Erbium-doped phosphate glass waveguide on silicon with 4.1 dB/cm gain at 1.535 μm

Y. C. Yan,[a] A. J. Faber, and H. de Waal
TNO–Institute of Applied Physics, P.O. Box 595, 5600 AN Eindhoven, The Netherlands

P. G. Kik and A. Polman
FOM Institute for Atomic and Molecular Physics, Kruislaan 407, 1098 SJ Amsterdam, The Netherlands

(Received 28 July 1997; accepted for publication 17 September 1997)

Erbium-doped multicomponent phosphate glass waveguides were deposited by rf sputtering techniques. The Er concentration was 5.3×10^{20} cm^{-3}. By pumping the waveguide at 980 nm with a power of ~21 mW, a net optical gain of 4.1 dB at 1.535 μm was achieved. This high gain per unit length at low pump power could be achieved because the Er–Er cooperative upconversion interactions in this heavily Er-doped phosphate glass are very weak [the upconversion coefficient is $(2.0\pm0.5)\times10^{-18}$ cm^3/s], presumably due to the homogeneous distribution of Er in the glass and due to the high optical mode confinement in the waveguide which leads to high pump power density at low pump power. © *1997 American Institute of Physics.* [S0003-6951(97)02746-0]

Erbium-doped planar optical waveguide amplifiers, operating at the third telecommunication window near 1.5 μm,[1] are attractive due to their small size and potential integration as loss-compensating components with other optical devices, such as passive splitters[2] or combiners.[3] Ideally, these waveguide amplifiers should have high gain, small size, and require low pump power. Silica-based glasses have been shown to be good hosts for Er, and optical gain of up to 4.2 dB/cm has been shown in channel waveguide amplifiers based on these glasses.[4,5] However, rather high pump powers are required to reach net gain. This is due to the fact that at the high Er concentrations required to reach high gain per unit length, cooperative upconversion interactions between the closely spaced Er ions reduce the effective excited Er population for a given pump power.[6] In addition, the high pump powers required to overcome these interactions can cause excited state absorption effects that also reduce the pump efficiency. It is therefore important to develop new materials which show low upconversion, combined with a suitable waveguide technology.

In this letter we present measurements on a newly designed Er-doped phosphate glass that shows very low upconversion. In addition, due to its relatively high refractive index ($n=1.56$ at 632.8 nm), small waveguide dimensions with tightly confined modes can be made in this material, enabling efficient pumping. Indeed, a net optical gain at 1.535 μm of 4.1 dB/cm is reached at a pump power at 980 nm of only 21 mW, the highest gain per unit length at such a low pump power reported for an Er-doped planar amplifier.

Erbium-doped phosphate glass films were deposited by magnetron rf sputtering in O_2/Ar atmosphere onto a thermally oxidized silicon substrate.[7] An Er-doped phosphate glass disk, 10 cm in diameter and 6 mm in thickness, was prepared as a target. The matrix glass was a multicomponent phosphate glass, containing Er_2O_3, Al_2O_3, Na_2O, La_2O_3, and P_2O_5. Care was taken in the target preparation procedure to minimize the presence of water, as that can cause severe concentration quenching in these highly Er-doped glasses.[8] The deposition system had a base pressure of 10^{-7} mbar, and the working pressure was $\sim3\times10^{-2}$ mbar. The substrate was positioned 5 cm above the target. The rf sputtering power was kept below 100 W to prevent target cracking due to thermal stress. The highest sputtering rate was ~0.27 μm/h at the center of the substrate. The thickness of the sputtered layer was measured by a prism coupling method.

Figure 1 shows a Rutherford backscattering spectrometry spectrum taken using 2.0 MeV He at a scattering angle of 45°. The various components, including O, Na, Al, P, La, and Er, can be distinguished in the spectrum. As can be seen in Fig. 1, the composition is perfectly homogeneous throughout the thickness of the film, which was 575 nm for the particular case in Fig. 1. The Er concentration in the film was determined to be 5.3×10^{20} cm^{-3} (0.75 at. %). The particular glass composition used in this work followed from a detailed

