S. Yliniemi, J. Albert, Q. Wang, and S. Honkanen, UV-exposed Bragg gratings for laser applications in silver-sodium ion-exchanged phosphate glass waveguides, Optics Express 14, 2898-2903 (2006).

UV-exposed Bragg gratings for laser applications in silver-sodium ion-exchanged phosphate glass waveguides

Sanna Yliniemi
Helsinki University of Technology, Optoelectronics laboratory
Tietotie 3, P.O. Box 3500, Espoo, FIN-02150 HUT, Finland
syliniem@cc.hut.fi

Jacques Albert
Carleton University, Department of Electronics
1125 Colonel By Drive, Ottawa, Ontario, Canada K1S 5B6

Qing Wang and Seppo Honkanen
University of Arizona, College of Optical Sciences
Meinel Building, 1630 East University Boulevard, Tucson, Arizona 85721, USA

Abstract: High reflectivity Bragg gratings have been written by ArF excimer laser through a phase mask into Schott IOG-1 hybrid phosphate glass. After grating exposure, a waveguide was fabricated by silver-sodium ion-exchange. Reflectivities around 80 % at a wavelength of $\sim$ 1535 nm were measured from the waveguide for both quasi-TE and -TM polarizations. Waveguide laser operation with the photowritten waveguide grating as another mirror was demonstrated. Output power of 3.8 mW with a pump power of 199 mW could be extracted from the laser configuration.

OCIS codes: (130.0130) Integrated optics, (230.7380) Waveguides, channelled, (230.1480) Bragg reflectors, (140.3500) Lasers, erbium

---

References and links

1. D. L. Veasey, D. S. Funk, N. A. Sanford, J. S. Hayden, "Arrays of distributed-Bragg-reflector waveguide lasers at 1536 nm in Yb/Er codoped phosphate glass," Appl. Phys. Lett. **74,** 789–791 (1999).
2. S. Blaize, L. Bastard, C. Cassagnètes, J. E. Broquin, "Multiwavelengths DFB waveguide laser arrays in Yb-Er codoped phosphate glass substrate," IEEE Photon. Tecnhnol. Lett. **15,** 516–518 (2003).
3. P. Madasamy, G. Nunzi Conti, P. Pöyhönen, M. M. Morrell, D. F. Geraghty, S. Honkanen, N. Peyghambarian, "Waveguide distributed Bragg reflector laser arrays in erbium doped glass made by dry Ag film ion exchange," Opt. Eng. **41,** 1084–1086 (2002).
4. T. Ohtsuki, S. Honkanen, S. I. Najafi, N. Peyghambarian, "Cooperative upconversion effects on the performance of Er^{3+}-doped phosphate glass waveguide amplifiers," J. Opt. Soc. Am. B **14,** 1838–1845 (1997).
5. Y. C. Yan, A. J. Faber, H. de Waal, P. G. Kik, A. Polman, "Erbium-doped phosphate glass waveguide on silicon with 4.1 dB/cm gain at 1.535 μm," Appl. Phys. Lett. **71,** 2922-2924 (1997).
6. F. D. Patel, S. DiCarolis, P. Lum, S. Venkatesh, J. N. Miller, "A compact high-performance optical waveguide amplifier," IEEE Photon. Technol. Lett. **16,** 2607–2609 (2004).
7. B.-C. Hwang, S. Jiang, T. Luo, J. Watson, G. Sorbello, N. Peyghambarian, "Cooperative upconversion and energy transfer of new hig Er^{3+}- and Yb^{3+}–Er^{3+}-doped phosphate glasses," J. Opt. Soc. Am. B **17,** 833–839 (2000).
8. J.-L. Archambault, S. G. Grubb, "Fiber gratings in lasers and amplifiers," J. Lightwave Technol. **15,** 1378–1390 (1997).

#10310 - $15.00 USD
Received 13 January 2006; revised 29 March 2006; accepted 29 March 2006

