Single-mode and high power waveguide lasers fabricated by ion-exchange

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Abstract: We report on a single-end diode-pumped waveguide laser providing output power in excess of 20 mW with 17% slope efficiency in robust single longitudinal and transverse mode operation at 1533.5 nm. The active medium was an Er:Yb-doped waveguide only 9-mm long fabricated by Ag-Na ion-exchange in a phosphate glass. The overall cavity length including butt-coupled fiber-Bragg-grating mirrors was <60 mm. We also report on high power waveguide lasers providing more than 160 mW output power and 46% slope efficiency in multimode operation. Feasibility of high power single mode waveguide lasers based on ion-exchange technology in phosphate glasses is also experimentally investigated by using a 50-mm long active waveguide specially designed for efficient single-end pumping.

OCIS codes: (140.3570) Lasers, single-mode; 140.3500 Lasers, erbium; (230.7380) Waveguides, channeled

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1. Introduction

Among the growing request of new high performance laser sources one of the key issue is to develop compact single-mode lasers at 1.5 μm. In fact, several applications like free space optical communications [1], laser radar and satellite based remote sensing [2], distribute fiber-optic sensors [3], and frequency domain reflectometry [4], are becoming more and more demanding in terms of power, compactness, insensitivity to environmental disturbance and high temporal coherence. The most exploited solution, which is represented by bulk lasers able to provide high output powers in view of large mode volume, actually suffers from several limitations in terms of compactness and robustness of the cavity. Recently, short fiber lasers [5] have demonstrated the potential to satisfy all the requirements previously outlined in view of an intrinsic compactness and robustness provided by a monolithic cavity structure. Furthermore, with the development of heavily-doped glasses and specially designed fibers, such as large-mode area or micro-structured fibers, fiber lasers demonstrated mode volumes even larger than several bulk lasers and the first watt-level single mode fiber laser at 1.5 µm has been already reported [6]. However, still the cavity was not so rigid as it can be in a waveguide device where all components can be realized, in principle, on the same substrate. Therefore waveguide laser cavities are expected to provide even better performance in terms of robustness and insensitivity to environmental noise, though demonstration of high output power, especially in single-mode operation, is still a challenging task. This limit stems from the difficulty in fabricating high quality active waveguides in heavily-doped glasses and in optimizing doping concentration for efficient pumping over short lengths. In fact a highly-doped material is required to meet the demand of high-power together with a compact laser cavity (around few cm long) allowing single longitudinal mode operation. This requirement makes glass-on-silicon technology unsuitable because erbium concentration is limited by quenching effects in silica [7]. On the contrary, other glasses offer better solubility of erbium. In particular, phosphate glass offers a far better solubility with respect to silica and also makes codoping with Yb ions more beneficial for pumping in view of higher phonon energies in the phosphate, resulting in efficient energy transfer from Yb to Er. The use of Yb is also the key solution for high pump absorption over short lengths.

We recently demonstrated 50 mW single-mode operation in a diode-pumped waveguide laser based on a 22-mm long active waveguide fabricated by femtosecond laser writing in an Er:Yb-doped phosphate glass [8]. Another method to fabricate high quality active waveguides in a phosphate glass base is the ion-exchange (see [9] and references therein), which offers the advantage of being a well developed technique, providing high reliability and mass production. Furthermore, channel waveguides fabricated by ion-exchange technology are close enough to the glass surface to allow mode-field interaction with materials placed at the surface or with a micro-structured surface. This allows an integration of cavity mirrors into ion-exchanged waveguides by means of surface patterning with mask lithography [10] or laser irradiation [11]. For these reasons, ion-exchanged waveguide lasers have attracted much interest, but only few mW output power have been demonstrated up to now [10,11,12], except from a Ti:Sapphire-pumped large mode area waveguide laser providing few tens of mW [13].

In this paper we report on the development of a single-mode and single-end diode-pumped waveguide laser based on a 9-mm long Er-Yb-doped waveguide fabricated by Ag-Na ion exchange in a heavily doped phosphate glass. Furthermore, we report on preliminar experiments on high power waveguide lasers based on longer waveguides fabricated in the same phosphate base. An experimental investigation of power scaling feasibility towards 100 mW power level in single mode operation was also carried out by using a commercial 50-mm long active waveguide optimized for efficient single-end pumping.

