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. Phosphorescence at 1060 nm from the Nd$^{3+}$ ions with a lifetime of 130 $\mu$s 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 $1 \times 10^{20}$ 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 $\mu$m$^2$ Nd-complex-doped channel waveguides were realized after thermal curing. An additional 5-$\mu$m-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 $^4$I$_{9/2}$ $\rightarrow$ $^4$F$_{5/2}$ and $^4$I$_{9/2}$ $\rightarrow$ $^4$F$_{3/2}$, 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 $1.03 \times 10^{20}$ 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 $^{4}F_{3/2} \rightarrow ^{4}I_{11/2}$ 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.

**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 $\alpha$ (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

$$\gamma = 10 \cdot \log_{10} \left( \frac{I_p}{I_u} \right) - \alpha,$$
where \( l \) is the length of the waveguide channel.

![Schematic of the experimental setup](image)

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 \(^{4}F_{3/2}\) 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 \(1.03 \times 10^{20}\) cm\(^{-3}\). When further increasing the Nd\(^{3+}\) concentration, the gain decreases, indicating the detrimental influence of energy-transfer upconversion at these elevated concentrations.

![Net gain at 1060 nm as a function of pump power at 800 nm](image)

**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 \(1.03 \times 10^{20}\) cm\(^{-3}\), which indicates that a Nd-complex-doped polymer waveguide is well suited for optical amplification and potentially lasing.
References