9. B. Malo, J. Albert, F. Bilodeau, T. Kitagawa, D. C. Johnson, K. O. Hill, K. Hattori, Y. Hibino, S. Gujrathi, "Photosensitivity in phosphorus-doped silica glass and optical waveguides," Appl. Phys. Lett. **65,** 394–396 (1994).
10. S. Pissadakis, A. Ikiades, P. Hua, A. K. Sheridan, J. Wilkinson, "Photosensitivity of ion-exchanged Er-doped phosphate glass using 248nm excimer laser radiation," Opt. Express **12,** 3131–3136 (2004).
11. J. Albert, S. Yliniemi, S. Honkanen, A. Andreyuk, 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, 2005) 402–404 (2005).
12. S. D. Gonzone, J. S. Hayden, D. S. Funk, A. Roshko, D. L. Veasey, "Hybrid glass substrates for waveguide device manufacture," Opt. Lett. **26,** 509–511 (2001).
13. P. Madasamy, S. Honkanen, D. F. Geraghty, N. Peyghambarian, "Single-mode tapered waveguide laser in Er-doped glass with multimode-diode pumping," Appl. Phys. Lett. **82,** 1332–1334 (2003).
14. P. Pöyhönen, S. Honkanen, A. Tervonen, M. Tahkokorpi, "Planar 1/8 splitter in glass by photoresist masked silver film ion exchange," Electron. Lett. **27,** 1319–1320 (1991).
15. D. L. Veasey, D. S. Funk, P. M. Peters, N. A. Sanford, G. E. Obarski, N. Fontaine, M. Young, A. P. Peskin, W.-C. Liu, S. N. Houde-Walter, J. S. Hayden, "Yb/Er-codoped and Yb-doped waveguide lasers in phosphate glass," J. Non-Cryst. Solids **263&264,** 369–381 (2000).

---

1. Introduction

Ion-exchanged erbium doped glass waveguide lasers have been studied extensively due to their potential applications in the field of sensors and in telecommunications [1, 2, 3]. Phosphate glass has been the preferred host material because of its high solubility of rare-earth ions, which allows for doping high concentrations without significant lifetime reduction [4]. This in turn, results in high gain in short waveguides [2, 5, 6], and potential for short cavities, a desirable feature in single-frequency lasers. Pump absorption is usually increased by co-doping the glass with ytterbium, and in phosphate glass, the energy transfer efficiency from ytterbium to erbium can be close to 100% [7]. In previous demonstrations, the Bragg gratings required for the optical feedback have been etched in the glass waveguide surface by Ar ion-milling [1, 2, 3].

It would be beneficial, if the Bragg gratings for the waveguide lasers could be formed by using UV-irradiation through a phase mask, as is common in fiber optics [8]. Photosensitivity of phosphorus-doped silicate-glass was reported by Malo et al. [9] already in 1994. However, phosphorus-doped silicate glass is very different from phosphate glass, and it was only recently that photoinduced index changes in slab waveguides made by silver ion exchange in Er-doped IOG-1 phosphate glass were demonstrated by irradiation with KrF laser light [10]. The estimated refractive index modulation was $\sim 2 \times 10^{-3}$ over a depth of 3μm. It was reported that the index change obtained was 2 orders of magnitude larger in the ion-exchanged region than in the substrate glass alone. This was tentatively attributed to photo-induced silver ion migration and photo-ionization of Ag^0 and Ag^+ species. Our own experiments with Schott IOG-1 glass have confirmed these observations. However, these gratings are too shallow to provide high enough reflectivity and the stability of the gratings is a concern as well. A shallow surface-like grating with index modulation amplitude below 0.01 would not provide enough optical feedback at the lasing wavelength (1535 nm), since the overlap between the grating and the guided mode is small. In addition, our experiments have revealed that it is rather difficult to fabricate efficient UV-written gratings in active (i.e. Er/Yb-codoped) IOG-1 glass.

In this paper, we present results on high quality UV-written Bragg gratings in passive Schott IOG-1 phosphate glass channel waveguides using a different approach than in Ref. [10]. We also report on a first demonstration of a distributed Bragg reflector (DBR) waveguide laser using a photowritten grating in a hybrid IOG-1 glass.

2. Fabrication

In contrast to previous work [10], we chose to expose the gratings into undoped substrate glass, i.e., with no rare earth ions in the glass (Schott IOG-1), prior to fabricating the waveguides [11].

#10310 - $15.00 USD Received 13 January 2006; revised 29 March 2006; accepted 29 March 2006

This way, the large absorption associated with the presence of silver particles is avoided. Furthermore, the gratings were written through a phase mask using a pulsed ArF excimer laser emitting at a wavelength of 193 nm instead of a pulsed KrF excimer laser emitting at longer wavelength of 248 nm due to the increased absorption at a wavelength of 193 nm in Schott IOG-1 glass. The phase mask used in our initial experiments had a periodicity of 1065 nm corresponding to the Bragg grating period of 533 nm in glass. The ArF excimer laser was emitting 100 pulses per second with a fluence of 300 $\mathrm{mJ/cm^2}$. These exposure conditions allow the formation of volume gratings strong enough to survive the thermal processes involved in waveguide fabrication. It is important to note that these gratings were fabricated in a passive, un-doped IOG-1 glass and they are not directly suitable for DBR-lasers. However, we also made 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 substrate [12, 13].