2. Waveguide fabrication and laser set-up

2.1 Waveguide fabrication

The ion-exchange method is a very reliable, rugged and low cost technique for waveguide fabrication, and was already demonstrated for several exchanging ions, including K-Na [10,13] and Ag-Na [11,12]. In order to address compactness of the waveguide laser cavity, a heavily doped glass substrate allowing high gain per unit length is required. Phosphate glasses are good candidates, allowing for much higher doping levels Er and Yb with respect to silicate glasses. Among commercially available phosphates we selected Schott IOG-1, which already demonstrated high optical quality and, in view of a high content of sodium (20%wt of Na_2O), allows both K-Na and Ag-Na ion exchange fabrication. Doping concentration was 3.43×10^{20} ions/cm^3 of Er^{3+} and 2.49×10^{20} ions/cm^3 of Yb^{3+}. A two-step Ag-Na ion-exchange process was adopted for waveguide fabrication. In the first step the glass substrate was immersed for 8 minutes in a ternary mixture of molten salts (8%wt $AgNO_3$, 5.25%wt $NaNO_3$, 86.75%wt KNO_3) at 330°C (see [14]). A titanium mask with 6-µm wide linear apertures was previously deposited onto the glass substrate thus allowing fabrication of linear channel waveguides at the surface. A second burial step was performed by applying a transversal driving electric field to the substrate in order to reduce waveguide propagation losses and coupling losses to single-mode fibers (see [15] for fabrication details). After fabrication, the waveguide end-facets have been polished and the resulting waveguide length was 9 mm. In total we fabricated a linear array consisting of sixteen 250-µm spaced buried channel active waveguides.

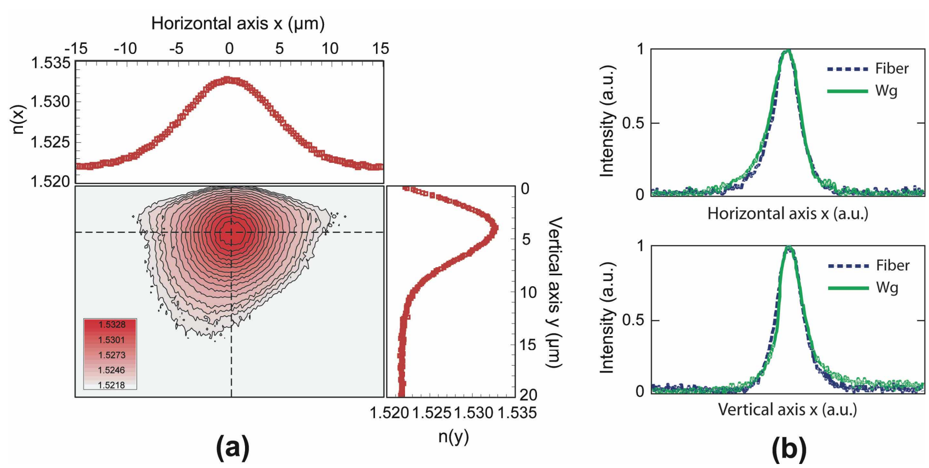

Fig. 1. (a). Typical waveguide refractive index profiles. (b) Typical near-field mode profiles of the waveguide compared to near-field mode profiles of standard SMF-28 fiber at 1550 nm.

Figure 1(a) shows typical refractive index profiles of the waveguides fabricated by this double-step process, measured according to standard refracted-near-field technique by means of a commercial refractive index profilometer (Rinck Elektronik). A maximum refractive index change of 0.0112 was measured and the waveguide resulted to be about 4 µm buried in

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the glass substrate. The waveguides exhibited a single transverse mode at 1550 nm, and by using an infrared camera the mode-field profiles were recorded and compared to mode-field profiles of SMF-28 telecom fiber [see Fig. 1(b)]. We obtained a quite circularly symmetric waveguide mode, resulting to be fully compatible with standard SMF-28 telecom fiber, which is an essential requirement to minimize laser intracavity losses, especially in an ultra-short active medium. From the overlap between waveguide and fiber near-field profiles we estimated coupling losses to standard single-mode fiber as low as 0.2 dB/facet. Overall insertion losses (namely coupling losses plus propagation losses) of the 9 mm long waveguide were measured to be about 0.8 dB.

