Characterization of an Er^{3+}/Yb^{3+} Codoped Two Core Integrated Waveguide Femtosecond Laser written in a Phosphate Glass

(Student paper)

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ABSTRACT

Integrated dual core waveguides have been fabricated in Er^{3+}/Yb^{3+} co-doped phosphate glasses by femtosecond laser writing. Two-core waveguides have been characterized. First, an isolated one has been used in order to fit the theoretical model of the optical powers propagation equations coupled to the energy levels population rate equations. Then, measurements of the optical power at the two-core waveguides output end have been carried out. A good agreement between measurements and simulations has been found.

Keywords: dual-core waveguides, integrated optics, erbium ytterbium codoped optical waveguide amplifier, femtosecond written waveguides, multicore fibers.

1. INTRODUCTION

Multicore fibers (MCF) are expected as good candidates for enhancing the capacity of optical transmission systems and for power scaling of fiber active devices [1]. The dual core fiber turns out to be the simplest case of MCF, and it can be used as simple fiber optic elements like couplers and power splitters. Owing to new developments in writing optical waveguides with femtosecond lasers, integrated multicore structures with a wide range of refractive index contrast can also be inscribed in rare earth doped glasses, thus allowing the transfer of multicore fiber structures potentialities to active integrated devices.

Irradiation of phosphate glasses with femtosecond laser pulses allows the inscription of 3D integrated waveguides with high refractive index contrast by ion migration mechanisms [2]. Waveguides written in phosphate glasses with high La_2O_3 content obtain high refractive index differences in the guiding region due to the incoming migration of La accompanied by the out-diffusion of K. Together with the La, there can be other lanthanides present in the glass composition (Er^{3+}, Yb^{3+}) that experience similar local concentration changes upon femtosecond laser writing [3], increasing the active ions concentration in the guiding region.

The characterization of the two-core waveguides entails not only the difficulties of rare earth doped integrated waveguides characterization but also the issues associated with the multicore structure, like multimode propagation that depends on the coupling between individual core modes.

2. MODEL PARAMETERS DETERMINATION

The isolated and the two-core integrated waveguides have been fs-laser written in an Er^{3+}/Yb^{3+} codoped phosphate glass. In order to model the amplification of an optical signal along a rare earth doped waveguide, both the rate equations system (describing the time evolution of the population densities of the involved active ions energy levels) and the coupled optical power equations system (describing the propagation of the optical powers), are required. We follow the conventional diagram of cooperative energy transfer from ytterbium to erbium in phosphate codoped glass, and represent the system by a five-level diagram [4]. Some of the parameters needed in the theoretical model must be obtained experimentally. In order to do that, we first characterize an isolated waveguide written in the same bulk glass.

In order to obtain the absorption and emission cross sections of the active ions, together with its cooperative energy transfer coefficients, we characterize an individual waveguide by measuring pump/signal absorption and signal amplification. The integrated waveguide is excited with a standard single mode fiber (SMF) carrying both pump (980 nm) and signal (1534 nm) optical powers. At the output end of the waveguide, another SMF is placed to collect the resultant power and a multiplexer separates the pump power from the signal one. The optical power is measured with an optical power detector and its spectrum with an optical spectrum analyser. $P_s(P_p)$ being the signal power at the waveguide output end as a function of pump power, signal enhancement is given by

