On-chip Gain in Neodymium-doped Aluminium Oxide Waveguide Amplifiers

B. Jongebloed, E. J. Degan, D.J.M. Wojcik, C.E. Osornio-Martínez, D. B. Bonneville, M. Dijkstra, and S. M. García-Blanco

Integrated Optical Systems Group, MESA+ Institute for Nanotechnology, University of Twente, 7500 AE Enschede, The Netherlands

Aluminium oxide (Al_2O_3) has emerged as a promising platform for the development of photonic integrated circuits. The material has attracted significant attention due to its notable high rare-earth ion solubility. The substantial high rare-earth ion solubility of Al_2O_3 enables the fabrication of waveguide structures embedded with optically active rare earth ions, resulting in high gain waveguide amplifiers. Prior work involving co-sputtering of doped-Al_2O_3 layers has resulted in polycrystalline ridge waveguides doped with erbium, ytterbium and thulium ions. However, neodymium-doped aluminium oxide (Al_2O_3:Nd^{3+}) waveguides have not yet been fabricated with this method.

The choice of Al_2O_3:Nd^{3+} as material composite is interesting due to its distinct light-matter interactions. Contrary to Er^{3+}, Yb^{3+}, and Tm^{3+} ions, the Nd^{3+} ions form a four-level system. The four-level characteristics prevent reabsorption of signal photons by the gain medium. Total on-chip gain of 17 dB at a wavelength of 1064 nm has been observed.

Introduction

The use of photonic integrated circuits (PICs) has become more and more widespread in recent years. These on-chip circuits, based on waveguides that transport and process optical signals in waveguides, find extensive applications in the telecommunications sector, amongst others. In the context of integrating PICs in telecommunication applications, the preservation of high optical power throughout the signal processing is of paramount importance. Consequently, there is a necessity for on-chip components that allow for amplification of the signal power. In this study, such a waveguide amplifier is realized in neodymium-doped aluminium oxide (Al_2O_3:Nd^{3+}), and the initial results of the characterization of on-chip gain are presented.

To create the waveguide amplifier, an aluminium oxide (Al_2O_3) layer is fabricated using RF sputtering. By simultaneously using a second target, a rare earth target, the Al_2O_3 layer can be doped with rare-earth ions [1]. These dopants allow for amplification at different wavelengths, with erbium being the most notable for its emission at 1550 nm, in the C-band [2]. However, there is a variety of other rare-earth ions that allow for emission at useful wavelengths. Neodymium ions (Nd^{3+}), for example, emit in the O-band at 1330 nm. Therefore, this material combination is interesting to explore for on-chip gain in the O-band.

The rare-earth ion Nd^{3+} is interesting for another reason. Its emission follows a four-level scheme at 1330 nm and 1064 nm [3, 4]. In this work, the emission at 1064 is studied. The four-level characteristics become clear from studying the energy levels in Nd^{3+} ions, as shown in figure 1a.

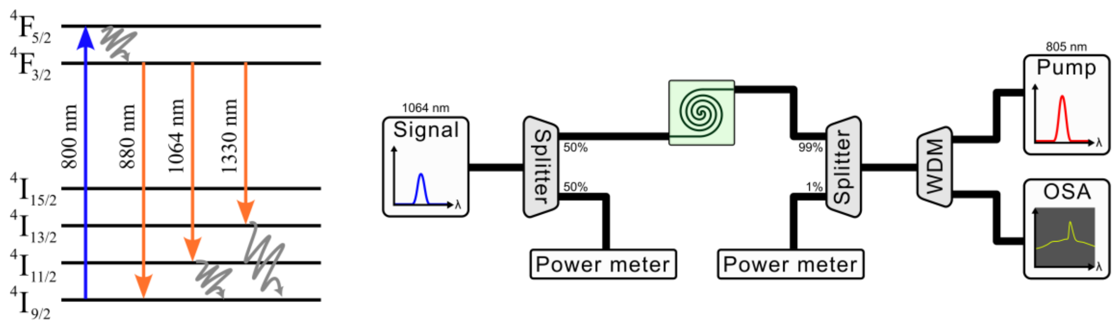
To enable emission at the aforementioned wavelengths, Nd^{3+} ions are optically pumped with light around a wavelength around 800 nm. Upon absorption of a pump photon, the ion is promoted from the ground state $^4I_{9/2}$ to the $^4F_{5/3}$ state. Fast non-radiative decay forces the ion to the metastable $^4F_{3/2}$ state. From that state, the ion can decay radiatively to other states spontaneously, or the process is stimulated by another photon. The latter process is responsible for the signal amplification.

