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Silver film ion-exchanged Er-doped waveguide lasers and photowritten waveguide gratings in phosphate glass

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ABSTRACT

We report on an experimental study of waveguide lasers in Er/Yb-codoped phosphate glass. The waveguides serving as laser cavities were fabricated by electric field assisted silver-film ion exchange technology. Threshold power, slope efficiency, and output power were measured from these lasers and compared to previously reported data. We also report on waveguide DBR-lasers using photowritten gratings in a hybrid glass.

Keywords: waveguide lasers, ion exchange, UV-writing, waveguide gratings, phosphate glass

1. INTRODUCTION

Phosphate glass is an excellent host for compact channel waveguide lasers due to the high amount of rare earth ions that can be incorporated into it without significant gain reduction due to the upconversion processes. High gain, typically 3-4 dB/cm, can be obtained in short cavity lengths. They also contain alkali ions that enable easy-of-fabrication of planar waveguides by ion exchange techniques. In ion exchange, the alkali ions of the glass are replaced with ions of larger size and/or higher polarizability. These ions produce a local refractive index change which can be used to form optical waveguides. Ion exchange processes can be performed either using molten salts or thin metal (mainly silver) films. In contrast to conventional molten salt ion exchange processes silver film ion exchange process is a dry process, causing no damage to the phosphate glass.

Solid state lasers provide several advantages over the widely used semiconductor lasers. They have large optical bandwidth and high energy storage capacity, important features in mode locking and ultrashort pulse generation.[1, 2] Large optical bandwidth also enables broad wavelength tunability required in many sensor and telecommunications applications. For example, erbium-doped waveguide and fiber lasers can operate on the whole C-band. Compared to their semiconductor counterparts, solid state lasers provide narrower laser linewidths, lower relative intensity noise, higher output powers, and good modematching with optical fibers.

Only recently, phosphate glasses were found to be photosensitive for ultraviolet irradiation similarly to Ge-doped silicate glasses.[3, 4] This provides further possibilities in developement of narrow linewidth, single-frequency distributed Bragg reflector (DBR) and distributed feedback (DFB) lasers, and in dispersion management.

In this paper, we report on results from short cavity Er/Yb-codoped waveguide lasers fabricated by silver-film ion exchange. In addition, we demonstrate permanent photowritten gratings in channel waveguides made from phosphate glass. We also report on waveguide DBR-lasers using photowritten gratings in a hybrid glass.

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2. FABRICATION

2.1. Er/Yb-codoped short cavity lasers

In silver-film ion exchange process, we first introduce silver ions in glass just beneath the surface, where they replace sodium ions and locally increase the refractive index, thus forming a waveguide. The silver ions are released from a thin film deposited on the glass surface and are driven into glass with an electric field. The process can be performed at a relatively low temperature and photoresist can be used as a diffusion mask. The use of photoresist as a mask makes the channel waveguide patterning very simple and accurate. The second step in waveguide fabrication is a thermal annealing which redistributes the silver ions to modify the waveguide index profile.

The active waveguides are fabricated in commercially available Schott IOG-1 phosphate glass, which is doped with high concentrations of erbium and ytterbium. Three different Er- and Yb-ion doping levels were studied here and they are listed in Table 1. For single-mode channel waveguides in IOG-1 glass the mask aperture widths range from 2 μm to 5 μm and the ion exchange is done at 90°C for 2 hours with a voltage of 200 V. After removing the remaining silver film and resist the glass substrate is annealed at 230°C for about 1 h 30 min. The background propagation loss of our waveguides is ~ 0.15 dB/cm.

After waveguide fabrication, Er/Yb- codoped waveguides were diced and end-polished into 1-cm long cavities.

2.2. Single frequency DBR waveguide laser with photowritten grating

The gratings are written prior to fabricating the waveguides. This way, the large absorption induced during the ion exchange by the silver particles is avoided and the grating planes extend deep below the surface of the sample.[4] The gratings were written through a phase mask into the substrate glass using a pulsed ArF excimer laser emitting at 193 nm 100 pps with an estimated energy density of 140 mJ/cm^2. Bulk gratings exposed in this way are strong enough to survive the thermal processes involved in waveguide fabrication. The reflectivity of about 80% is achieved with 7 mm long waveguide grating, which is suitable for DBR lasers. It is important to note that these gratings are fabricated in a passive, i.e. an un-doped, IOG-1 glass and are not directly suitable for DBR lasers. However, we also make these gratings in the passive section of a hybrid IOG-1 glass. In a hybrid glass, active and passive sections are monolithically integrated in a single s! ubstrate.