$$g(P_p) = 10 \cdot \log_{10}\left[\frac{P_s(P_p)}{P_s(0)}\right], \quad (1)$$

Once we have measured the signal enhancement as a function of wavelength and pump power, we fit the model coefficients until the numerical results reproduce the experimental measurements. The core diameter and refractive index contrast is 5.3 µm and $6.3\cdot10^{-3}$, respectively, and Er^{3+} and Yb^{3+} concentration is $3.0\cdot10^{26}$ and $6.3\cdot10^{26}$ ions/m^3. The waveguide is 9.35 mm long and the signal power has 0.9 dB losses. Adjusted stimulated emission cross section between $^4I_{15/2}$ and $^4I_{13/2}$ erbium level is $9.73\cdot10^{-25}$ m^2 (@1534 nm), and the absorption cross section between $^2F_{7/2}$ and $^2F_{5/2}$ ytterbium level is $1.25\cdot10^{-24}$ m^2 (@980 nm). Estimated erbium upconversion coefficient, considered as homogeneous, is $5.5\cdot10^{-24}$ m^3/s, while direct and back energy transfer coefficients between $^2F_{5/2}$ and $^4I_{11/2}$ levels are $5.0\cdot10^{-24}$ and $1.5\cdot10^{-21}$ m^3/s, respectively. Figure 1 (a) shows signal enhancement, both measured and simulated, as a function of the bidirectional pump power. Figure 1 (b) shows the gain spectrum for different values of unidirectional pump power.

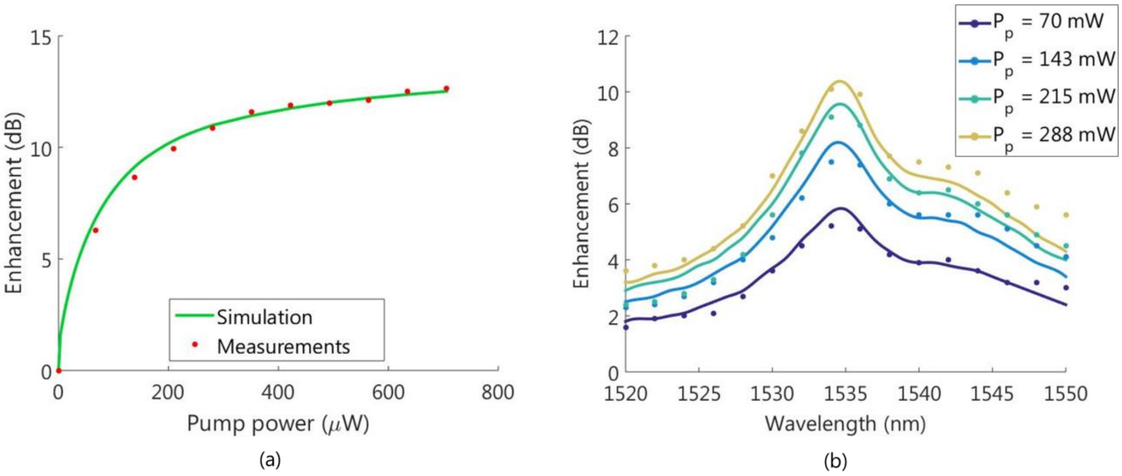

Figure 1. Comparison between measurements and simulations of the amplified gain in an isolated waveguide. Figure (a) shows the enhancement as a function of the bidirectional symmetric pump power. Initial signal power is of 100 µW. Figure (b) shows the enhancement spectrum for different pump powers.

3. TWO CORE WAVEGUIDES

Once the isolated waveguide has been characterized and the model parameters have been adjusted, the model can be used to simulate the light amplification along the two-core waveguide. In order to do that we compute the modes of the multicore waveguide, the so called supermodes, and simulate its optical powers propagation through the guiding structure. With the aim of taking into account modal competition we need to include multimode propagation in our model [5]. The transversal distribution of the electromagnetic supermodes field of the two core waveguide has been computed with the RSoft Cad software.

Inside the phosphate bulk glass there are several fs-laser written two-core waveguides with different core-to-core separation. The setup is similar than the one used for characterizing the isolated waveguide, but both input and output SMFs are placed symmetrically between the waveguide cores. It is also possible to place a microscope objective at the waveguide output, instead of the SMF, so that we can register the intensity distribution with an infrared camera as a function of the core-to-core separation. Figure 2 shows those intensity profiles for different waveguides, when only signal power is being propagated along the two core waveguide. The registered images help us to align our system and compare it with the intensity distributions simulated with the RSoft Cad program.