The transition from the $^4F_{3/2}$ state to $^4I_{11/2}$ or $^4I_{13/2}$ states, accompanied with emission of photons wavelength of 1064 nm or 1330 nm, prohibits reabsorption of the signal photons. Reabsorption of the emitted photons is negligible, since the lifetimes of the fourth occupied energy levels, the $^4I_{11/2}$ or $^4I_{13/2}$ states, are too small to promote the Nd^{3+} back to the $^4F_{3/2}$ by absorbing a photon with wavelength of 1064 nm or 1330 nm. This reabsorption would be possible in the transition to the ground state of the ion, upon emission of a photon of 880 nm. In other words, the four-level characteristics, accompanying the stimulated emission at 1064 and 1330 nm allow for a more efficient energy transfer between pump photons and signal photons. Since there is no reabsorption of emitted signal photons, higher gain values are expected. Other processes like energy-transfer upconversion (ETU) and excited state absorption (ESA) take place. These two processes are known to influence the light-matter interaction in the amplifiers, but they are not studied in this first characterization.

Pump and signal characteristics

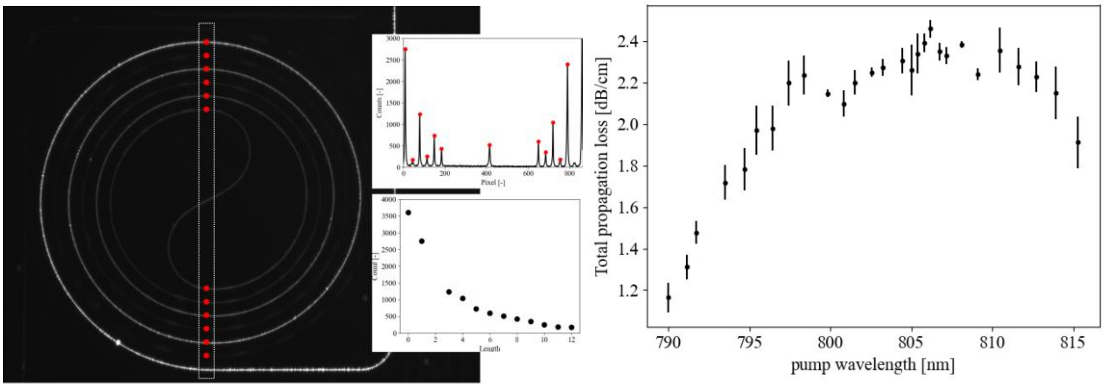
The waveguide amplifiers are formed by so-called Archimedean spirals, fabricated from an Al_2O_3:Nd^{3+} wafer. This study focusses on the main emission peak in the Nd^{3+} emission spectrum, the 1064 nm emission. One could opt for using a pump laser emitting at 800 nm and a signal wavelength of 1064 nm, since these numbers have been mentioned in literature [3]. However, these numbers are not set in stone, and can vary from host material to host material and they might be influenced by the fabrication process and subsequent spectroscopic parameters. Therefore, the pump wavelength is optimized, before continuing the actual gain measurements.

To select the optimal pump wavelength, a set of pump wavelengths are launched into the spiral amplifier through butt coupling, using the setup depicted in figure 1b. The light that scatters in the waveguide is collected from the top with a CCD camera. An example of such a measurement is shown in figure 2a.



(a) (b)

Figure 1. (a) Simplified energy diagram depicting the absorption and emission processes in Nd^{3+} ions showcasing the difference between three- and four-level processes. (b) Schematics of the setup used to couple both the signal and pump light into the amplifier. The transmitted signal power is sent through a wavelength demultiplexer (WDM) to an optical spectrum analyzer (OSA) to investigate the on-chip gain.



(a) (b)

Figure 2. (a) Illustration showing how pump absorption in the amplifiers is quantified. (b) Measured losses, including background propagation loss and absorption losses, as a function of pump wavelength.

The intensity of the scattered light is determined by inspecting different points along the length of the Archimedean spiral. Accordingly, the propagation loss α, including the pump absorption, can be extracted using

$$\mathrm{P} = \mathrm{P}_0 \exp(-\alpha L), \tag{1}$$

with P the intensity of the scattered light and L the propagation distance. By pumping with a tunable Ti:Sapphire laser, the propagation plus absorption loss α is obtained as a function of wavelength. The optimal pump wavelength is the one showing the highest absorption, or rather the highest losses, as this is anticipated to lead to the highest generation of amplified signal photons due to increased absorption. The measured values for α are shown in figure 2b. From this figure, an optimal pump wavelength of 805 nm is found. The same measurement is taken for a signal wavelength, to extract the propagation losses at the signal wavelength. This number, equal to 0.64 dB/cm, is required to calculate to gain at the 1064 nm.

