Neodymium-complex-doped, photo-defined polymer channel waveguide amplifiers

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Polymer-based, 6-FDA/epoxy channel waveguides doped with a Nd complex, Nd(TTA)$_3$phen, are fabricated by a simple and reproducible procedure mainly based on spin coating and photo-definition. Photoluminescence at 1060 nm from the Nd^{3+} ions with a lifetime of 130 μs is observed. Optical gain at 1060 nm is demonstrated in channel waveguides with different Nd^{3+} concentrations. By accounting for the waveguide loss, an internal net gain of 8 dB is demonstrated for a 5.6-cm-long channel waveguide amplifier. Due to the nature of the Nd^{3+} complex, energy-transfer upconversion affects the gain only at Nd^{3+} concentrations above 1×10^{20} cm^{-3}.

Introduction

Rare-earth-ion-doped planar waveguide amplifiers are attractive, e.g., for high-speed data communication. Polymers are promising host candidates for these applications due to their low cost and simple processing technologies. In our work, an optical gain of 8.0 dB at a wavelength of 1060 nm was measured in a 5.6-cm-long Nd(TTA)$_3$phen-doped 6-FDA/epoxy photo-definable channel waveguide.

Fabrication and characterization

Polymers are usually poor host materials for luminescence emission from rare-earth ions due to the presence of high-energy vibrations from C-H and O-H chemical bonds. To suppress the luminescence quenching of rare-earth ions in polymer hosts they were encapsulated in fluorinated chelates in addition to doping them into a fluorinated polymer. The fluorinated neodymium complex, Nd(TTA)$_3$phen, was synthesized according to the procedure described in [1] and doped into the fluorinated host 6-FDA/epoxy.

By spin-coating and subsequently photodefining of a cycloaliphatic epoxy prepolymer (code name CHEP) [2, 3], inverted channels in the low-refractive-index CHEP polymer were obtained on a thermally oxidized silicon wafer. The core material, a Nd(TTA)$_3$phen doped 6-FDA/epoxy solution, was then backfilled via spin-coating twice and the 5×5 μm^2 Nd-complex-doped channel waveguides were realized after thermal curing. An additional 5-μm-thick CHEP layer was spin-coated on top of the channels as the upper cladding layer.

The optical loss of these channel waveguides was determined with the cut-back method. With a broadband white-light source (FemtoPower1060, SC450, Fianium) at the input of the samples of different lengths, the optical output was collected by a spectrum analyzer (Spectro320, Instrument System). Figure 1 shows the loss spectrum of a Nd^{3+}-complex-doped 6-FDA/epoxy channel waveguide from 750 nm to 1350 nm. The peaks around 800 nm and 860 nm are caused by the absorption transitions $^4I_{9/2} \rightarrow {}^4F_{5/2}$ and $^4I_{9/2} \rightarrow {}^4F_{3/2}$, respectively, of the Nd^{3+} ions, while the peak around 1200 nm is due to the

absorption of the polymer host. The measured waveguide loss at 1060 nm is ~0.1 dB/cm.
Figure 2 shows a partial photoluminescence spectrum of the Nd^{3+}-doped polymer. The Nd^{3+} concentration is 1.03×10^{20} cm^{-3}. A Ti:Sapphire laser operating at a wavelength of 800 nm was used as the excitation source, and the fluorescence peak near 1060 nm due to the $^4F_{3/2} \rightarrow {}^4I_{11/2}$ transition of Nd^{3+} was detected by a spectrum analyzer. It indicates that Nd^{3+} in this polymer host is optically active at 1060 nm. The luminescence lifetime of Nd^{3+} in the 6-FDA/epoxy host was measured to be about 130 µs.

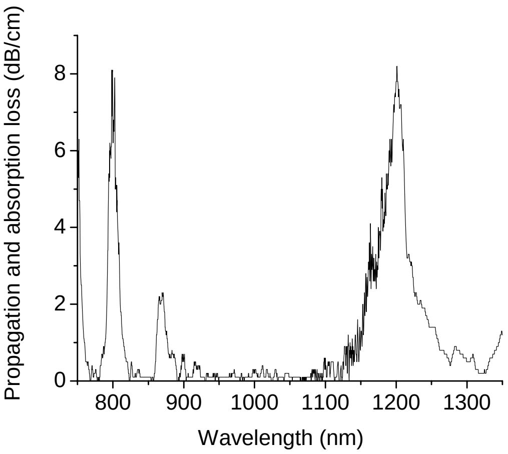

Fig. 1. Loss spectrum of Nd^{3+}-doped 6-FDA/epoxy

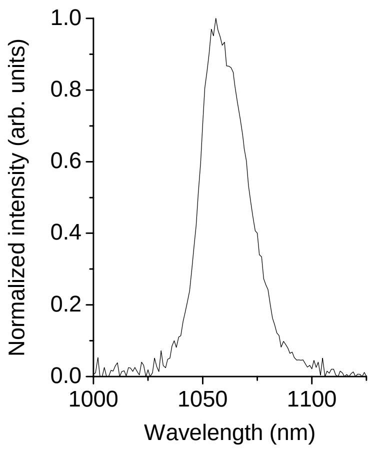

Fig. 2. Luminescence spectrum at the $^4F_{3/2} \rightarrow {}^4I_{11/2}$ transition of Nd^{3+}-doped 6-FDA/epoxy

