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Phosphate Glass Optical Amplifier

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Research Article

Fabrication and Characterization of a High-Gain Yb-Er Codoped Phosphate Glass Optical Amplifier

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We present the fabrication and characterization of a short core pumped fiber amplifier made of Yb^{3+}-Er^{3+} codoped phosphate glasses. The 27 mm long amplifier provides a maximum internal gain of 10.7 dB for a signal of −30 dBm at 1535 nm with a 479 mW pump power operating at 975.6 nm. This leads to a gain of 4.0 dB/cm, which compares favorably to other recent works.

1. Introduction

Thanks to the high spatial and spectral quality of their output beam, fiber lasers appear as a promising infrared light source for LIDAR systems. As fiber laser material, phosphate glasses allow to incorporate high levels of rare-earth ions, which enables the manufacturing of short optical fiber devices with a high output power. These features redound into compact, portable lasers that can reach longer distances when compared with other emitting devices. Usually, a one-piece fiber laser having all these characteristics cannot be easily conceived. A convenient way to achieve all the specifications at once is to proceed through a master oscillator power amplifier (MOPA) architecture. In this configuration, the output of a low-power seed laser having the required spectral characteristics is carried into a high-power fiber amplifier. This, in turn, provides the required amplification level without impairing on the other desired specification. This paper focuses precisely on the fabrication and characterization of a short core pumped fiber amplifier based on Yb^{3+}-Er^{3+} codoped phosphate glasses to be used at the second stage of a MOPA configuration.

2. Experimental Details

2.1. Optical Fiber Fabrication and Characterization. The core glass was doped with 2.81 wt% of Er_2O_3 (1.08 mol%, $2.5 \cdot 10^{26}$ ions/m³) and 2.87 wt% of Yb_2O_3 (1.09 mol%, $2.5 \cdot 10^{26}$ ions/m³). The optical fiber preform was produced by means of rotational casting technique developed in-house. The preform and fiber fabrication parameters were set to generate a double-cladding fiber with the following diameters: 7 μm, 25 μm, and 70 μm for the core, inner, and outer cladding, respectively. The preform was drawn into fiber using a drawing tower developed in-house. The core diameter was chosen to provide an acceptable coupling efficiency to the commercial Flexcore fibers used in the system. The double cladding topology allows us to test the fiber as either core or cladding pumped; the latter case will be addressed elsewhere. The refractive indexes of the core and inner cladding were designed in order to obtain a numerical aperture NA = 0.17. This value guarantees that the active fiber presents an almost single-mode behavior at the signal wavelength. The quality and morphology of the optical fiber were inspected by means of a Nikon ECLIPSE E 50i microscope. The active fiber loss measurements were obtained by the cut-back technique using

a single-mode fiber laser diode operating at 1.3 μm. The laser was butt coupled to one of the active fiber ends. A set of near-field images were taken at the other end of a 280 cm long fiber section in order to analyze the modal properties.

2.2. Amplifier Gain Experiments. The components used in the experimental setup are summarized in Table 1. A single-mode laser diode working at 975.6 nm with a maximum power of around 500 mW was used for the pump. A tunable laser ranging from 1500 to 1600 nm with output power levels from −30 dBm up to +5 dBm was used for the signal. Both components were spliced to the corresponding inputs of a wavelength division multiplexer (WDM). Its output was butt coupled to the active fiber, which consists of a 27 mm Yb^{3+}/Er^{3+} codoped phosphate glass fiber. All these components except for the amplifier section use Flexcore 1060 fibers with 5.6 μm diameter. This ensures a correct matching among them. A photograph of the in-house fabricated active fiber is shown in Figure 1. A pigtail with 9 μm core diameter was used to convey the active fiber output power to the optical spectrum analyzer (OSA) in order to measure the output power of the amplified signal.

