Simultaneous Spatial and Temporal Focusing of Femtosecond Laser Pulses for Directly Writing Optical Waveguides in Pr^{3+} doped ZBLAN Glass

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Abstract: We present characteristics of optical waveguides fabricated in Pr^{3+} doped ZrF_4-BaF_2-LaF_3-AlF_3-NaF (Pr:ZBLAN) glass using simultaneous spatial and temporal focusing (SSTF) of femtosecond laser pulses. Thanks to SSTF, the axial two-photon excitation length is confined to ~20 μm. A primitive example of waveguide shows an NA of ~0.015 and a propagation loss of 0.56dB/cm.

OCIS codes: (230.7380) Waveguides, channeled; (320.7130) Ultrafast processes in condensed matter, including semiconductors; (130.2755) Glass waveguides.

1. Introduction

Three-dimensional (3D) micro- and nano-scale patterning with femtosecond laser pulses receives broad attentions in wide fields such as optofluidics, quantum information technologies, and novel waveguide laser development [1,2]. The type of modification obtained from femtosecond laser exposure depends on the material composition and laser parameters. Positive change in the refractive index exploits heat accumulation and isotropic thermal diffusion and is able to create a circular-cross-section core of a waveguide. This type of waveguides has several advantages, for example low birefringence and single-mode propagation; however it is difficult to apply for active devices, such as laser media, optical amplifiers, and nonlinear optical materials because the optically modified volume may change also its functional property. If negative change in the refractive index is induced by femtosecond laser pulses, the optically modified volume could be used as a clad of a waveguide. ZrF_4-BaF_2-LaF_3-AlF_3-NaF (ZBLAN) glass shows negative change in refractive index using low repetition rates (<~10 kHz) femtosecond laser pulses [3]. The ZBLAN glass is one of promising hosts of trivalent praseodymium (Pr^{3+}) that exhibits efficient stimulated emission in the visible region. Continuous wave laser operation using a Pr^{3+} doped ZBLAN (Pr:ZBLAN) glass fiber has been reported in the visible and near-infrared regions of 479-497, 515-548, 597-737, and 849-960 nm [4].

In this study, we present fabrication of a Pr:ZBLAN waveguide using a low-repetition (1 kHz) femtosecond laser at 800 nm toward a diode-pumped visible waveguide laser. We employed a simultaneous spatial and temporal focusing (SSTF) scheme. SSTF has been used to form a frequency-distributed array of low numerical aperture (NA) beam-lets. Only at a temporal focus, all of the frequencies overlap spatially and temporally, and the pulse is compressed to a Fourier transform-limit in time as well as diffraction limit in space. One of significant merits in the SSTF scheme is that we can suppress intensity out of the temporal focus, therefore two-photon excitation can be limited in a small volume, particularly in the depth direction, than that in a conventional spatial focusing. Therefore, the SSTF scheme brings more flexibility and better quality in waveguide fabrication.

2. Experiment and Results

Our experimental setup for processing waveguides is illustrated in Fig. 1 (a), which is composed of a diffraction grating, two cylindrical lenses, and an achromatic focusing lens. Femtosecond laser pulses are angularly dispersed by the 600 line/mm diffraction grating, and are collimated by the f = 500 mm cylindrical lens. The dispersed light is temporally compressed only at the focal plane of the f = 30 mm focusing lens. In the monochromatic perspective, the beam passes through two cylindrical lenses of which separation is set as 2f (= 1000 mm), therefore the beam diameter does not change at the focusing lens. This setup realizes small processing size in both the cross-section and the axial directions. The femtosecond laser pulses (800 nm, 50 fs (FWHM)) generated from a Ti:Sapphire regenerative amplifier were used. The laser processing threshold energy was observed at ~0.9 μJ. To fabricate a clad structure, we mounted a 6 x 10 x 30 mm^3 Pr:ZBLAN bulk glass on a 3-axis motorized stage and moved the stage in a circular pattern as illustrated in Fig. 1 (b). We succeeded to suppress the axial processing length down to ~20 μm by the SSTF.

An example of fabricated waveguide is depicted in Fig. 2 (a). The incident laser pulse energy was 1.25 μJ, and we moved the motorized stage as a 25-μm circular pattern with a 10-μm pitch at a velocity of 1000 μm/s. The locus of focal point is illustrated as a white dashed line in Fig. 2 (a). The propagated light was well confined in the area surrounded by a thick clad fabricated by the femtosecond laser pulses. The propagated mode was in an ellipse since the focal plane moves by ~1.5 times longer than the motorized stage moves in the axial direction because of the refractive index of Pr:ZBLAN glass of 1.5. The far field image at 300 mm from the waveguide is shown in Fig. 2 (b). The NA of the waveguide is calculated as ~0.015 from the far field beam diameter. The propagation loss is measured as 0.56dB/cm at 630 nm.