After grating inscription, the waveguides are fabricated by ion exchange as described above. The sample was diced and end-polished in such a way that the active section of the hybrid glass was 24 mm long. The rare earth doping concentrations in the active part of the sample are 1.0×10^{20} for erbium and 6.0×10^{20} ions/cm^3 for ytterbium.

3. EXPERIMENTS

The short cavity laser operation was tested by constructing a cavity using a Corning SMF28 fiber coated with a broadband SiO_2/TiO_2 dielectric mirror stack at one cavity end and a flat SiO_2/TiO_2 dielectric mirror grown on silica substrate at the other end. The setup for measuring the spectral characteristics and the slope efficiency is presented in Fig. 1. The coated fiber mirror has a reflectivity close to 93 % in the 1550 nm wavelength region and 0 % at the pump (980 nm) wavelength. The pump power was delivered through this fiber. The output power was measured using the same fiber and a 980/1550 wavelength division multiplexer (WDM). The other mirror has a reflectivity of 99 % at 1550 nm wavelength region. A fiber pig-tailed single-mode semiconductor diode laser emitting at 980 nm was used as a pump laser. The threshold power, the slope efficiency, and the output power were measured by a fiber coupled power meter while the mode spectr! um was detected with an optical spectrum analyzer (OSA).

The laser characteristics of the single frequency DBR laser realized in the hybrid glass sample were also measured with the coated pump fiber as one cavity mirror (reflectivity $\sim 100\%$ at 1550 nm) on the active glass side of the sample but with a photowritten grating in the passive glass section to act as the other cavity mirror and output coupler.

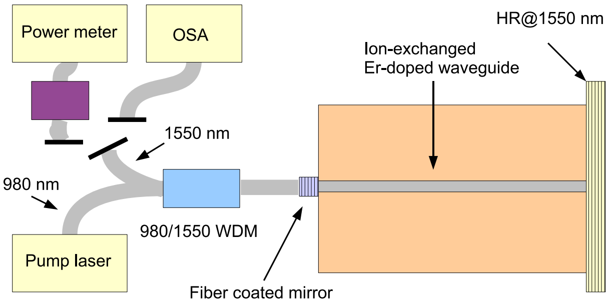

Figure 1. A set-up for measuring waveguide laser slope efficiency and output spectrum. OSA = Optical Spectrum Analyzer, WDM = Wavelength Division Multiplexer

4. RESULTS

For the short cavity laser shown in Figure 1, the threshold pump power, the slope efficiency, and the maximum output power for samples containing different amounts of erbium and ytterbium are presented in Table 1. The maximum output power, 18 mW with a pump power of 182 mW, was extracted from a sample containing the most of erbium and the least of ytterbium. Also the threshold pump laser power was the lowest and the slope efficiency was the highest for this sample. The slope efficiency and the maximum output power were almost the same for the two heavily ytterbium-doped samples. No dependence on the mask opening width in the output power, the threshold, or the slope efficiency was observed. Samples containing very high concentrations of ytterbium ($> 8 \times 10^{20}$ ions/cm^3) did not show lasing at all since the pump power was depleted in a length considerably shorter than the cavity length.

Table 1. Threshold power, slope efficiency and output power at different erbium and ytterbium concentrations.

Sample	$C_{Er^{3+}}$ [ions/cm^3]	$C_{Yb^{3+}}$ [ions/cm^3]	Threshold [mW]	Slope efficiency [%]	P_{out} [mW]
M4	1.5×10^{20}	4.0×10^{20}	130	11	18
M5	1.0×10^{20}	6.0×10^{20}	154	8	13
M6	1.25×10^{20}	6.0×10^{20}	170	8	11

We were also able to observe lasing action in the DBR hybrid glass cavity with photowritten grating as an output coupler. The output spectrum is shown in Fig. 2, where the bandwidth of the laser is not fully resolved by the Optical Spectrum Analyzer and the output wavelength is determined by the peak reflectivity of the photowritten Bragg grating. We are in the process of optimizing the laser cavity with photowritten gratings and of fully characterizing the laser parameters including the threshold power, the slope efficiency, the maximum output power, the linewidth, and the relative intensity noise.