3. Results

3.1. Optical Fiber Modal Properties. The near-field image of the active fiber end face at 1300 nm is presented in Figure 2(a). The transversal profile is depicted in Figure 2(b). As can be observed, the power is almost entirely confined inside the core. A slightly diffused area corresponding to evanescent wave can barely be seen inside the inner cladding. The confinement ensures that the pump power is not irradiated outside the active area and therefore it is available to excite the active ions with which the signal can interact. While adjusting the launching condition, the presence of a profile similar to the LP_{11} mode could be observed. This observation confirms the multimode behavior of the core at 1300 nm.

3.2. Optical Fiber Attenuation Measurements. Fiber losses were measured by cut-back technique using a length of 280 cm with a source at 1300 nm. The results are depicted in Figure 3. The fitted attenuation coefficient was 7.11 dB/m. Measurements data show a deviation with respect to the fitted slope. This deviation can be attributed to experimental errors caused by several factors such as the hand cleaving procedure, the presence of scattering particles, or short range changes on the fiber diameter.

3.3. Optical Fiber Amplifier Demonstration. The output spectrum of the amplifier is shown in Figure 4 after the fiber had been excited with a +0 dBm signal at 1535 nm and 479 mW of pump power. It is worth mentioning that a spurious laser peak at 1534 nm could be observed on the OSA during the experiments when refractive index matching gel was not applied at the coupling ends of the phosphate glass fiber with the launching and exiting commercial silica glass fibers. For that reason, all measurements reported in this paper were carried out using index matching gel. Not only did the gel

TABLE 1: Material and components.

| Component	Value/description	Relevant parameters
Pump laser	1999CHP (3SGroup) HI1060 fiber output	975.6 nm 650 mW (max) Ø 5.6 μm/0.125 NA PM
Tunable laser	HP8168F	$\lambda > 1500$ nm $\lambda < 1600$ nm
WDM	Go4fiber WDM9890-250-A-1	Ports: 976–1090 nm 26 dB isolation Fiber Ø = 5.6 μm SM
Yb^{3+}/Er^{3+} fiber	In-house developed phosphate glass fiber	Fiber $Ø_{core} = 7 \mu$m Fiber $Ø_{innerclad} = 25 \mu$m NA = 0.17
Collector pigtail		Fiber Ø = 9 μm (SM) Fiber $Ø_{clad} = 125 \mu$m
OSA	Agilent 86140B	Max 30 dBm or 23 dBm in 10 nm
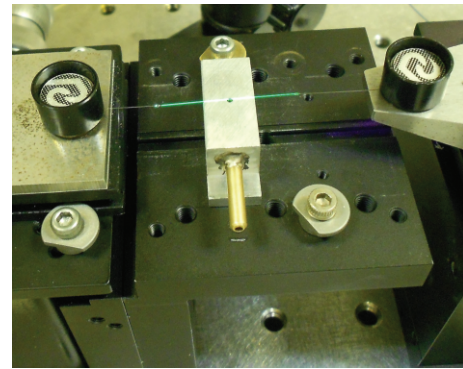
FIGURE 1: A detailed view of the fabricated amplifier section.

improve the coupling efficiency between butt-coupled fibers but it also because contributed to the mechanical stability of the measurement by maintaining the fibers correctly faced one to another and by avoiding spurious movements produced by small air fluctuations.