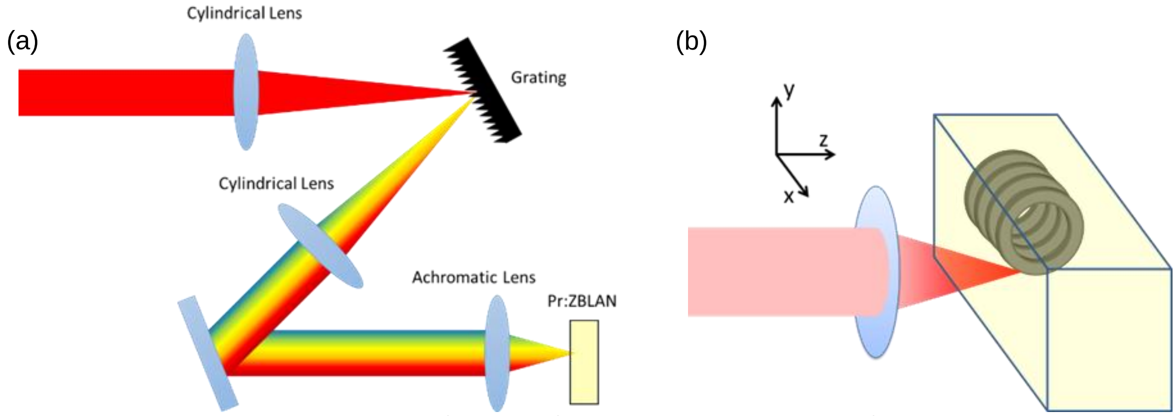

Fig. 1. (a) Experimental setup of waveguide fabrication. (b) Fabrication scheme of waveguide clad.

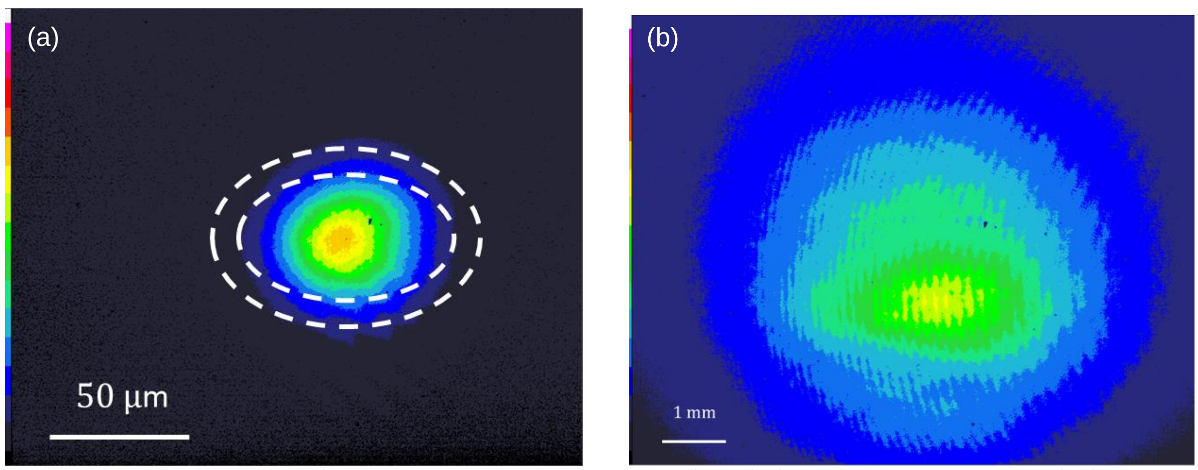

Fig.2. Intensity distribution of propagated light at 630 nm: (a) at the end facet of a fabricated waveguide; and (b) at far-field.

3. Conclusion

We fabricated optical waveguides in a Pr:ZBLAN glass by multi-photon induced refractive index modification using femtosecond laser pulses in the SSTF setup. The SSTF enables to shorten the axial processing length and fabricate smaller modified region in a glass which acts as a laser waveguide clad. The fabricated waveguide has ~0.015 of NA and 0.56dB/cm of propagation loss, which works enough as a waveguide for laser oscillation. We believe that this technology supports to create complex optical waveguide circuits in functional materials.

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