2.2 Laser cavity setup

Figure 2 shows the laser cavity set-up based on the 9-mm long active waveguide. Two fiber-Bragg-gratings (FBGs) were butt-coupled to the waveguide by using a suitable index matching fluid (allowing high pump intensity). The high-reflectivity (HR) FBG has a 99.8% reflectivity centered at 1533.5 nm with 125-GHz bandwidth (FWHM). To enhance erbium inversion along the 9-mm long waveguide we adopted a laser diode emitting at 976 nm, thus matching the Yb absorption peak and maximizing pump absorption over such a short length. The diode provides a maximum incident pump power of 250 mW. Note that the employment of an ultra-compact active waveguide allows a linear laser cavity as short as few cm, resulting in a free-spectral-range as large as few GHz.

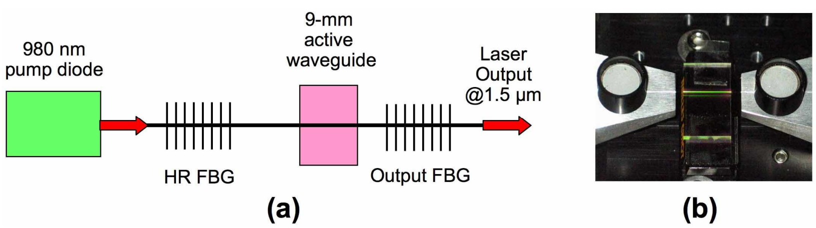

Fig. 2. (a). Schematic of waveguide laser set-up. (b) Picture of the 9-mm waveguide laser.

3. Single-mode laser experiment

To evaluate the optimum output coupling we performed a first set of laser experiments employing several FBGs of different reflectivity as output couplers.

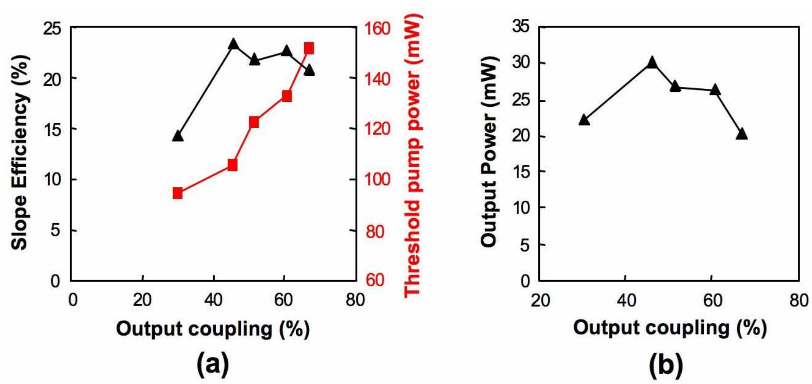

Fig. 3. (a). Slope efficiency (triangles) and pump power threshold (squares) vs. output coupling. (b) Maximum output power vs. output coupling.

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Figure 3 shows the slope efficiency, pump power threshold and output power for five FBG output couplers with peak reflectivity centered at 1533.5 nm and 30 GHz bandwidth (FWHM).

During the test the cavity length was of the order of 1 m and the laser was therefore not operating in single-mode. However the laser bandwidth was of few GHz only, as defined by FBG reflection bandwidth, and only few modes were oscillating within a bandwidth of about 1.5 GHz. From Fig. 3 the FBG with 46% output coupling is found to provide the best laser performance. However to ensure single-mode operation we preferred the 52% output-coupling FBG, because of a narrower bandwidth, of about 80 pm (10 GHz) against 100 pm (12.5 GHz) of the 46% output-coupler. After selection of the proper output coupler the cavity was shortened by cutting FBG fiber. We estimated an overall cavity length of about 55 mm. The active waveguide was also displaced from the center of the cavity in order to reduce spatial hole burning effect and thus longitudinal mode competition.