3.4. Optical Fiber Gain Measurements. The presence of green light scattered out of the fiber—as seen in Figure 1—indicates that the pumping efficiency is limited by upconversion processes. It also increased with increasing pump power. Moreover, the losses introduced by the fiber couplings in the input-output path have been evaluated to be between 4.52 and 5.17 dB. Additionally, since the WDM was designed to work with 1090 nm signals, the losses that the device exerts on injected signals of other wavelengths ranging from 1510 to 1590 nm had to be evaluated. The values found were between 0.65 dB and 0.47 dB, almost independently of the signal power used. Although these losses were present, the amplifier showed net gain (see Figure 5) for signal wavelengths ranging from 1527 nm up to 1549 nm and signal powers from −30 dBm up to 0 dBm. The net gain reached a maximum level of 4.7 dB at 1534 nm. The internal gain was also evaluated taking into account the coupling losses. In order to provide the most
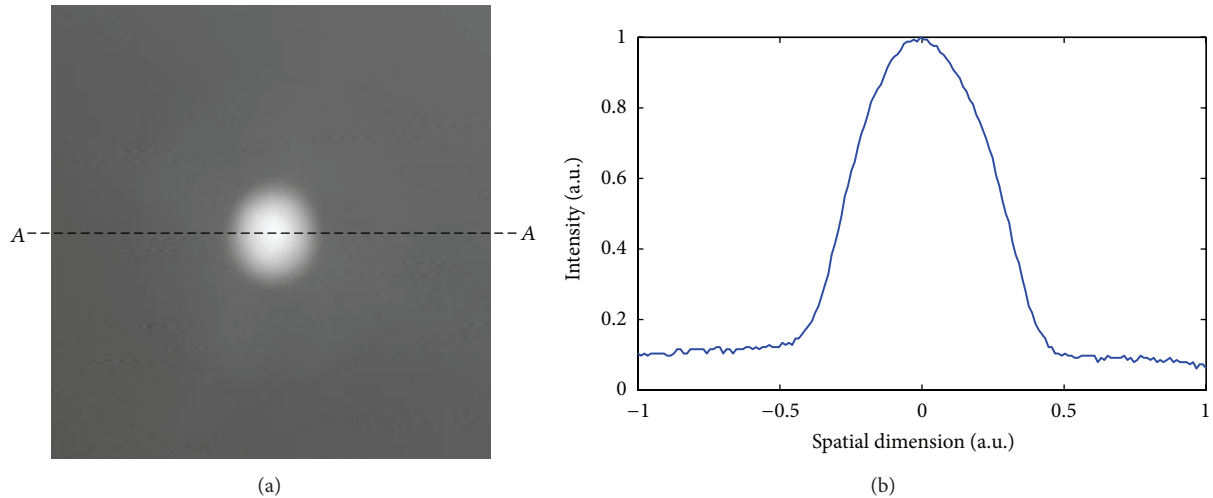
(a)

(b)

FIGURE 2: (a) Near-field image of the active fiber end at 1300 nm. (b) Intensity profile corresponding to the transversal dashed line A-A shown in (a).
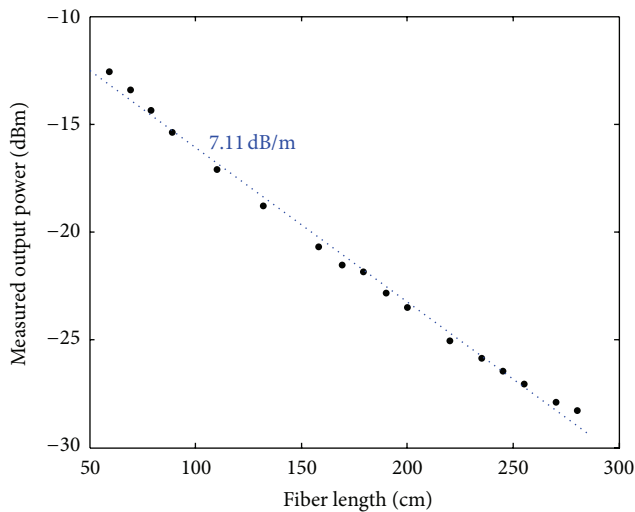

