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

K. van Dalfsen, J. Yang, F. Ay, K. Wörhoff, and M. Pollnau
Integrated Optical MicroSystems Group, MESA+ Institute for Nanotechnology, University of Twente
Enschede, The Netherlands
k.vandalfsen@utwente.nl

*Abstract*—**Neodymium-doped $Al_2O_3$ layers were deposited on thermally oxidized Si substrates and channel waveguides were patterned using reactive-ion etching. Internal net gain on the $Nd^{3+}$ 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 $Nd^{3+}$ 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 $Al_2O_3:Nd^{3+}$ 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

$Al_2O_3$: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 $Nd^{3+}$ concentrations from $0.65 \times 10^{20}$ cm$^{-3}$ to $2.95 \times 10^{20}$ 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 $Nd^{3+}$ ions at 802 nm from the $^4I_{9/2}$ ground level into the $^5F_{5/2}$ 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 $^4F_{3/2} \rightarrow {}^4I_{11/2}$ luminescence at 1064 nm is approximately five times stronger than the $^4F_{3/2} \rightarrow {}^4I_{9/2}$ and $^4F_{3/2} \rightarrow {}^4I_{13/2}$ 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 802 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, $I_p$ and $I_u$, 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):

$$g_{meas}(l) = 10 \cdot \log_{10}\left(I_p(l)/I_u(l)\right)/l - a(l) \qquad (1)$$

Figure 2a shows the measured internal net gain per unit length as a function of $Nd^{3+}$ concentration at a launched power of 45 mW. At a concentration of $1.68 \times 10^{20}$ 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 $1.40 \times 10^{20}$ cm$^{-3}$, a maximum of 1.57 dB/cm was found at 880 nm.

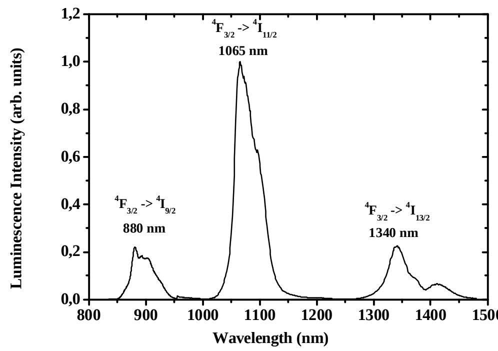


Figure 1. Broadband luminescence spectrum of a $Al_2O_3$:Nd channel waveguide

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 $Nd^{3+}$ concentration in Fig. 2a and the gain saturation visible in Fig. 2b are mainly attributed to energy-transfer upconversion (ETU) processes from the $^4F_{3/2}$ level into higher-lying energy levels [9,10].

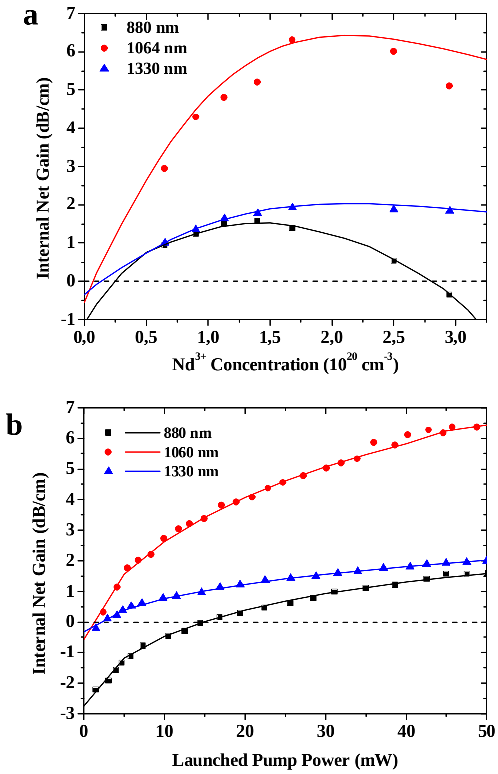


Figure 2. Measured (dots) and calculated (lines) internal net gain per unit length at 880, 1064 and 1330 nm versus (a) $Nd^{3+}$ concentration for a launched power of 45 mW and (b) launched pump power for the samples with maximum gain per unit length in (a)