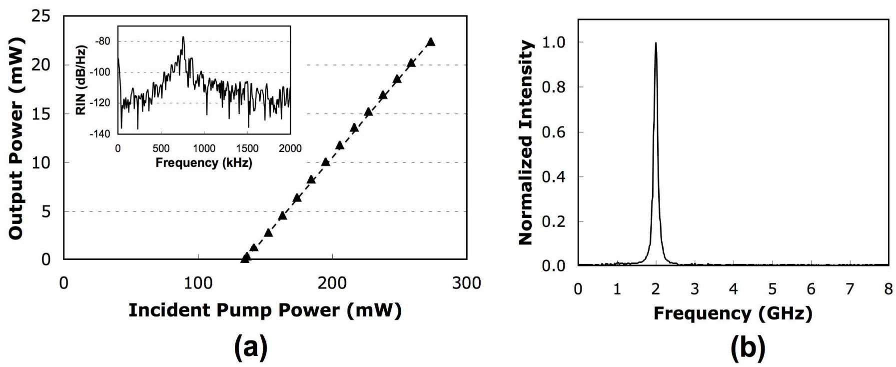

Fig. 4. (a). Single mode laser output power as a function of pump power. Inset shows RIN spectrum at 22 mW output power. (b). Fabry-Perot spectrum of the single mode laser. The frequency offset shows drift without mode-hopping.

Figure 4(a) shows the output power characteristic of the 55 mm long laser cavity. The pump power threshold was 135 mW and we measured a maximum output power of 22 mW with 17% slope efficiency with respect to the incident pump power. We noticed a remarkably stable single-mode operation at all pump power levels, even in the absence of thermal stabilization. Figure 4(b) shows the laser spectrum recorded by means of a high-finesse Fabry-Perot interferometer (Burleigh Mod. SA201), ascertaining single mode operation (the interferometer has a fixed free spectral range of 8 GHz, a finesse of 100, and the signal to noise ratio on the photodiode was about 26 dB). Inset in Fig. 4(a) shows the relative intensity noise (RIN) spectrum of the laser when operating at maximum output power. The relatively high peak value is due to the structure of the cavity, still discrete in nature because of the butt-coupling between the waveguide and FBG fibers. We believe that a RIN peak reduction is achievable once FBG fibers are bonded to the waveguide, thus providing a monolithic waveguide structure. Note also that, in view of the high doping level of the glass substrate, no saturation behavior of the laser output power was observed, as ascertained by the fairly linear input-output characteristic of Fig. 4(a). Therefore, the maximum output power of 22 mW was only limited by the pump power available.

This result represents, to our knowledge, the best performance in robust single-mode operation and single-pump scheme for a fiber-coupled waveguide laser. Actually, Ref. [13] reported on a single-end pumped single-mode DBR waveguide laser (though showing mode-hopping behaviour) able to provide 80 mW output power with 500 mW incident pump power and 19% slope efficiency. But the better performance is ascribable to a larger mode field area, being the mode field supported by the active waveguide quite larger than the mode of standard telecom fiber. The modal mismatch results in a significant (at least 3dB) reduction of the

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output power available in fiber and also prevent from the simple butt-coupling configuration for pumping (microscope objectives are used to efficiently couple pump light into the cavity).

4. Power scaling towards single-mode high power waveguide lasers

On the base of previous results, we evaluated the feasibility of power scaling towards 100 mW output power level, which can be reasonably assumed as a benchmark for high-power waveguide lasers. To this purpose, it's worth to introduce a figure of merit, FOM, defined as the maximum output power divided by the waveguide length. Note that FOM allows to evaluate how much laser power is reasonable to be expected from a given active waveguide length. For the 9 mm waveguide we calculated a FOM of 24.4 mW/cm, thus a 40 mm long active waveguide is expected to provide about 100 mW laser output power.

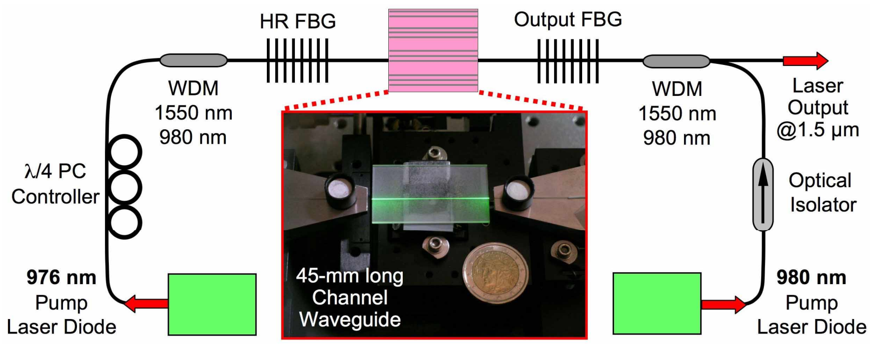

Fig. 5. Laser cavity setup for high power waveguide laser experiments. PC: polarization controller. Picture shows a 45 mm long active waveguide butt-coupled to FBG fibers under double-end pumping.

