ACTIVE DEVICES FABRICATED IN BULK GLASS VIA FEMTOSECOND LASER PULSES

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Abstract

A symmetrical optical waveguide amplifier fabricated in erbium/ytterbium co-doped phosphate glass using direct femtosecond laser writing is demonstrated. The waveguides are manufactured using 800 nm radiation from a femtosecond laser operating at a 1 kHz repetition rate, with sub 120 fs pulse duration. Peak internal gain of 2 dB is obtained at 1535 nm.

Introduction

Significant attention has recently been directed to the use of femtosecond laser pulses to inscribe optical components inside transparent materials with the goal to fabricate photonic devices for optical networking applications. In 1996 it was shown that tightly focused infrared femtosecond laser pulses induced a refractive index change inside a glass sample \cite{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.

We have demonstrated that waveguides and couplers can be written in a range of passive materials such as silica and phosphate glasses. Symmetrical waveguides with propagation losses as low as 0.39 dB/cm have been fabricated which compares well with other reports in the literature \cite{2}.

In our most recent experiments we employed a novel beam shaping technique \cite{3} that uses a slit in order to fabricate low-loss symmetric waveguide devices in erbium/ytterbium (Er:Yb) co-doped phosphate glass. Er:Yb co-doped samples were chosen because the resonant, non-radiative interaction between these two ions opens the possibility to access a wide variety of laser transitions specifically in the 1.5 – 1.6 μm range. This wavelength range has been shown to be particularly important in telecommunication applications where waveguides written in active glasses can be used as single pass amplifiers or as compact laser sources following the addition of cavity reflectors \cite{4}.

Experimental Setup

Waveguides were fabricated using a regeneratively amplified, low-repetition rate Ti:Sapphire femtosecond laser system (Hurricane) from Spectra-Physics. This system produces sub 120 fs, 1 kHz pulses and can deliver an average power of 1 W. Laser pulses at 800 nm were focussed through a 20\times microscope objective (Olympus UMPlanFL, NA 0.46, WD 3.1 mm) and injected into polished 55\times5\times5 mm Er:Yb phosphate glass samples (Kigre Inc.) that have a refractive index of 1.535 and the following dopant concentrations: 1.5% wt Er\textsubscript{2}O\textsubscript{3} and 3.7% wt Yb\textsubscript{2}O\textsubscript{3}. The average power of the laser beam was varied by neutral-density filters that were inserted between the laser and the microscope objective. A power of 1.5 mW, after passing through the slit, was used for 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 a speed of 40 μm/s. The experimental setup used to fabricate photonic waveguides is illustrated in Fig. 1.

![Fig. 1. Writing setup used to fabricate waveguides: A - Femtosecond Laser, B - CCD Camera, C - Slit, D - Focussing Objective, E - Glass Sample.](image)
In order to probe the optical waveguides, a fibre carrying 635 nm light was brought into contact with the polished end of the sample. By careful adjustment of the fibre waveguide coupling, single propagation modes were excited and their field distributions captured by a CCD camera at the back-side of the waveguide. The induced refractive index changes were determined by measuring the near-field profile at a wavelength of 635 nm, and then by solving the Helmholtz-Equation [5]. The propagation loss of waveguides was determined by taking the appropriate difference between the transmitted powers of two different length waveguides written under identical conditions, i.e. the cut-back method. Images of fabricated waveguides were taken with an Olympus differential interference contrast (DIC) microscope.

Fig. 2. Waveguide amplifier configuration and characterisation setup.

Fig. 2 shows a schematic of the waveguide amplifier configuration used. The active waveguide of length L is butt-coupled on both sides to standard Hi-980 Corning telecom fibres. A 980 nm laser diode is used in a co-propagating pumping scheme to supply up to 500 mW incident pump power through a 980/1550 nm wavelength division multiplexer (WDM). Signal radiation at 1535 nm is provided via a tuneable laser diode. Light exiting the waveguide is split into its 980 nm and 1535 nm components via another WDM. The 980 nm part is dumped whilst the 1535 nm signal is input into an optical spectrum analyser (OSA) used for gain measurements.

