Femtosecond laser writing of symmetric, low loss waveguides in active glasses.

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Abstract- Beam shaping techniques are used to write symmetric, low transmission loss waveguides in bulk media using fs-lasers. The characteristics of waveguides written in active glasses and the implications for miniature waveguide lasers will be presented.

I. Introduction

Multiphoton absorption in bulk materials using ultra-fast lasers has generated a great deal of activity in the field of photonics. In 1996 it was shown that tightly focused infrared femtosecond laser pulses induced a refractive index change inside a glass sample [1]. By moving a polished sample perpendicularly through the focal point of these high-intensity pulses, waveguides of arbitrary length and design can be fabricated, however when using conventional spherical focussing optics this method produces waveguides with strong core asymmetry and significant losses [2]. To overcome this problem, focussing geometries using either a high (de)magnification astigmatic cylindrical telescope [3]. Most recently, Cheng *et al.* reported a simple beam shaping method that uses a slit inserted before the focussing lens [4] to reshape the beam near focus.

In this paper we demonstrate the use of the simple slit beam shaping for fabricating low-loss, circular optical waveguides in erbium doped phosphate glass with a long working distance microscope objective. Experimental results underpinning the development of 3D, compact waveguide lasers will also be presented.

II. Experiment

Optical waveguides were fabricated using a regeneratively amplified, low-repetition rate Ti:sapphire femtosecond laser system (Hurricane) from Spectra-Physics. This system produces 120 fs, 1 kHz pulses and can deliver an average power of 1 W. Laser pulses at 800 nm were focussed through a 20x microscope objective (Olympus UMPlanFL, NA 0.46, WD 3.1 mm) and injected into polished 5x5x5 mm phosphate glass samples (Toplent Photonics). A slit width 500 μm was inserted directly in front of the objective lens. The long axis of the slit was set parallel to the translation direction

The average power of the laser beam was varied by neutral-density filters that were inserted between the laser and the microscope objective. Powers ranging from 0.2 mW to 5 mW, after passing through the slit, were used in the formation of optical waveguides. Using a computer controlled XYZ stage, samples were scanned in the *x* direction, perpendicular to the direction of beam propagation, at speeds ranging between 40-100 μm/s.

III. Results and Discussion

The simulations of beam evolution shown in Fig. 1(a), (c) assume that the laser bean has a Gaussian spatial profile and evolves via paraxial theory. Other parameters used in these simulations include a numerical aperture of 0.46, a slit width of 500 μm and a refractive index for phosphate glass of 1.54. The corresponding energy distribution plots near the focal point are shown in Fig. 1(b), (d). The shape of a waveguide written without a slit would have an elliptical shaped core of aspect ratio ≈4:1 consistent with previous reports [5]. By introducing a slit of width ≈ 500 μm, before the focussing objective, a waveguide can be written using the circular distribution shown in Fig. 1(d). Fig. 2(a) shows a waveguide and its cross-section produced in undoped phosphate glass when translating at a speed of 40 μm/s without a slit. The incident pulse energy before focussing was 0.24 μJ. Because of its elliptical cross-section we were unable to couple light into this waveguide. Inserting a slit with width of 500 μm produced the optical waveguide shown in Fig. 2(b). This waveguide was fabricated in phosphate glass using a translation speed of 40 μm/s, and a pulse energy of 1.5 μJ. The core of the waveguide is shown in the inset to have a circular diameter less than 15 μm. The refractive index change induced in the glass was estimated from fitting simulate mode profiles to the measured near field profile as $\Delta n = 3.5 \times 10^{-3}$.

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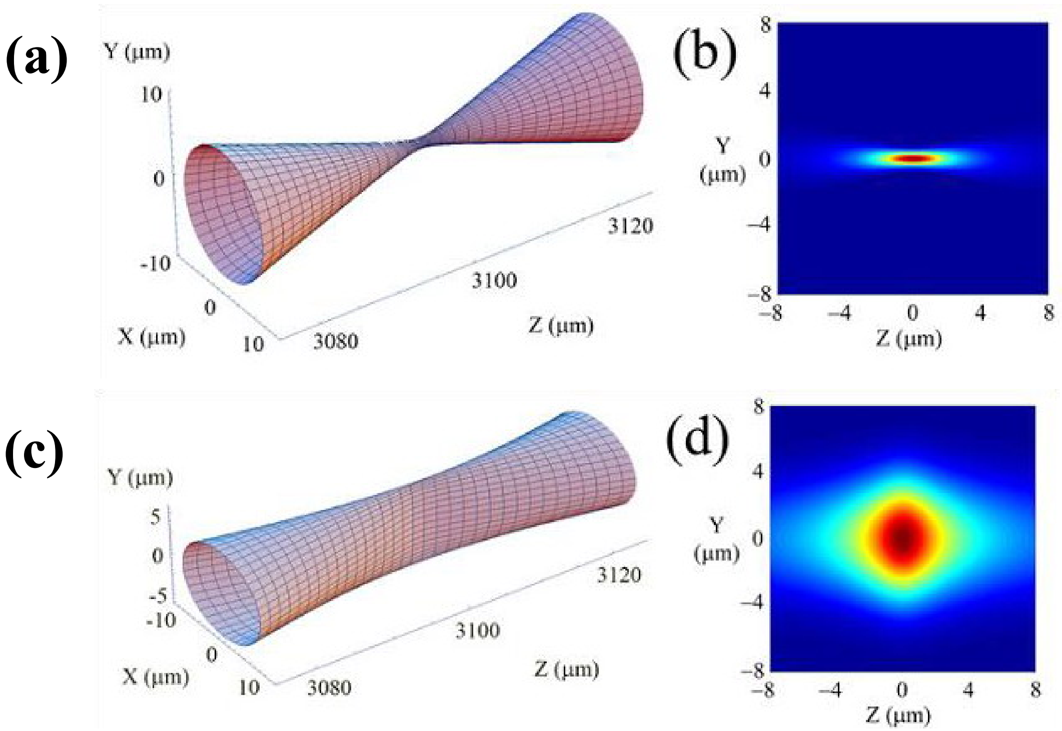

Figure 1: Beam evolution (a) and energy distribution in the YZ focal plane (b) when using a standard spherical focusing geometry. Beam evolution (c) and energy distribution in the YZ focal plane (d) when beam shaping using a slit.

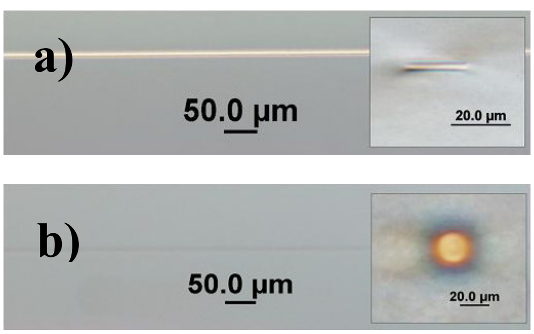

Figure 2: Differential interference contrast (DIC) microscope images of waveguides fabricated in phosphate glass using a) a standard spherical focusing geometry and b) the slit beam shaping technique.

The propagation loss of these waveguides were measured as ≈ 0.39 dB/cm at 1550 nm. The high symmetry and associated low transmission has important implications for the fabrication of compact waveguide lasers with net gain. Results will be presented of the optical characteristics and gain measurements of waveguides fabricated in rare earth doped glasses using femtosecond laser direct write processing.

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