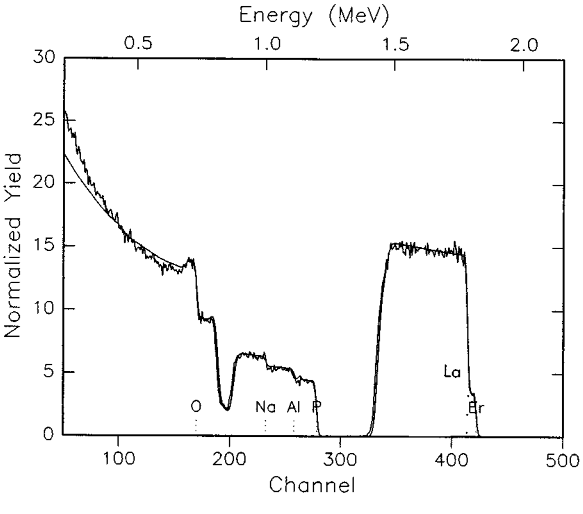

FIG. 1. Rutherford backscattering spectrometry spectrum of an Er-doped multicomponent phosphate glass film taken using 2.0 MeV He at a scattering angle of 45°. The surface channels for the various constituents are indicated in the spectrum, and the lines show the contributions of each element to the spectrum.

---

[a] Electronic mail: jyan@tpd.tno.nl

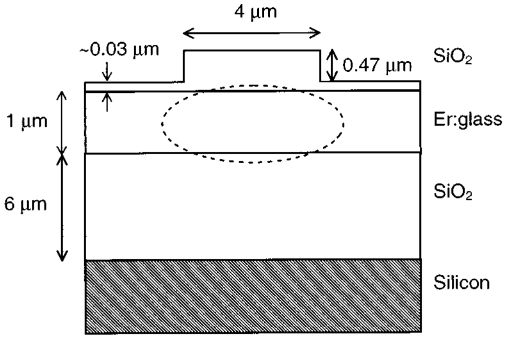

FIG. 2. Schematic cross section of the strip-loaded phosphate glass waveguide structure on silicon. The oxide buffer layer thickness is not to scale. The 1/*e* mode intensity contour is also plotted in the dashed line.

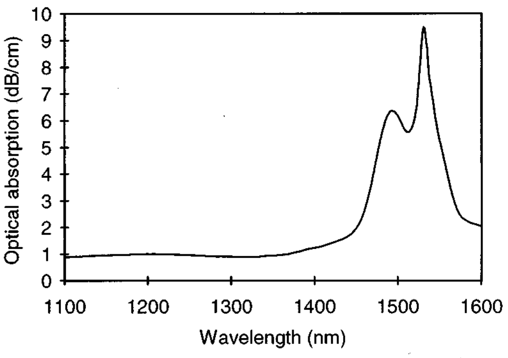

FIG. 3. Attenuation spectrum for an optimized Er-doped phosphate glass waveguide measured using a two-prism coupling technique. The background loss is 0.9 dB/cm, and the Er^{3+} absorption at 1.535 μm is 8.7 dB/cm.

optimization study in which the glass composition, Er concentrations, and deposition conditions were varied.[9] P_2O_5-based glasses are known to be good host materials for Er, enabling a homogeneous distribution without clustering of the Er.[1,10] Na_2O is added as a network modifier, Al_2O_3 to increase the chemical resistance, and La_2O_3 to increase the refractive index.

Strip-loaded waveguides were made by sputtering a SiO_2 film ($\sim$500 nm thick) onto a 1-μm-thick deposited Er-doped glass layer, and then etching the waveguide pattern into this SiO_2 layer using standard photolithography techniques. Photoresist ($\sim$1 μm thick) was used as the masking layer during etching. The etching was carried out in two steps: first a wet chemical process with a buffered HF etch was used to remove 400 nm of the SiO_2 layer and then a plasma dry etching process with CHF_3/O_2 further etched the remaining SiO_2 layer to a thickness of $\sim$30 nm. This remaining SiO_2 layer outside the 4-μm-wide waveguide strip protects the Er-doped glass layer through the whole fabrication process. As we have shown before,[9] this fabrication process had only a small effect on the Er luminescence properties of the films. A cross section of the strip-loaded waveguide structure and its dimensions are shown in Fig. 2. The 1/*e* mode intensity contour is also indicated, and shows that the mode is well confined within a cross section of roughly $1\times4\ \mu m^2$. The waveguide was 10 mm long. To enable fiber butt-end coupling, the samples were cleaved perpendicular to the waveguide. Finally, the completed waveguide was annealed in flowing pure oxygen at 510 °C for 2 h.