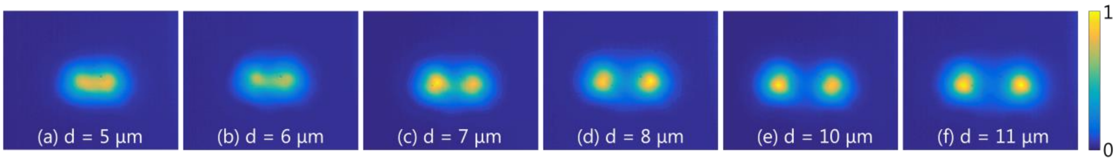

Figure 2.Transversal intensity distribution at the two core waveguide output for different core-to-core separation waveguides. The optical power wavelength is 1534 nm and the intensity distribution has been normalized.

The two dual waveguide supermodes can be excited in different proportions depending on the position of the SMF. To numerically compute the excited modal amplitudes we need to calculate the projection of the SMF electromagnetic field mode over each one of the supermodes field distributions. After simulating the propagation and amplification of both supermodes optical powers, we calculate the output power and project its electromagnetic field distribution over the SMF one. The enhancement given by equation (1) is computed with the optical power collected by this SMF at the waveguide output. Figure 3 (a) shows the signal power at the end of the waveguide as a function of the core-to-core separation of the dual waveguide for different fixed pump powers. On the other side, in Fig. 3 (b) one can see the enhancement evolution with the pump power for three different dual core waveguides with 5, 7 and 8 μm core-to-core separations. In both images one can see the good agreement between measurements and numerical results.

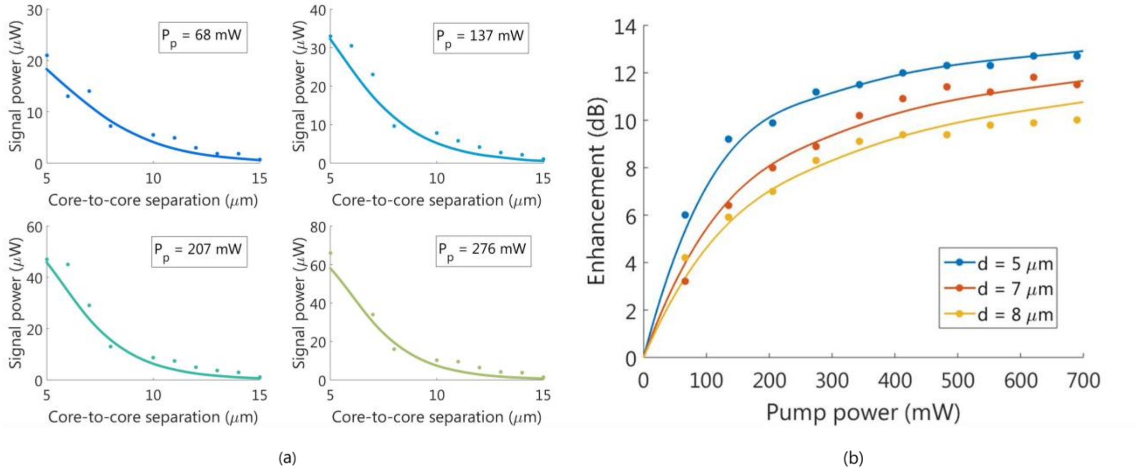

Figure 3. The four images in (a) show the signal power as a function of the core-to-core separation of the dual waveguides for different input pump power:_ 68, 137, 207 and 276 mW. Initial signal power is 100 μW. Image (b) shows the enhancement as a function of the pump power for three different dual waveguides with 5, 7 and 8 μm core-to-core separations.

4. CONCLUSIONS

The parameters from the theoretical model of the power propagation equations coupled to the rate equations have been obtained with the characterization of a femtosecond laser written isolated waveguide in an Er^{3+}/Yb^{3+} codoped phosphate glass. We have carried out the measurements of the signal power at the end of the two core waveguide as a function of both pump power and core-to-core distance. Once the model is adjusted, we have compared the simulations of the propagation and amplification of signal power along the two core waveguide with the measurements taken. We have found a good agreement between measurements and simulations.

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