5. DISCUSSIONS AND CONCLUSIONS

The output power of 18 mW with a pump laser power of 182 mW was achieved from a multimode Er/Yb-codoped waveguide laser with only a 1-cm long laser cavity. In potassium-sodium ion-exchanged waveguide lasers output powers as high as 170 mW using a tunable Ti:sapphire laser as a pump laser (pump power ∼610 mW) and an output coupling of 20% has been reported.[5] Potassium-sodium ion-exchanged waveguides have smaller refractive index difference and therefore they are singlemode with wider mask opening widths, which on the other hand results in bigger mode volumes, and furthermore, higher output powers. However, our lower measured output power values with smaller mode areas are high enough for modelocking applications. In modelocking by saturable absorbers, it is the internal intensity that is crucial. Also, the cavity length and the laser output coupling were

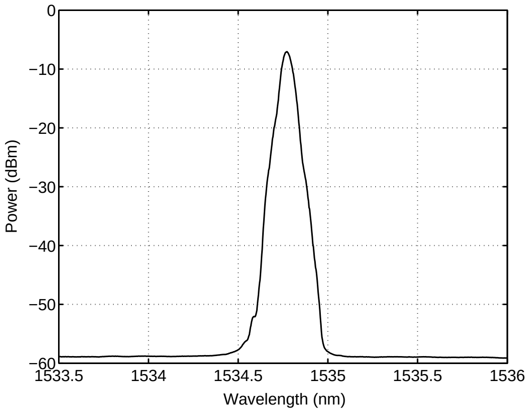

Figure 2. The output spectrum of the singlemode waveguide laser utilizing a photowritten Bragg grating as the other cavity mirror. The wavelength resolution of the OSA is 0.07 nm.

not optimized in our experiments. It is noteworthy to mention that our output coupling was three times smaller than the one in Ref. 5.

There is one benefit in silver-sodium ion-exchanged waveguides over the potassium-sodium ion-exchanged waveguides: the refractive index difference is higher and therefore the effective index variation in waveguides with different width is higher resulting in a wider wavelength tunability in waveguide laser arrays used in WDM applications. Blaize et al.[6] reported 10-nm wavelength range in their laser array. This result shows a significant improvement in wavelength tunability over the 1.4-nm wavelength tunability obtained in potassium-sodium waveguides.

Finally, the wavelength selective Bragg gratings have been typically etched into glass by Ar-ion milling.[6–8] Here, we demonstrated a single mode operation of an Er/Yb-codoped DBR laser in a hybrid substrate utilizing an UV-written Bragg grating. Because of their easy-of-fabrication, photowritten Bragg gratings in ion-exchanged channel waveguides in phosphate glass provide multitude of possibilities in phosphate glass integrated optics, including the development of compact, cost-effective arrayed DFB lasers, add/drop multiplexers, and in the field of supercontinuum generation and dispersion management, just to mention a few.

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REFERENCES

1. U. Keller, "Recent developments in compact ultrafast laser," *Nature* **424**, pp. 831–838, 2003.
2. T. Udem, R. Holzwarth, and T. W. Hänsch, "Optical frequency metrology," *Nature* **416**, pp. 233–237, 2002.
3. S. Pissadakis, A. Ikiades, P. Hua, A. K. Sheridan, and J. Wilkinson, "Photosensitivity of ion-exchanged Er-doped phosphate glass using 248nm excimer laser radiation," *Opt. Ex.* **12**, pp. 3131–3136, 2004.
4. J. Albert, S. Yliniemi, S. Honkanen, A. Andreyuk, and A. Steele, "UV-written Bragg gratings in silver ion-exchanged phosphate glass channel waveguides," in *Proceedings of the 2005 Topical Meeting on Bragg Gratings, Photosensitivity and Poling*, B. Eggleton, ed., *Sydney, Australia*, pp. 402–404, 2005.
5. D. L. Veasey, D. S. Funk, P. M. Peters, N. A. Sanford, G. E. Obarski, N. Fontaine, M. Young, A. P. Peskin, W.-C. L. S. N. Houde-Walter, and J. S. Hayden, "Yb/Er-codoped and Yb-doped waveguide lasers in phosphate glass," *J. Non-Cryst. Solids* **263&264**, pp. 369–381, 2000.

6. S. Blaize, L. Bastard, C. Cassagnètes, and J. E. Broquin, "Multiwavelengths DFB waveguide laser arrays in Yb-Er codoped phosphate glass substrate," *IEEE Photon. Tecnhnol. Lett.* **15**, pp. 516–518, 2003.
7. D. L. Veasey, D. S. Funk, N. A. Sanford, and J. S. Hayden, "Arrays of distributed-Bragg-reflector waveguide lasers at 1536 nm in Yb/Er codoped phosphate glass," *Appl. Phys. Lett.* **74**, pp. 789–791, 1999.
8. P. Madasamy, G. N. Conti, P. Pöyhönen, M. M. Morrell, D. F. Geraghty, S. Honkanen, and N. Peyghambarian, "Waveguide distributed Bragg reflector laser arrays in erbium doped glass made by dry Ag film ion exchange," *Opt. Eng.* **41**, pp. 1084–1086, 2002.