The photoluminescence spectrum of the completed waveguide structure showed a broad peak[9] centered around 1.535 μm due to the ${}^4I_{13/2}\rightarrow{}^4I_{15/2}$ transitions in Er^{3+}. The spectral width was 28 nm at full width at half-maximum, enabling a relatively wide gain bandwidth. The luminescence decay was single exponential with a lifetime of 4 ms. Figure 3 shows the attenuation spectrum of a planar waveguide, measured in the wavelength range from 1100 to 1600 nm, using a two-prism coupling method. The optical loss at 1.3 μm was determined to be less than 0.9 dB/cm. The Er^{3+} absorption at 1.535 μm was measured to be 8.7 dB/cm. Using the known optical mode profile in the waveguide and the Er concentration of 0.75 at. %, the peak absorption cross section around 1.535 μm was calculated to be $5.4\times10^{-21}\ cm^{-2}$. The absorption cross section at the 980 nm pump wavelength was determined from a similar measurement and amounted to $2.2\times10^{-21}\ cm^{-2}$.

Optical gain measurements were performed with the strip-loaded channel waveguide in a fiber butt-coupling setup. A 980 nm beam, emitted from a Ti:sapphire laser and coupled into a single-mode fiber, was used as the pump. This wavelength is resonantly absorbed in the ${}^4I_{11/2}$ manifold of Er^{3+}. A signal beam at 1.535 μm, emitted from an external-cavity diode laser, was mechanically chopped before it was coupled into a single-mode fiber. The signal power was below -40 dBm ($<0.1\ \mu W$). The pump and signal were combined by a 980 nm/1530 nm fiber wavelength division multiplexer, and were then coupled into the waveguide with a tapered optical fiber. The signal transmission change through the 10-mm-long waveguide as a function of pump power in the input fiber is shown in Fig. 4.

As the pump power is increased, the signal rapidly increases and an enhancement of 13.7 dB is reached at a pump power of 66 mW in the fiber. The power in the waveguide is

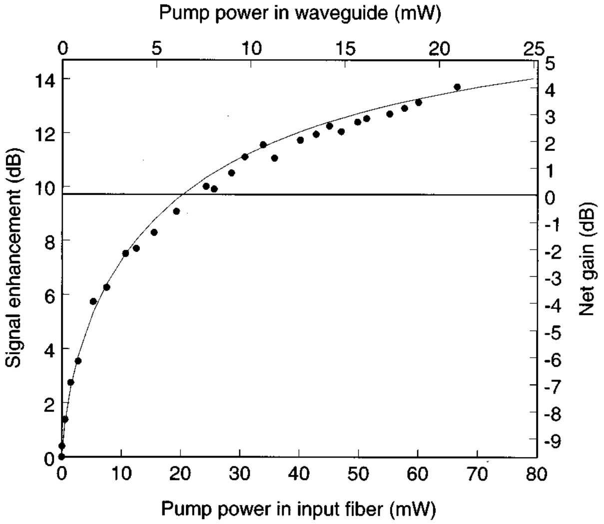

FIG. 4. Measurement of the optical signal enhancement at 1.535 μm in a 10-mm-long Er-doped phosphate glass channel waveguide amplifier as a function of 980 nm pump power. (●) Experimental data. The solid line is a calculation based on a cooperative upconversion coefficient $C_{up}=(2.0\pm0.5)\times10^{-18}\ cm^3/s$.

shown on the top horizontal axis of Fig. 4 and is calculated using a coupling loss of 30% estimated using measurements of the pump power at the output end of the waveguide and taking into account the absorption in the waveguide. The signal enhancement data were converted to net optical gain (right vertical axis) by setting the gain at zero pump power equal to the measured Er absorption at 1.535 μm (8.7 dB) plus the known waveguide loss (0.9 dB). The net optical gain is reached at a pump power of ~ 7 mW in the waveguide. At a pump power of ~ 21 mW in the waveguide a net (small-signal) optical gain of 4.1 dB at 1.535 μm is reached for the 10-mm-long waveguide. To our knowledge, this is the highest optical gain per unit length reported in the literature for an Er-doped planar waveguide amplifier at such a low pump power.