FIGURE 3: Attenuation coefficient measured on Yb^{3+}/Er^{3+} phosphate glass fiber obtained by exciting at 1300 nm. After fitting the curve, a mean value of 7.11 dB/m was found.
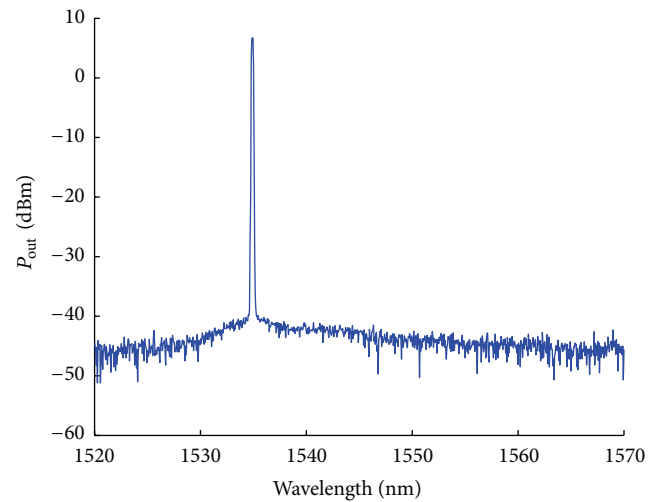

FIGURE 4: Amplifier output spectrum of the Yb^{3+}/Er^{3+} phosphate glass fiber obtained by exciting with a 479 mW pump at 975 nm and a 0 dBm signal at 1535 nm. The highest peak obtained at these conditions is shown (+6.714 dBm).

conservative value for the internal gain in all the cases, it was adopted a value of 4 dB for the coupling losses. As a result, it can be deduced that the active medium provides amplification for a wider range of wavelengths, extending from 1515 nm to 1575 nm. In this set of measurements, the fiber provided an internal gain as high as 8.7 dB for a −20 dBm signal.

The internal gain per unit length at wavelength λ = 1535 nm is presented in Figure 6. It presents gain value between 1 and 4 dB depending on the available pump power. As discussed in Section 3.3 and despite all the efforts that have been taken, errors related to stability issues impaired slightly some of the measurements. This is evident in Figure 6 where the gain curves tend to be closer one to each other. Due to the experimental errors, lower pump powers produce higher

gain results when it should be the contrary. For instance, the gain for a signal of −20 dBm at a 378.2 mW pump power is higher than for a pump power 479.8 mW. The same situation occurs for a +5 dBm at 237.7 mW.

A maximum value of 4.0 dB/cm was obtained for a −30 dBm signal and 479.8 mW pump power. Here, the curves show that the amplifier presents a clear sign of saturation at high pump or signal powers. This is in agreement with the fact that further increments in the pump power do not have a corresponding linear increase on the internal gain. At low pump conditions, the internal gain levels maintain almost a constant value independent of the input signal power (at least for the range of tested signal powers). This observation suggests that, in this regime, the Er^{3+} is not yet fully inverted
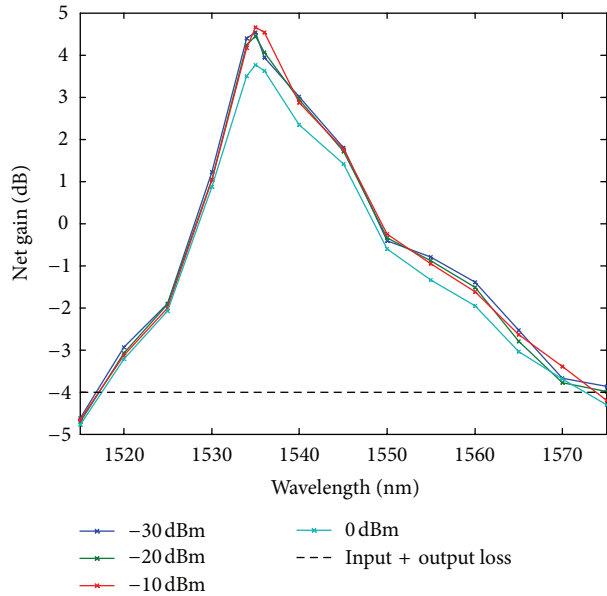
FIGURE 5: Signal net gain spectrum obtained for four different signal input powers −30 dBm, −20 dBm, −10 dBm, and 0 dBm at wavelengths ranging from 1515 to 1575 nm. Injected pump power is P_p = 237 mW.
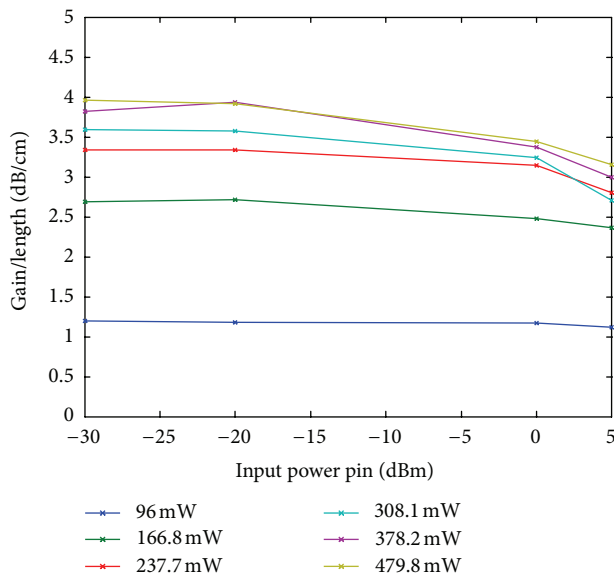