After grating exposure, the waveguides were fabricated by electric field assisted silver-film ion exchange [14]. First, the waveguides were patterned onto the glass by standard photolithography. Next, a thin silver film was sputtered on top of the sample. The electric field assisted ion exchange was performed at 90°C with a voltage of 200 V. The residual silver and the photoresist were removed in a NH_4OH/H_2O_2 wet etch. Then the sample was diced and the end facets were polished. Finally, the sample was annealed at 225°C for 90 min during which the silver ions diffused further into the glass and formed a waveguide.

After fabrication, the reflection and transmission spectra of the waveguide grating were measured, and the results are presented in Fig. 1. A narrowband reflection maximum occurs at 1608.63 nm. The grating reflectivity is 44 % for a grating length of 4 mm. This first result demonstrates the feasibility of our approach but the reflectivity is not high enough for laser applications. Thereafter, we wrote a 10 mm long grating using a phase mask with a periodicity matching with the gain peak of 1535 nm of Erbium doped phosphate glass. The grating fabrication procedure was the same as described above with the exception that the gratings were exposed through beam expanders that increase the spatial coherence of the laser irradiation. This resulted in a reduction of the fluence to 140 $\mathrm{mJ/cm^2}$. The waveguide fabrication procedure was as described above.

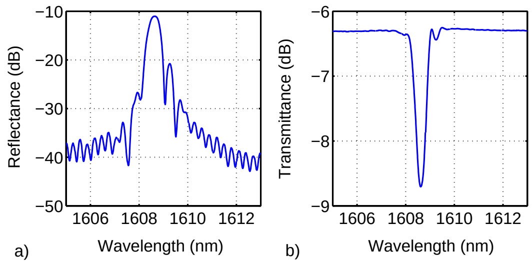

Fig. 1. (a) Reflection and (b) transmission spectrum of a photowritten grating in a silver-sodium ion-exchanged waveguide. The measurement was done with polarized light.

The second grating was fabricated into a passive section of a hybrid phosphate IOG-1 glass. In addition to a 20 mm long passive section, the fabricated hybrid glass waveguide sample contains a 19 mm long erbium-ytterbium doped active section with concentrations of 1.0×10^{20} for erbium and 6.0×10^{20} $\mathrm{ions/cm^3}$ for ytterbium. The active waveguide section provides the gain required in the laser operation, and the UV-written grating exposed into the passive waveguide section provides the optical feedback and the wavelength selection. It also serves as an output coupler for the DBR waveguide laser.

The grating strength for a hybrid sample was measured separately for quasi-TE and -TM po-

#10310 - $15.00 USD Received 13 January 2006; revised 29 March 2006; accepted 29 March 2006

larization modes in transmission geometry and the measured spectra are presented in Fig. **??**. At the Bragg wavelength the grating transmission is around 20 % for both polarizations, and the Bragg wavelength for the TE polarized mode is 1534.71 nm while for the TM-mode it is 1534.52 nm.

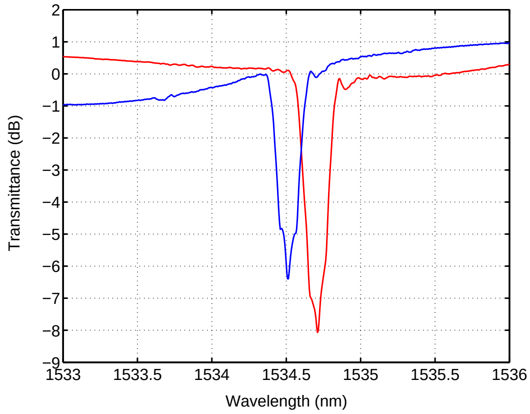

Fig. 2. Transmission spectra of the waveguide Bragg grating. Red line refers to the quasi-TE-polarization and blue line to the quasi-TM-polarization.

3. Results

The setup for measuring the laser characteristics is presented in Fig. **??**. The laser cavity was constructed by using a Corning SMF28 fiber coated with a broadband SiO_2/TiO_2 dielectric mirror stack with reflectivities close to 100 % at 1550 nm wavelength region and 0 % at a pump (980 nm) wavelength region. The pump power was delivered through this fiber too. The fiber-to-waveguide/waveguide-to-fiber coupling loss is estimated to be approximately 1 dB. The UV-written grating operated as the other, narrowband mirror with a reflectivity around 80 % at $\sim$ 1535 nm as well as an output coupler. The laser output spectrum and the slope efficiency were measured, respectively, by an optical spectrum analyzer (OSA) and by a fiber connected power meter. The OSA resolution is 0.07 nm. A standard single-mode fiber was butt coupled to the waveguide end facet at the passive section.