Model calculations were performed to fit the measured gain data in Fig. 4 as a function of pump power. A quasi-two-level rate equation model was used, taking into account the cooperative upconversion as a quenching effect that is quadratic in the concentration of excited Er ions.[6] The evolution of the pump and signal light was calculated using a numerical integration of loss and gain processes and assuming a homogeneous distribution of pump power over the waveguide cross section along the length of the waveguide. All input data for the model were taken from our previous experiments,[7] apart from the upconversion coefficient (C_{up}) that was used as a fit parameter. The best fit is found for $C_{\mathrm{up}} = (2.0 \pm 0.5) \times 10^{-18}$ cm^3/s, which is the lowest upconversion coefficient reported for a glass material known to us.

Cooperative upconversion is an effect in which energy is exchanged between two closely spaced excited Er ions, thereby reducing the effective Er population at a given pump power. As this dipole–dipole interaction depends on the distance to the sixth power, it is very sensitive to the precise Er distribution in the glass. In addition, the spectral overlap and the phonon density of states are also parameters that affect the interaction rate. The latter two effects are expected to be quite similar in phosphate glasses as in, e.g., silicate glasses. The low upconversion coefficient found for this phosphate glass therefore indicates that the Er is more homogeneously distributed than in other glasses, with no clustering. Indeed, it has been suggested,[11] that a high amount of nonbridging oxygens as in the present phosphate glass strongly promotes a homogeneous distribution of Er ions.

The low upconversion coefficient then enables efficient excitation of the high Er concentration, and therefore high gain per unit length. Additional simulations show that for a pump power of 30 mW the optical gain can be further increased by increasing the waveguide length to 4 cm. In that case a net gain of more than 10 dB can be achieved. With a higher pump power of 100 mW, a net optical gain of 35 dB is expected for a waveguide length of 8 cm.

In conclusion, Er-doped phosphate glass waveguides (0.75 at % Er) were fabricated by rf sputtering techniques on thermally oxidized silicon substrates. A net optical gain at 1.535 μm of 4.1 dB has been measured in a 10-mm-long Er-doped phosphate glass waveguide amplifier pumped at 980 nm at a pump power of ~ 21 mW. This high gain at relatively low pump power is due to the very low cooperative upconversion coefficient in this glass $[C_{\mathrm{up}} = (2.0 \pm 0.5) \times 10^{-18}$ cm^3/s], caused by the homogeneous distribution of Er in the glass, as well as by the high mode confinement due to the high refractive index. Calculations show that a gain of up to 35 dB may be achieved by extending the waveguide length.

The authors would like to acknowledge the financial support from the IC Technology Program (IOP Electro-Optics) of the Dutch Ministry of Economic Affairs. The work at the FOM Institute is part of the research program of FOM, and was also financially supported by NWO and STW.

[1] W. J. Miniscalco, J. Lightwave Technol. **9**, 234 (1991).
[2] P. Camy, J. E. Roman, F. W. Willems, M. Hempstead, J. C. van der Plaats, C. Prel, A. Beguin, A. M. J. Koonen, J. S. Wilkinson, and C. Lerminiaux, Electron. Lett. **32**, 321 (1996).
[3] J. P. Delavaux, S. Granlund, O. Mizuhara, L. D. Tzeng, D. Barbier, M. Rattay, F. S. Andre, and A. Kevorkian, Proceedings of ECOC'96, 1996, p. 123.
[4] J. V. Gates, A. J. Bruce, J. Shmulovich, Y. H. Wong, G. Nykolak, M. R. X. Barros, and R. N. Ghosh, Mater. Res. Soc. Symp. Proc. **392**, 209 (1995).
[5] T. Kitagawa, K. Hattori, K. Shuto, M. Oguma, J. Temmyo, S. Suzuki, and M. Horiguchi, Proceedings of ECOC'93, September 1993, p. 41.
[6] E. Snoeks, G. N. van den Hoven, A. Polman, B. Hendriksen, M. B. J. Diemeer, and F. Priolo, J. Opt. Soc. Am. B **12**, 1468 (1995).
[7] Y. Yan, A. J. Faber, and H. de Waal, Proc. SPIE **2695**, 144 (1996).
[8] Y. Yan, A. J. Faber, and H. de Waal, J. Non-Cryst. Solids **181**, 283 (1995).
[9] Y. Yan, Ph.D. thesis, TNO, Eindhoven, The Netherlands, 1997.
[10] M. J. Weber, J. Non-Cryst. Solids **123**, 208 (1990).
[11] J. Wang, W. S. Brocklesby, J. R. Lincoln, J. E. Townsend, and D. N. Payne, J. Non-Cryst. Solids **163**, 261 (1993).