FIGURE 6: Internal gain per unit length as a function of the input power level at 1535 nm. The amplifier shows some degree of saturation.

and that the amplifier is not yet saturated. When increasing the pump power, the gain starts to saturate for both low and high signal input cases. However, one can notice that the saturation gain tends to decrease as the input signal increases. Actually, deeming the amplifier as a power reservoir, this latter is not large enough to sustain the same gain value for high input signal as it does for low signal input power. It is believed that in order to increase the gain per length value

a further improvement of the fabrication process is required. For instance, the reduction of particles and defects located at the core-cladding interface would allow reducing the optical loss and thus achieving more gain. Additionally, avoiding the creation of micro-clusters could be useful to reduce up-conversion in order to increase the output power.
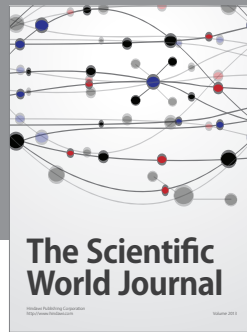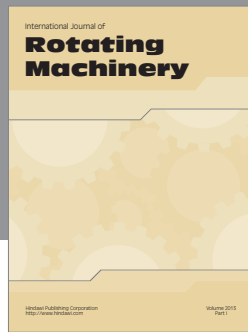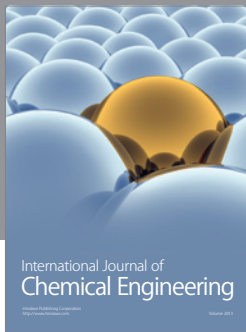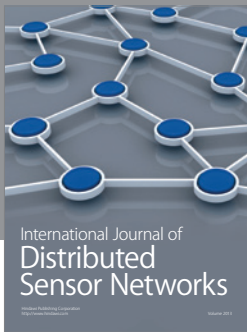
Also, at high pump power a large amount of pump remained unabsorbed and was in fact observed experimentally at the amplifier output. An amplifier slightly longer would allow to fully exploit the pump power available for reaching higher output powers.

4. Conclusions

A fiber amplifier based on Yb^{3+}-Er^{3+} codoped phosphate glasses was fabricated and characterized. At the highest input signal (+5 dBm) the amplifier provided 6.39 dB and 8.52 dB internal gain for medium and highly saturated operation (166.8 mW and 479.8 mW pump power, resp.). The internal gain per unit length was thus 2.37 dB/cm and 3.15 dB/cm, which is higher than or near to values reported in [1, 2] (0.94 dB/cm and 3.3 dB/cm). In addition, the maximum observed internal gain was 10.71 dB, obtained with the minimum input signal (−30 dBm) and a 479 mW pump power. This leads to an internal gain of 4.0 dB/cm, a value that is comparable to the values reported in [3, 4] (4.2 dB/cm and 5.2 dB/cm, resp.).

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