Nd-doped aluminum oxide integrated amplifiers at 880 nm, 1060 nm, and 1330 nm

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Abstract—Neodymium-doped Al₂O₃ layers were deposited on thermally oxidized Si substrates and channel waveguides were patterned using reactive-ion etching. Internal net gain on the Nd³⁺ transitions at 880, 1064, and 1330 nm was investigated, yielding a maximum gain of 6.3 dB/cm at 1064 nm. Values for the energy-transfer upconversion parameter for different Nd³⁺ concentrations were deduced.

Keywords—Neodymium, aluminum oxide, channel waveguide, optical amplifiers, energy-transfer upconversion

I. INTRODUCTION

Integrated optical channel waveguides doped with rare-earth ions have been subject to investigations over the last two decades. Various host materials and different waveguide fabrication techniques have been employed to demonstrate gain in Nd-doped channel waveguides [1-4] and lasers [5,6]. Amorphous aluminum oxide is an excellent host for rare-earth ions, having low optical loss and high refractive index [7,8]. The latter allows for small bending radii and correspondingly small on-chip devices. In this work, optical gain in Al₂O₃:Nd³⁺ is investigated at 880, 1064, and 1330 nm. We report a maximum gain of 6.3 dB/cm for the transition at 1064 nm. In addition, internal net gain is reported for 880 and 1330 nm. Values of the energy-transfer upconversion (ETU) parameter were obtained from the measured gain by simulations.

II. CHANNEL WAVEGUIDE FABRICATION

Al₂O₃:Nd layers with a thickness of 600 nm were reactively co-sputtered onto thermally oxidized 10-cm Si wafers. Al and Nd targets of high purity were sputtered using Ar guns, while oxygen was supplied as a gas. By varying the Nd-target power, different Nd³⁺ concentrations from 0.65x10⁻²⁰ cm⁻³ to 2.95x10⁻²⁰ cm⁻³ have been obtained. The dopant concentrations were confirmed by Rutherford Backscattering Spectroscopy (RBS). Straight channel waveguides with a width of 2.0 μm were fabricated in the layers by means of reactive ion etching (RIE). The channels were shallow etched by 70 nm. These channels are single-mode at a wavelength of 1064 nm and multi-mode at the pump wavelength of 802 nm. The channel waveguides use air as the cladding.

III. EXPERIMENTAL RESULTS

The luminescence spectrum of Fig. 1 was obtained by pumping the Nd³⁺ ions at 802 nm from the ⁴F₉/₂ ground level into the ²F₅/₂ level and collecting light from the waveguide top into a spectrophotometer (Jobin Yvon iHR550). The obtained luminescence spectrum was corrected for the response of the used InGaAs detector. The measured ⁴F₉/₂ → ⁴I₉/₂ luminescence at 1064 nm is approximately five times stronger than the ⁴F₉/₂ → ⁴I₈/₂ and ⁴F₉/₂ → ⁴I₆/₂ luminescence at 880 nm and 1340 nm, respectively. The luminescence at 1330 nm has a value equaling 75% of the peak value at 1340 nm.

Small-signal internal net gain investigations were performed using a pump-probe method. A Ti:Sapphire laser (Spectra-Physics 3900s) was employed as the pump source at 880 nm, while diode lasers at 880 nm and 1330 nm and a Nd:Yag laser at 1064 nm were employed as signal sources. Attenuation of the signal to a power of 1-10 µW ensured operation in the small-signal regime. Signal light modulated by a mechanical chopper and pump light were combined via a dichroic mirror and coupled into and out of the waveguides using high-numerical-aperture (0.85 and 0.4 NA, resp.) microscope objectives. The unabsorbed pump light was filtered from the signal light using a high-pass filter at 850 nm placed behind the outcoupling objective, while the signal light was measured by a Germanium detector and amplified by a lock-in amplifier connected to the chopper. The optical gain was determined by measuring the ratio of the transmitted intensities in the pumped and unpumped case, Iₚ and Iₙ, respectively. The internal net gain per unit length was obtained by dividing by the sample length l and subtracting the combined measured propagation and absorption losses (α):

$$\gamma_{\text{meas}}(\lambda) = 10 \cdot \log_{10}(I_p(\lambda)/I_n(\lambda))/l - \alpha(\lambda)$$  \hspace{1cm} (1)

Figure 2a shows the measured internal net gain per unit length as a function of Nd³⁺ concentration at a launched power of 45 mW. At a concentration of 1.68x10⁻²⁰ cm⁻³, a maximum optical gain of 6.3 dB/cm and 1.93 dB/cm was found at 1064 and 1330 nm, respectively. At a concentration of 1.40x10⁻²⁰ cm⁻³, a maximum of 1.57 dB/cm was found at 880 nm.
The internal net gain per unit length at these optimum concentrations as a function of launched power is displayed in Fig. 2b. Both the decrease in gain per unit length as a function of Nd³⁺ concentration in Fig. 2a and the gain saturation visible in Fig. 2b are mainly attributed to energy-transfer upconversion (ETU) processes from the \( {^4}F_{3/2} \) level into higher-lying energy levels [9,10].

\[
\frac{dN_d}{dt} = R_{05} - R_{4i} - R_{6i} - \tau_4^{-1} N_d - W_{\text{ETU}} N_d^2 \quad (2)
\]
\[
N_0 = N_d - N_i \quad (3)
\]

where \( N_d \) and \( \tau_4 \) are the population density and lifetime of the \( {^4}F_{3/2} \) level, respectively, \( N_0 \) is the ground-state population and \( N_i \) is the dopant concentration. \( W_{\text{ETU}} \) is the combined upconversion coefficient of three ETU processes originating in the metastable \( {^4}F_{3/2} \) level [9,10]. The pump absorption rate from the \( {^4}I_{9/2} \) ground-state into \( {^4}F_{3/2} \) is expressed by \( R_{05} \), stimulated emission from \( {^4}F_{3/2} \) into the lower-lying levels \( i = 0, 1, \) and \( 2 \) for 880 nm, 1064 nm, and 1330 nm, respectively, by \( R_{4i} \), and reabsorption from the ground state into \( {^4}F_{5/2} \) by \( R_{6i} \) (taken into account only for the 3-level transition at 880 nm). The values for the ETU parameter at 1064 nm thus obtained are 0.51, 0.89, 1.32, and \( 2.32 \times 10^{-16} \) cm/s for Nd³⁺ concentrations of 0.65, 1.13, 1.68, and \( 2.95 \times 10^{-20} \) cm³, respectively.

V. CONCLUSIONS

Nd\(_{3}^{+}\)/Si layers have been deposited onto thermally oxidized Si substrates and single-mode channel waveguides have been fabricated. A maximum small-signal gain of 1.57 dB/cm, 1.93 dB/cm, and 6.3 dB/cm at 880, 1330, and 1064 nm, respectively, was obtained. By fitting the simulated to the measured gain values for the ETU parameter in Nd\(_{3}^{+}\)/Si at four different Nd³⁺ concentrations have been obtained.

REFERENCES


