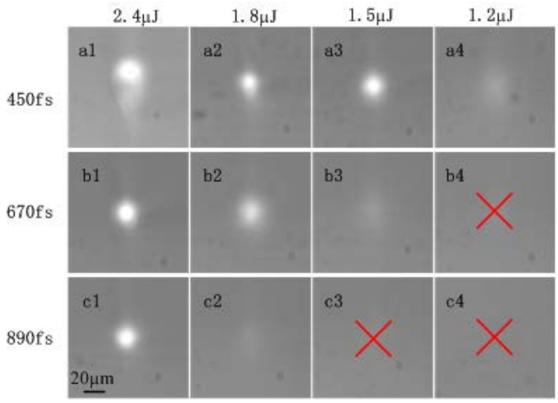

Fig. 3 Effect of pulse duration on the guiding features. (a) Guiding features of waveguides fabricated by 450 fs ultra short pulses, (b) by 670 fs ultra short pulses and (c) by 890 fs ultra short pulses. Column 1-4 refer to the pulse energy of 2.4 µJ, 1.8 µJ, 1.5 µJ and 1.2 µJ. The scale bar applies to all images.

3.2 Elongated trace and expanded-core waveguide

We are motivated by the notion of applying the expanded-core conception [19] in active laser materials (it is shown in next paragraph) for which would have prospect in applications requiring high power or large mode dimensions [20]. The goal first is to seek the possibility of writing a trace guiding type waveguide with an elongated cross section. Therefore in this section we remove the beam shaping facilities (i.e. the telescope and the slit), thus filaments are produced in the bulk material. It's verified by many teams that in longitudinal focusing geometry, majority phosphate glasses will typically exhibit negative changes to the index of refraction inside the fs-laser irradiated region [21, 22].

Our experiment however indicates that the threshold effect is still valid in producing the positive modifications. Thanks to the upgraded laser repetition rate, more refined pulse energy could be generated and actually guiding filaments could be achieved when the pulse energy is between 0.12 µJ-0.22 µJ with translation speed of 100 µm/s and pulse width of 120 fs. All images in Figure 4 are under same condition and the 53 µm length filament indicated in (a) is for the scale reference. Figure 4(a)-(d) shows the evolution of the morphology of the filaments as the pulse energy reduced from 1.0 µJ to 0.2 µJ. It can be noted in Figure

4(a)-(c) that the tips of the filaments are white under transmission white light microscope, which implies the guiding properties. As the pulse energy goes down, void zones in the middle part begin to shrink and white tips on both end become conjoint in (d). Two kinds of guiding zones marked in red and yellow are demonstrated in Figure 4(e). Guiding on the yellow zone could be explained by photo-elastic effect due to the void expansion in the middle and the stress accumulation on both sides. Guiding on the tips marked in red region is confirmed experimentally in Figure 4(f)-(g).

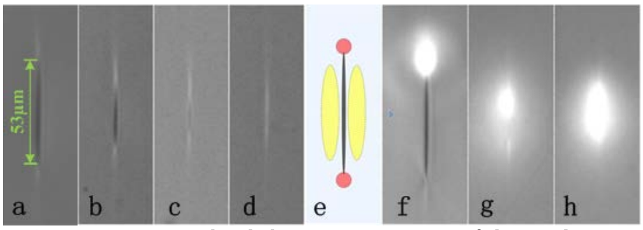

Fig. 4 Transmission white light microscope images of elongated traces and the guiding features. (a)-(d) indicates the formed filaments irradiated by pulse with energy of 1.0 μJ, 0.6 μJ, 0.3 μJ and 0.2 μJ at translation speed of 100 μm/s. (e) sketches two kinds of guiding zones exist near the filament under stronger exposure of laser, red regions located at tips and yellow regions on both sides of the filament. (f)-(h) indicates the tip guiding properties from (a), (c) and (d).

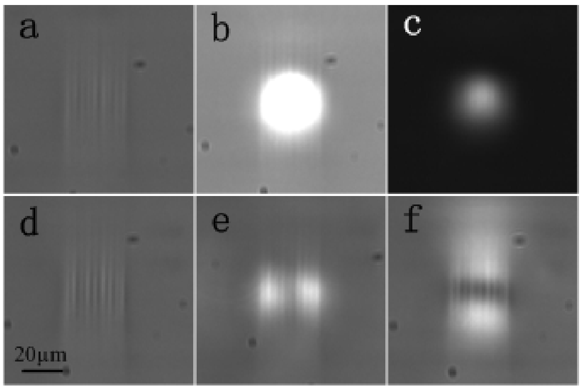

Fig. 5 Optical transmission microscopy image of expanded-core waveguides (ECW) consisting of 9 Type I layers with 4 μm separation and the corresponding guiding modes at 980 nm. (a) ECW end face structure written by 0.16 μJ, 50 kHz, 120 fs ultrafast laser, (b) over exposed guiding image with white LED illumination (c) near field mode image with diameter of about 37 μm, (d) ECW end face written by 0.22 μJ, 50 kHz, 120 fs ultrafast laser, (e)-(f) the corresponding LP_{11} guiding mode. The scale bar applies to all images.

Based on the accomplishment of the elongated guiding trace, expanded-core waveguides (ECW) consisting of 9 layers with 4 μm separation are fabricated in Qx phosphate glass. Figure 5(a)-(c) shows the ECW written by 0.16 μJ, 50 kHz, 120 fs ultrafast laser and its guiding mode. To verify the stability of the operation we change the injecting spatial position on the facet, no other higher mode is excited, confirming the solely fundamental mode supported operation with large effective mode of about 37 μm diameter at 980 nm. This is count more than 3 times the size of beam shaped single trace in Figure 2(d). The ECW shown in the bottom row of Figure 5 is written by 0.22 μJ, 50 kHz, 120 fs ultrafast laser. With an enhanced inscription dose we can speculate that the effective index of the latter ECW is also increased, thus LP_{11} guiding mode is supported as shown in Figure 5(e)-(f). Guiding mode could also be manipulated in ECW by extra design in the structure parameter, and ECW generally support larger effective mode area light transporting. Finally laser oscillating experiment is also carried out in the ECW, but waveguide lasing failed in the ECW. We attribute this to the insufficient power supply of 980 nm pumping since to acquire the same level of pumping density in the waveguide, ECW in this case calls for ~9 times the power of pumping in contrast with the one used in Figure 2(d) for ~900 mW or even higher (transmitting loss of laser also matters), which is not available for us in the laboratory.

4. Summary

Waveguide (trace guiding type) inscription condition inside Yb^{3+} doped phosphate bulk glass was investigated under irradiating of 50 kHz repetition rate volume ultrafast lasers. Firstly beam shaped ultrafast laser was used for single trace fabrication. Waveguide lasing was achieved in the waveguide which was produced under the shortest pulse duration of 120 fs. The maximum laser output of 11 mW was obtained under mono-directional of 980 nm space light pumping and 5% coupling mirror, with ~2% corresponding slope efficiency. Pulse duration scanning is performed to investigate the sensitivity in fabricating a positive modification, and the result shows that guiding trace could also be obtained by irradiation of longer pulses as long as enough energy. Finally we extrapolate the ECW concept in this Ytterbium doped (9% by weight) phosphate glass of Qx series, Kigre. Guiding mode could be manipulated in ECW by extra design in the structure parameter, and ECW generally support larger effective mode area light transporting.

Acknowledgments

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