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Optical gain via multi-layer monolithic integration of Si_3N_4 with $Al_2O_3:Er^{3+}$ waveguide amplifiers

(Student paper)

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In this work we report on the multi-layer integration of Si_3N_4 with $Al_2O_3:Er^{3+}$ waveguide amplifiers. Small signal internal gain of 2.5 dB is demonstrated at 1532 and 1550 nm as well as 2.1 dB at high signal powers, including powers up to 7.1 dBm launched at 1550 nm. Gain saturation was not demonstrated at high signal powers, which is promising for high power amplifiers for LIDAR sources. The result demonstrates the successful integration of an erbium doped gain medium on an established passive platform with insights towards maximizing the output power and the necessary material optimization steps.

Keywords: *Erbium doped waveguides, aluminium oxide, integrated amplifiers*

INTRODUCTION

Photonic integrated circuits (PICs) are a rapidly growing technology with applications in a variety of fields such as telecommunications, computing, healthcare, and sensing. To satisfy a large number of applications, it is becoming necessary to provide optical gain on-chip at a variety of wavelengths, on a variety of material platforms. Rare earth ions doped into various host materials are a promising optical gain media due to the available wavelengths, flexibility of processing techniques available and host insensitive properties. For this reason many of these devices have shown promise for integrated light sources that can be integrated into VLSI processes on silicon substrates [1,2]. Recently, industrially relevant gain levels were demonstrated in ion-implanted Si_3N_4 waveguides showing the promise of rare earth doped amplifiers in PICs with gain levels comparable to erbium doped fibres [3]. However, achieving scalable wafer processing of rare earth ion doped amplifiers that can be integrated onto a variety of underlying waveguide platforms, requires fabrication techniques that are more flexible and applicable to different material platforms [4]. In this work, we demonstrate the multi-layer integration of Si_3N_4 photonic circuits with $Al_2O_3:Er^{3+}$ waveguide amplifiers realized with reactive co-sputtering, electron beam lithography and reactive ion-etching. Gain is reported for low and high signal powers at wavelengths of 1532 and 1550 nm using bidirectional pumping at a wavelength of 1480 nm. Material optimization steps such as annealing and erbium concentration variation are discussed with the goal of maximizing the gain and increasing signal powers coming out of the chip.

RESULTS

Si_3N_4 waveguides were fabricated by LioniX International to achieve low-loss underlying circuits using a mature fabrication process. Devices on this passive layer were also used for characterizing waveguide and fiber-to-chip coupling losses via ring resonator measurements, 50/50 couplers for splitting light to a reference branch and taper structures for coupling the light from the underlying Si_3N_4 layer to the $Al_2O_3:Er^{3+}$ layer. A 200 nm buffer SiO_2 separates the Si_3N_4 from the Al_2O_3 waveguides. Reactive co-sputtering was used with purity controlled solid target precursors in oxygen ambient with a flow of 3.0 sccm following procedures outlined in [5]. A deposition rate of 4.5 nm/min was used to deposit a ~770 nm layer of $Al_2O_3:Er^{3+}$ with a dopant concentration of approximately 1.4×10^{20} ions/cm^3. Electron beam lithography was used to align to a revealed patterned Si_3N_4 feature to define the amplifiers on top of the vertical couplers using a dose of 1100 $\mu C/cm^2$. Reactive ion-etching (RIE) was performed to define the waveguides with 25 and 10 sccm of BCl_3 and HBr gas flows respectively at a chamber operating pressure of 3 mTorr and 25 W RF power. Plasma-enhanced chemical vapour deposition (PECVD) was used to deposit a SiO_2 cladding at a deposition rate of 37 nm/min using 200 and 710 sccm of SiH_4/N_2 and N_2O respectively, with a chamber pressure of 650 mTorr at 300 °C stage temperature and 60 W of power. Chips were diced and measured after annealing in a tube furnace in N_2 ambient at 600 °C.

