High gain fs-laser written Yb^{3+}/Er^{3+}-codoped phosphate glass waveguide

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***Abstract*—In the present work we report a high gain femtosecond-laser directly written waveguide in an Er/Yb co-doped phosphate glass with a maximum internal gain per unit length of 4.1 dB/cm at 1535 nm.**

Keywords- erbium-doped waveguide amplifier; femtosecond laser micromachining; optical waveguides; phosphate glass

I. INTRODUCTION

Femtosecond (fs) laser micromachining of photonic devices inside transparent materials is based on the local structural modification that appears around the focal volume (FV) upon the irradiation. This is a consequence of the nonlinear ionization processes undergoing in this region and the subsequent relaxation mechanisms [1].

The first so fabricated photonic device (waveguide) was demonstrated in 1996, by Davis and coworkers [2]. Since then, several passive devices such as power splitters [3] or directional couplers [4] amongst others have been reported. Active devices such as waveguide based optical amplifiers [5] or lasers [6] have been successfully demonstrated as well. Er:Yb-codoped active devices are of remarkable interest for signal amplification in the C-Band (1530-1565 nm) communications window [7]. In this field of devices, several efforts have been done such as those reported by Della Valle and coworkers [8], where the authors reported a full C-band amplification as well as a peak internal gain per unit length of ~2.5 dB cm^{-1} in a 37 mm-long device. This figure compares well with the 3 dB cm^{-1} value reported previously in state-of-the-art Er:Yb-codoped waveguide amplifiers fabricated by ion exchange in a phosphate glass with similar doping concentrations [9].

The aim of the present work has been to optimize the peak internal gain per unit length, in order to fabricate shorter devices with higher internal gains. In this letter we report a 1.4 cm-long fs-laser directly written waveguide amplifier, fabricated in a custom made phosphate glass in which we have measured a peak internal gain per unit length of 4.1 dB cm^{-1}.

II. EXPERIMENTAL

In order to optimize the Er^{3+} and Yb^{3+} concentrations of the phosphate glass sample, a set of simulations similar to those reported in [10] were performed, using the concentrations as fitting parameters for internal gain per unit length optimization. In this way, the phosphate glass was fabricated following the procedure depicted as well in [10]. During the glass fabrication process, water incorporation in the matrix may occur because of the hygroscopic nature of the reactants used. Because of this phenomenon, the final composition may be slightly different from the calculated on. For this reason, after glass fabrication its composition has been measured by Particle Induced X-Ray spectroscopy. The corresponding measurements are presented in Table I. The optical absorption of the sample was measured with a commercial spectrophotometer, which at 1535 nm reaches a value as high as 1.91 cm^{-1}. Since the sample has a total length of 1.40 cm, this figure corresponds to an absorption loss at 1535 nm of 11.6 dB.

A waveguide has been written in this glass using a setup similar to that presented in [11], using 43 nJ and 370 fs laser pulses at 1036 nm and a repetition rate of 500 kHz. The polarization was set to circular. The irradiation beam was slit-shaped as shown in [12,13] with a 830 µm-width slit, it was focused 100 µm below the surface with a 0.68 NA aspheric lens, and the sample was translated perpendicularly to the incident beam at 60 µm/s. In Fig. 1, the so-written waveguide is presented as seen by a white light transmission microscope (Fig. 1a) as well as its guided mode at 1550 nm (Fig. 1b). The waveguide presents propagation losses of ~0.5 dB/cm and coupling losses of ~0.1 dB/facet with respect to the Hi1060 fiber (used to couple light inside), as measured according to [13]. The guided mode of this coupling fiber is shown in Fig. 1c so as to compare with the waveguide's one (Fig. 1b). The total insertion losses were measured to be 1.27 dB (including

TABLE I. PHOSPHATE GLASS COMPOSITION

Compound	Concentration (molar ± 0.3)	Compound	Concentration (molar ± 0.3)
P_2O_5	68.0	Yb_2O_3	2.6
La_2O_3	12.4	Er_2O_3	1.3
Al_2O_3	10.1	Ce_2O_3	0.9
K_2O	4.8		

Fresnel losses).

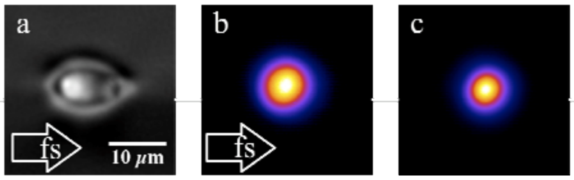

Fig. 1. (a) White light micrograph of the waveguide. (b) 1550 nm guided mode of the waveguide. (c) 1550 nm guided mode of the Hi1060 fiber.

The waveguide was then implemented in an optical amplifier, bi-directionally pumped at 976 nm, as the one described in [10]. The co-propagating pump power was set to its maximum value (366 mW), while the counter-propagating one was systematically increased.

III. Results and discussion

The curve of the relative gain of the small signal (1535 nm) as a function of the counter-propagating pump power is shown in Fig. 2 (bottom). Before every relative gain measurement, both pumps were set to zero and the signal attenuation was measured as a reference of the stability of the system (red line with circles in Fig. 2).

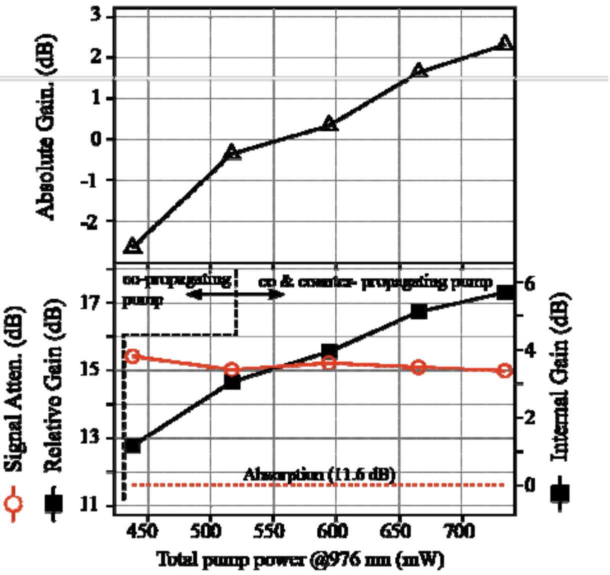

Fig. 2. Signal attenuation (red curve, circles) at 1535 nm, relative gain (black line, squares, left), internal gain (black line, squares, right) and absolute gain (black line, triangles) of the waveguide amplifier fabricated in a Er:Yb-codoped phosphate glass.

The internal gain of the amplifier (Fig. 2) was obtained by subtracting the 11.6 dB of the sample absorption at the signal wavelength, resulting in a maximum value of 5.7 dB. For the 1.4 cm-length amplifier, this figure results in a relative gain per unit length of 4.1 dB/cm, which is one of the highest reported so far. By further subtracting the signal attenuation to the relative gain curve, one may get the absolute gain curve (Fig. 2, top). This amplifier presents a maximum absolute gain of 2.3 dB for a total pump power of 734 mW. These results state the excellent active properties of the glass for the fabrication of compact integrated optical amplifiers in the communications window.

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