Gain measurements

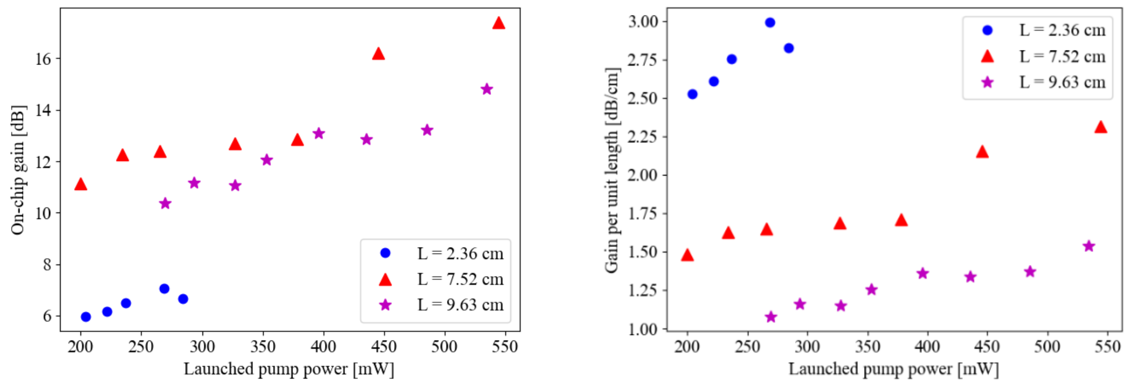
The spiral amplifiers are further characterized by determining the on-chip gain, using the setup as depicted in figure 1a. The pump and signal light are launched from opposite sides of the chip. To characterize the on-chip gain, the optical signal power transmitted through the waveguide is monitored with an optical spectrum analyzed (OSA). The signal power is measured without pumping, $\mathrm{P}_{\mathrm{unpumped}}$, and with pumping, $\mathrm{P}_{\mathrm{pumped}}$. Furthermore, the optical power at the signal wavelength is measured when the pump is launched into the waveguide, without launching a signal. The measured power represents the amplified spontaneous emission, $\mathrm{P}_{\mathrm{ASE}}$. From these three parameters, measured with the OSA in dBm as show in figure 3, the signal enhancement (SE) is calculated using

$$\mathrm{SE} = 10\log_{10}\frac{10^{\mathrm{P}_{\mathrm{pumped}}/10} - 10^{\mathrm{P}_{\mathrm{ASE}}/10}}{10^{\mathrm{P}_{\mathrm{unpumped}}/10}} \tag{2}$$

From the SE, the on-chip gain can be extracted by subtracting the waveguide propagation losses at the signal wavelength, so that

$$\mathrm{Gain} = \mathrm{SE} - \alpha_{1064\ \mathrm{nm}}. \tag{3}$$

The gain is measured with a pump wavelength of 805 nm since this wavelength results in the highest absorption, as shown in figure 2b. The gain at 1064 nm is measured as a function of amplifier length and launched pump power for a Nd^{3+} concentration of 1.516 x 10^{20} ions/cm^3 in a waveguide width a width of 400 nm and height of 295 nm.



(a) (b)

Figure 3. (a) Measured gain in $Al_2O_3:Nd^{3+}$ amplifiers for waveguides of different lengths as a function of launched pump power. The amplifier has an ion concentration of 1.516 x 10^{20} ions/cm^3. (b) Measured losses, background propagation and absorption, as a function of pump wavelength.

The measured values for the total on-chip gain are shown in figure 3a. From these numbers, the gain per unit length is obtained, which is depicted in figure 3b. A maximum on-chip gain as high as 17 dB is measured in a 7.52 cm spiral waveguide. On the contrary, the highest gain per unit length is measured in a significantly shorter waveguide. In a 2.36 cm long waveguide, a gain per unit length of close to 3 dB/cm is observed. The higher gain per unit length in shorter waveguides can be explained from having insufficient pump power. Once the pump power has been fully absorbed, no further generation of signal photons takes place, while the existing signal still suffers from propagation losses, effectively reducing the gain per unit length. As a result, the gain might be further improved by using higher pump power or employing other pump schemes like bi-directional pumping.

Conclusion

From this first study, on-chip gain has been measured in $Nd^{3+}:Al_2O_3$ waveguide amplifiers. The highest gain that has been observed approximately 17 dB, while the maximum gain per unit length is around 3 dB/cm. This gain has been measured using a pump wavelength of 805 nm and pump wavelength of 1064 nm. The total on-chip gain values are comparable to what has been reported in literature [4], although the gain per unit length is lower. However, it is important to note that the gain can be increased further by annealing the chips. In ongoing work, a substantial increase in gain in $Al_2O_3:Er^{3+}$ has been observed. Therefore, the effect of annealing has to be investigated in $Al_2O_3:Nd^{3+}$ to potentially achieve even higher gain.

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