From the single mode experiment we also found that a linear cavity as short as 60-mm with an output coupler providing 80-pm reflectivity bandwidth is able to ensure stable single-mode operation. This means that a 40-mm to 50-mm long waveguide could be suitable for high-power single-mode operation.

To address this aim, we first tested the feasibility of high-power lasers based on active waveguides fabricated in a 50 mm long IOG-1 substrate under the same ion-exchange parameters as reported above. The refractive index profiles as well as the near-field mode profiles resulted to be almost the same as the ones reported in section 2. After polishing of the end facets the waveguide length was 45 mm.

Considering the quasi-three level nature of Er systems, a lower doping concentration of erbium is required, for a given pump power, to achieve high average inversion in this much longer waveguide [16]. According to preliminary numerical simulations (based on a rate-equation model similar to the one reported in [17]), we selected, among commercially available concentrations, an erbium doping level of 1.88×10^{20} ions/cm^3. Considering the available pump power we also adopted a double-end pumping scheme with a second pump diode at 980 nm because the pump diode at 976 nm was already significantly absorbed after about half of the waveguide. To avoid feedback and interplays between the two pumps we used a polarization controller and a pump isolator. The test laser cavity set-up is shown in Fig. 5. The cavity was as long as 1 m and the total maximum available pump power was 500 mW. Fig. 5 also shows a picture of the 45-mm long waveguide under double-end pumping. Note that the green light emission (due to fluorescence from erbium energy levels populated by up-conversion processes) is almost uniform along the waveguide, indicating that a high inversion of Er is achieved all along the waveguide.

Before starting laser experiments we measured the small-signal gain and the insertion loss of the 45-mm long waveguide. Results are reported in the inset of Fig. 6(a), showing a peak

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internal gain of 19 dB at 1534 nm, and insertion loss as low as 2.4 dB, resulting in a peak net gain exceeding 16 dB. This ascertains the high optical quality and efficiency of the 45-mm long ion-exchanged waveguide amplifier and suggests feasibility of high power waveguide lasers by exploiting this longer active medium and a laser cavity with high output coupling. For the laser experiment we tested several output couplers and the best result was obtained with the lowest reflectivity available, indicating the possibility of even better performance providing higher output coupling. In Fig. 6(b) the output power versus pump power is reported for three different output couplers. With the 21.5% reflectivity FBG we obtained 164 mW fiber-coupled output power with 500 mW incident pump power. The slope efficiency (with respect to the incident pump power) was 46% and represents, to our knowledge, the highest value so far reported in erbium-ytterbium doped ion-exchanged waveguide lasers. Note that FOM = 36.4 mW/cm, but usually at least two main longitudinal modes were oscillating (on the same transverse mode), therefore this result refers to multi-longitudinal mode operation.

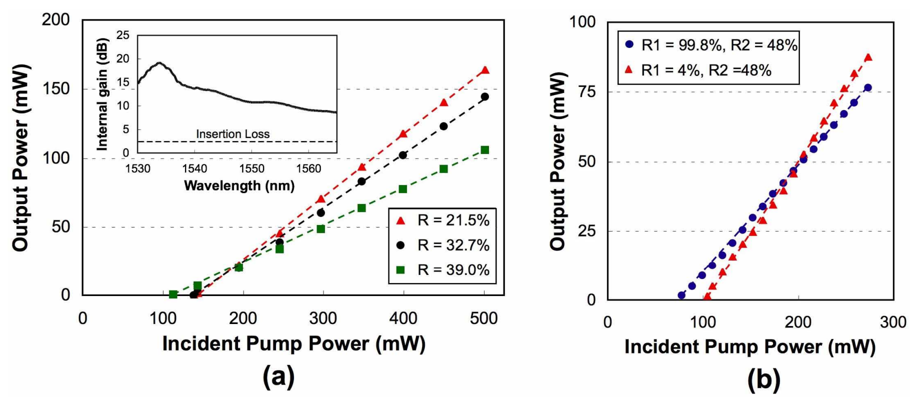

Fig. 6. (a). Laser output power (in multimode operation) vs. pump power (double-end pumping) for the 45-mm long active waveguide for three different output couplers. Inset shows the small-signal internal gain and insertion losses of the 45-mm long active waveguide under 500 mW total incident pump power (double-end pumping scheme). (b) Laser characteristics of the 60 mm long laser cavity based on a 50-mm long active waveguide specially designed to allow efficient single-end pumping at 980 nm.