## IV. GAIN SIMULATIONS

The optical gain in Fig. 2 was simulated by numerically solving a rate-equation model using the ETU parameter as a fitting parameter to the experimentally obtained gain. The simplified rate-equation model describing the population mechanisms of the $Nd^{3+}$ system can be described as follows:

$$dN_4 / dt = R_{05} - R_{4i} - R_{04} - \tau_4^{-1} N_4 - W_{ETU} N_4^2 \quad (2)$$

$$N_0 = N_d - N_4 \quad (3)$$

where $N_4$ and $\tau_4$ are the population density and lifetime of the $^4F_{3/2}$ level, respectively, $N_0$ is the ground-state population and $N_d$ is the dopant concentration. $W_{ETU}$ is the combined upconversion coefficient of three ETU processes originating in the metastable $^4F_{3/2}$ level [9,10]. The pump absorption rate from the $^4I_{9/2}$ ground-state into $^4F_{5/2}$ is expressed by $R_{05}$, stimulated emission from $^4F_{3/2}$ 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 $^4F_{3/2}$ by $R_{04}$ (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 2.32x$10^{-16}$ $cm^3s^{-1}$ for $Nd^{3+}$ concentrations of 0.65, 1.13, 1.68, and 2.95x$10^{20}$ $cm^{-3}$, respectively.

## V. CONCLUSIONS

$Al_2O_3$:$Nd^{3+}$ 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 $Al_2O_3$:$Nd^{3+}$ at four different $Nd^{3+}$ concentrations have been obtained.

## REFERENCES


[1] E. Lallier, J. P. Pocholle, M. Papuchon, M. De Micheli, M. J. Li, Q. He, D. B. Ostrowsky, C. Grezes-Besset, and E. Pelletier, “Nd:MgO:$LiNbO_3$ waveguide laser and amplifier,” Opt. Lett., vol. 15, pp. 682-684, June 1990.

[2] Y. Sikorski, A. A. Said, P. Bado, R. Maynard, C. Florea, and K. A. Winick, “Optical waveguide amplifier in Nd-doped glass written with near-IR femtosecond laser pulses,” Electron. Lett., vol. 36, pp. 226-227, February 2000.

[3] A. Peled, M. Nathan, A. Tsukernik, and S. Ruschin, “Neodymium doped sol-gel tapered waveguide amplifier,” App. Phys. Lett., vol. 90, 161125, April 2007.

[4] J. Yang, M. B. J. Diemeer, D. Geskus, G. Sengo, M. Pollnau, and A. Driessen, “Neodymium- complex-doped photodefined polymer channel waveguide amplifiers,” Opt. Lett., vol. 34, pp. 473-475. Feb. 2009.

[5] D. S. Gill, A. A. Anderson, R. W. Eason, T. J. Warburton, and D. P. Shepherd, “Laser operation of an Nd:$Gd_3Ga_5O_{12}$ thin-film optical waveguide fabricated by pulsed laser deposition,” Appl. Phys. Lett., vol. 69, 10-12, July 1996.

[6] J. Yang, M. B. J. Diemeer, C. Grivas, G. Sengo, A. Driessen, and M. Pollnau, “Rare-earth-ion complex-doped fluorinated polymer for steady-state lasing,” submitted (2010).

[7] K. Wörhoff, J. D. B. Bradley, F. Ay, D. Geskus, T. P. Blauwendraat, and M. Pollnau, “Reliable low-cost fabrication of low-loss $Al_2O_3$:$Er^{3+}$ waveguides with 5.4-dB optical gain,”IEEE J. Quantum Electron., vol. 45, pp. 454-461, May 2009.

[8] J. D. B. Bradley, F. Ay, K. Wörhoff, and M. Pollnau, “Fabrication of low-loss channel waveguides in $Al_2O_3$ and $Y_2O_3$ layers by inductively coupled plasma reactive ion etching,” Appl. Phys. B, vol. 89, pp. 311–318, Oct. 2007.

[9] 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., vol. 147, pp. 203-211, Feb. 1998.

[10] 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, vol. 58, 16076-16092, Dec. 1998.