In order to fabricate waveguides in the x direction, with a circular cross-section, we require the focal depth in the z direction to match the transverse width in the y direction. Given the numerical aperture (NA) of the focussing objective, the refractive index of the glass substrate and knowing the beam radius of the incoming beam, we derived equation (1) which specifies the required aspect ratio of the slit in order to produce circular cross-sectional waveguides.

\[
\frac{W_y}{W_x} = \frac{\text{NA}}{n} \sqrt{\frac{\ln 2}{3}} \quad \text{for} \quad W_x > 3W_y
\]  

Results & Discussion

In our previous work [3], optical waveguides were fabricated in non-doped phosphate glass using a slit with width of 500 μm and the setup shown in Fig. 1. The core of the waveguides had circular diameters less than 15 μm. Numerical simulations using BeamPROP (RSoft) predict a step-index change of \(\Delta n = 5 \times 10^{-4}\). The propagation loss of our waveguides was measured to be \(\approx 0.39 \text{ dB/cm}\) at 1550 nm.

Er:Yb co-doped dielectrics have recently received a great deal of attention due to applications in the telecommunications industry in the 1.5 – 1.6 μm range. The most efficient host material used for co-doping of Er\(^{3+}\) and Yb\(^{3+}\) ions has by far been that of phosphate glass.

Fig. 3 shows a DIC image of a waveguide produced in Er:Yb co-doped phosphate glass when translated at a speed of 40 μm/s and using a slit with width 900 μm. The waveguide was fabricated at a depth of 300 μm below the sample surface. The incident pulse energy before focussing was 1.5 μJ. The waveguide diameter was determined from the DIC image to be approximately 11 μm. The refractive index contrast and propagation loss of this waveguide are yet to be calculated.

Fig. 3. DIC microscope image of a waveguide fabricated in Er:Yb co-doped phosphate with a 900 μm slit.

Fig. 4 shows the Er:Yb co-doped phosphate waveguide positioned in amplifier configuration setup.

Fig. 4 shows the Er:Yb co-doped phosphate waveguide positioned in the amplifier configuration setup (Fig. 2). When the 980 nm pump source was switched on the amplified spontaneous emission (ASE) exiting the
waveguide was recorded on the OSA. Fig. 5 shows the ASE for two waveguide samples of different lengths fabricated under identical conditions.

The red curve shows a standard ASE profile common to unsaturated short sample lengths, however the longer sample (blue curve) shows an inverted ASE response. This inversion is possibly due to reabsorption of the signal source along the waveguide hence leading to the conclusion that the sample is ultimately too long and thus not yet optimised for use in signal amplification.

![Fig. 5. Emission from Er:Yb co-doped phosphate waveguides pumped at 980 nm.](image)

Nonetheless, using the signal source properly attenuated together with the 500 mW pump source, the small signal internal gain of the long amplifier at 1535 nm was measured. Amplification of the source signal by a factor of 1.6 (0.37 dB/cm) was observed when co-pumped by the 980 nm laser diode. A maximum internal gain of 2.5 dB/cm at 1535 nm has been reported elsewhere [2].

There is still great potential for further improvement of our measured gain by both reducing the insertion losses and optimising the doping concentrations of Er³⁺ and Yb³⁺. We can also incorporate a bi-directional pumping scheme which would help amplify the source signal towards the end of the waveguide. However, the main factor that will definitely increase the amount of internal gain exhibited by the waveguide amplifier is to find the optimal length that the waveguide must be given all other factors are known. Experiments into these parameters are ongoing. Optimisation of the waveguide amplifier based on cut-back measurements and reverse end pumping will be presented.

**Conclusion**

Using the femtosecond direct write technique, we fabricated a working erbium/ytterbium co-doped waveguide amplifier in a phosphate glass host. The waveguide has a symmetric core diameter of approximately 11 μm. When a small signal at 1535 nm was co-pumped with 500 mW at 980 nm, an internal gain of 0.37 dB/cm was observed. Improvements into increasing this gain are underway which include the optimisation of waveguide length, doping concentrations and pumping scheme. The femtosecond direct write technique has opened up new opportunities for all optical telecommunication networking.

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**References**