The measurement results for the slope efficiency and the spectrum are presented in Fig. **??**. The maximum output power is 3.8 mW with a coupled pump power of 199 mW, the slope efficiency being 6.1% with a threshold at 148 mW. The lasing occurred at a wavelength of 1534.71 nm in agreement with the measured Bragg wavelength for the quasi-TE mode. The maximum output power is relatively low compared with the previous experiments from similar kind of laser systems [1, 2, 3, 15]. There are three possible reasons that explain the laser inefficiency. First, the sample contained a very high concentration of ytterbium. In the relatively long active waveguide portion the high ytterbium concentration resulted in a rapid pump energy depletion along the gain material. This caused part of the active waveguide to remain underpumped and experience loss and the lasing threshold increased. Second, we performed the annealing process at lower temperature than usually, since we wanted to ensure that the grating survives the heat treatment. The purpose of annealing is to reduce the waveguide loss and to improve the mode overlap between the pump and the signal wavelengths, which increase the gain. Finally, it is possible that the mirror loss at the other cavity end is relatively high. According to our experience, the lasing and the output power are very sensitive to the alignment of the fiber mirror.

#10310 - $15.00 USD Received 13 January 2006; revised 29 March 2006; accepted 29 March 2006

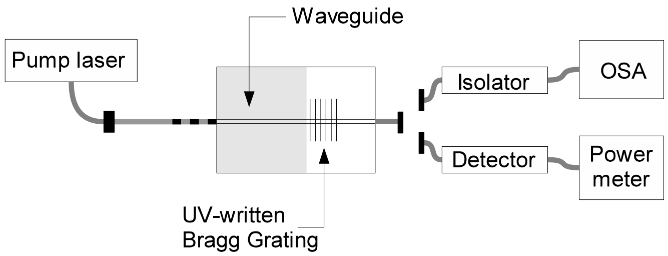

Fig. 3. Schematic of the set-up for measuring the slope efficiency and the laser spectrum. A fiber-pigtailed pump laser is connected to a fiber with a dielectric mirror on the output end, which is butt-coupled to a waveguide with a grating. The UV-written Bragg grating acts as the other cavity mirror as well as an output coupler. The laser output power is measured by a fiber-coupled detector and a power meter. The output spectrum is measured using an optical spectrum analyzer (OSA). The output fiber can be coupled either to the power meter or to the OSA. The black blocks in the figure represent fiber connectors.

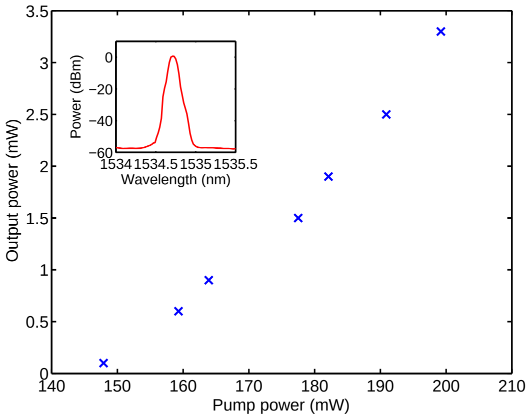

Fig. 4. The measured slope efficiency and the output spectrum of the waveguide laser.

4. Conclusions

We have demonstrated narrowband UV-written volume gratings in passive Schott IOG-1 phosphate glass. Grating reflectivities around 80 % were measured for both quasi-TE- and TM-polarizations after channel waveguide fabrication. The grating survived a long heat treatment at 225°C. Utilizing a hybrid glass we constructed a DBR laser using a photowritten grating as an output coupler. The maximum output power was 3.8 mW with a slope efficiency of 6.1 %. The lasing threshold was 148 mW. We believe that the pump efficiency can still be increased

Received 13 January 2006; revised 29 March 2006; accepted 29 March 2006

by shortening and by further annealing the sample. However, before proceeding to these experiments, more precise linewidth characteristic measurements will be performed.

Acknowledgments

Support from TRIF (State of Arizona Photonics Initiative) and from the University of Arizona is appreciated. Prof. J. Albert would like to acknowledge the financial support of the Canada Research Chairs Program. S. Yliniemi would also like to thank the Academy of Finland and Magnus Ehrnrooth's foundation for financial support. This work was performed while S. Yliniemi was with the College of Optical Sciences at the University of Arizona.