Demonstration of optical net gain

A pump-probe method was used for the small-signal-gain measurement. A schematic of the experimental setup is shown in Fig. 3. A Ti:Sapphire laser operating at 800 nm was used as the pump source. A Nd:YAG laser (FemtoPower1060, SC450, Fianium), which emits a narrow band (about 3 nm) around 1064 nm when operating at the lowest output power, was applied as the signal source. A mechanical chopper was inserted into the beam path to modulate the signal light and connected to a lock-in amplifier. Pump light at 800 nm and modulated signal light at 1064 nm were combined by a dichroic mirror and coupled into and out of the waveguide via microscope objectives. The unabsorbed pump light coupled out of the waveguide was blocked by a high-pass filter (RG850), and the signal light was measured by a germanium photodiode and amplified with the lock-in technique. The optical gain was determined by measuring the ratio of the transmitted signal intensities I_p and I_u with pump on and off, respectively. By subtracting the waveguide propagation and absorption loss α (dB/cm) at the signal wavelength around 1064 nm, the internal net gain was obtained. The small-signal-gain coefficient in dB/cm was calculated from the equation

$$\gamma = 10 \cdot \frac{\log_{10}(\frac{I_p}{I_u})}{l} - \alpha ,$$

where *l* is the length of the waveguide channel.

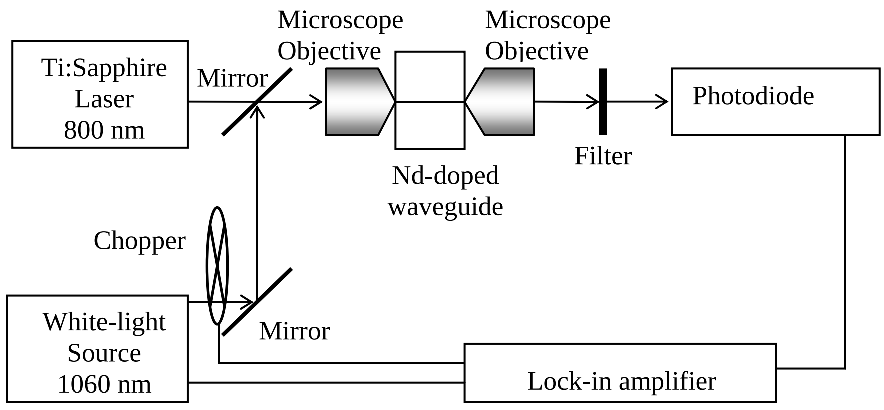

Fig. 3. Schematic of the experimental setup

Experimental data from the gain measurements are shown in Fig. 4, which displays the internal net gain as a function of pump power launched into the channel. The gain increases with increasing pump power and saturates at high power. The saturation is due to ground-state bleaching [4] and energy-transfer upconversion among neighboring Nd^{3+} ions in the $^4F_{3/2}$ level [4, 5]. The highest internal net gain of 8 dB, equal to 1.4 dB/cm, was measured for a Nd^{3+} concentration of 1.03×10^{20} cm^{-3}. When further increasing the Nd^{3+} concentration, the gain decreases, indicating the detrimental influence of energy-transfer upconversion at these elevated concentrations.

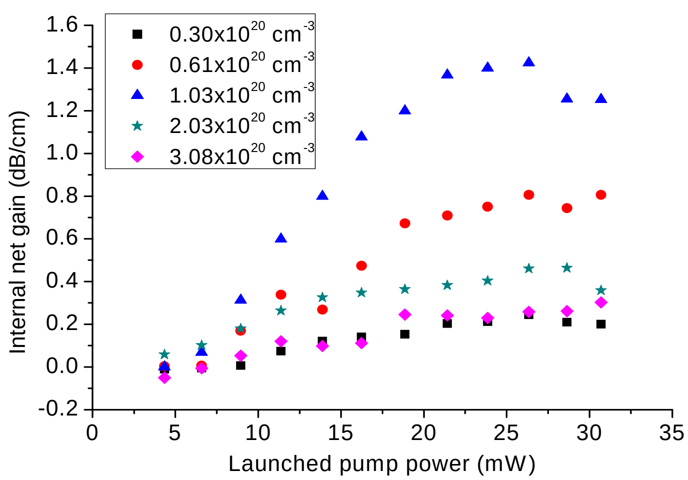

Fig. 4. Net gain at 1060 nm as a function of pump power at 800 nm

Conclusion

In conclusion, Nd-complex-doped, photo-defined polymer channel waveguides were realized on thermally oxidized silicon wafers with a simple fabrication procedure. An internal net gain of 8 dB was obtained in a 5.6-cm-long channel waveguide with a Nd^{3+} concentration of 1.03×10^{20} cm^{-3}, which indicates that a Nd-complex-doped polymer waveguide is well suited for optical amplification and potentially lasing.

References

[1] L.R. Melby, N.J. Rose, E. Abramson, and J.C. Caris, "Synthesis and fluorescence of some trivalent lanthanide complex", J. Am. Chem. Soc. **86**, 5117 (1964).

[2] M.B.J. Diemeer, L.T.H. Hilderink, R. Dekker, and A. Driessen, "Low-cost and low-loss multimode waveguide of photodefinable epoxy", IEEE Photon. Technol. Lett. **18**, 1624 (2006).

[3] M.B.J. Diemeer, L.T.H. Hilderink, H. Kelderman, and A. Driessen, "Multimode waveguides of photodefinable epoxy for optical backplane applications," in Proc. Annual Symposium IEEE/LEOS Benelux Chapter 2006, 53 (2006).

[4] M. Pollnau, P.J. Hardman, W.A. Clarkson, and D.C. Hanna, "Upconversion, lifetime quenching, and ground-state bleaching in Nd^{3+}:$LiYF_4$", Opt. Commun. **147**, 203-211 (1998).

[5] M. Pollnau, P.J. Hardman, M.A. Kern, W.A. Clarkson, and D.C. Hanna, "Upconversion-induced heat generation and thermal lensing in Nd:YLF and Nd:YAG", Phys. Rev. B **58**, 16076-16092 (1998).