We also tested a 50-mm long active waveguide manufactured by Teem Photonics by ion exchange technique using a proprietary phosphate glass with Er and Yb concentrations of 1.78×10^{20} ions/cm^3 and 3.45×10^{20} ions/cm^3 respectively. The waveguide was specially designed and fabricated to allow efficient single-end pumping at 980 nm pump wavelength. The efficiency of single-end pumping was ascertained by a preliminary test, in which the laser cavity was obtained by means of a 48% reflectivity FBG butt-coupled to the waveguide and by exploiting glass-air Fresnel reflection (R ~ 4%) at the other end of the waveguide. Pump laser threshold was as low as 100 mW and we estimated a maximum overall output power of about 90 mW [see Fig. 6(b), red triangles]. Even if output-coupling is beyond optimum value and most of the laser output power is actually not fiber-coupled, this cavity configuration demonstrates that the waveguide is very promising for the development of high power waveguide lasers and is able to sustain very high cavity losses. A more realistic laser cavity was obtained by using a flat-top (1 nm bandwidth) 99.8% reflectivity FBG to replace glass-air 4% Fresnel reflection (an index matching fluid was also applied). By exploiting the narrow bandwidth (80 pm FWHM) of the 48% reflectivity FBG output coupler and a compact cavity as short as 10 cm we obtained about 80 mW output power and 40% slope efficiency in almost single-mode operation, with one longitudinal and transverse mode oscillating and carrying over 85% of the total power [see Fig. 6(b), blue circles]. Residual power was carried by an adjacent longitudinal mode (approximately 1 GHz apart from the dominating one). Note that

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in this test experiment FOM is 18 mW/cm, namely only half of the FOM exhibited by the 45-mm long active waveguide fabricated in IOG-1. Anyway, single-end pumping still with high slope efficiency, low laser threshold and modal behavior with almost 85% of output power within a single mode contribute to a better overall laser performance of the 50-mm long waveguide. Note also that optimum output coupling is expected to be higher than 52%, so higher output power is attainable, as well as a more stable single-mode operation by shortening the laser cavity. In fact, as compared to the 9-mm long active waveguide, resulting in a 55-mm long single-mode laser cavity, the 50-mm long active waveguide by Teem Photonics results in an increased cavity length, with subsequent reduction of the cavity free spectral range with respect to the reflectors bandwidth which in turn results in spatial hole burning effects. By cutting the FBG fiber very close to the end of the FBG structure (whose position can be determined by standard optical low coherence measurements) a laser cavity as short as 6 cm is obtainable, thus resulting in a free spectral range which is expected to provide stable single mode operation with 80 pm FBG bandwidth.

5. Conclusion

We reported on a stable single-mode ion-exchanged waveguide laser providing more than 20 mW output power at 1533.5 nm under single-end diode pumping. The laser is based on an ultra-compact high gain Er-Yb-doped waveguide efficiently mode-matched to standard single mode telecom fibers. The waveguide was fabricated in a commercial (Schott IOG-1) phosphate glass by using an optimized double-step Ag-Na ion-exchange process. By exploiting the same fabrication technique we also demonstrated a high power multi-mode waveguide laser providing more than 160 mW output power and 46% slope efficiency, which represents to our knowledge the best power performance so far reported by Er-Yb-doped ion-exchanged waveguide lasers. We also evaluated the feasibility of single-mode power scaling to 100 mW output power by employing a state of the art ion-exchanged waveguide (by Teem Photonics) also fabricated in a phosphate glass. By using a 10-cm long linear laser cavity and this optimized waveguide we obtained 80 mW output power in quite single-mode operation with over 85% of the power carried by the main lasing mode under 260 mW incident pump power.

This preliminary result suggests that ion-exchange technique is a really promising solution to achieve 100-mW output power in single-mode operation out of a waveguide laser by exploiting the high erbium solubility in phosphate glass substrates.

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