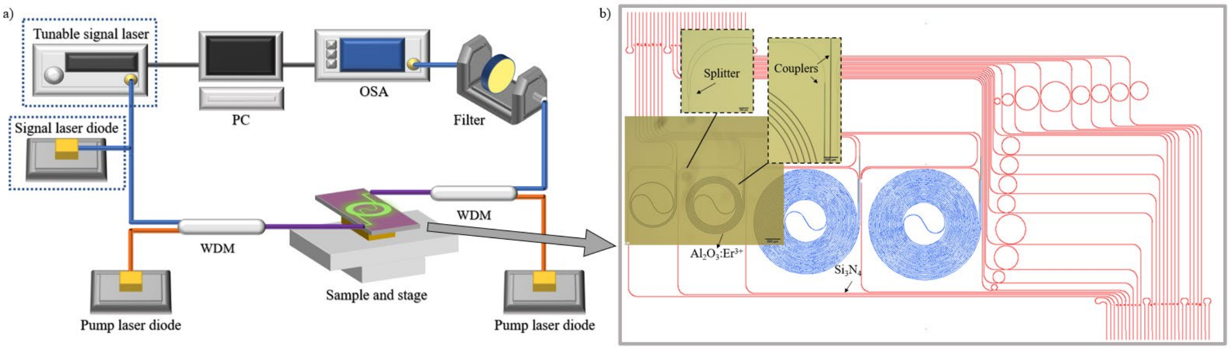

Fig. 1. a) Measurement setup used for characterization of amplifiers with a tunable and diode laser for low and high signal power outputs respectively. b) Layout of the multi-layer chips with Si_3N_4 circuits (red) patterned undeath Al_2O_3:Er^{3+} (blue) amplifier sections of varying length. On-chip 50/50 splitters and multi-layer couplers shown for measurement of a reference branch and vertically coupling to the gain medium respectively.

Bidirectional pumping was achieved with the setup shown in Fig. 1a) with the use of two Anritsu 1480 nm diode pump lasers, each capable of reaching ~500 mW of incident power to the chip. Piezo controlled stages were used to couple PANDA single-mode polarization maintaining fibers to the chip where Si_3N_4 nanotapers were used to optimize modal overlap. A high-pass blocking filter cutting off wavelengths below 1500 nm was used to ensure additional spectral interference from the pumps and on-chip generated amplified spontaneous emission (ASE) or up-conversion did not reach the detector. Figure 1b) shows the layout of the chip used for gain measurements, which includes adiabatic transition tapers as vertical couplers from Si_3N_4 to the amplifier layer shown via optical microscope images. Passive ring resonator arrays can also be seen, which were included to estimate the coupling efficiency of the chip and passive waveguide loss, which corresponds to ~0.27 dB/cm at 1550 nm. Gain calculations were made assuming 3 dB of chip coupling losses, as well as 3 dB of splitting into and out of the passive coupler to the reference branch and amplifier section. Further measurements on these passive components are suggested to reduce uncertainty in the measured gain.

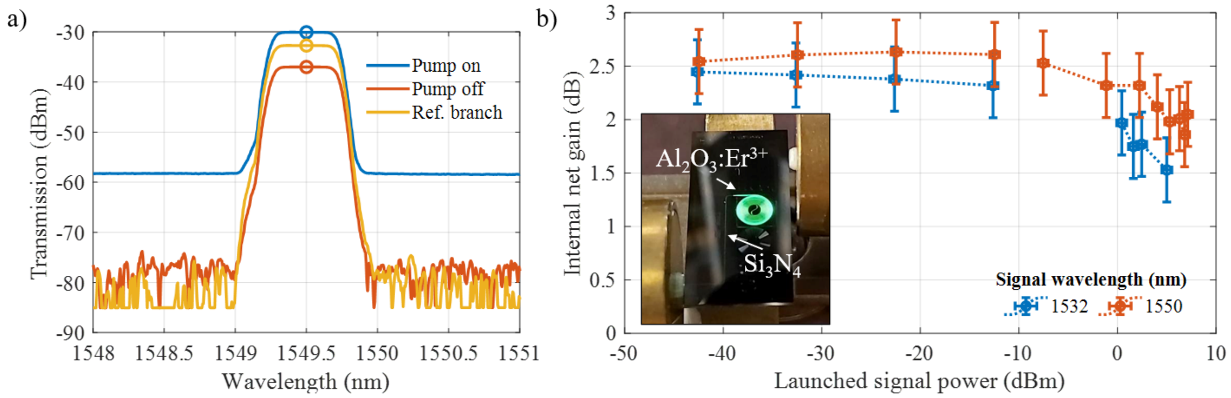

Fig. 2. a) Transmission data from the OSA showing a measurement of the Si_3N_4 reference branch and the amplifier with and without pumping. b) On-chip gain measured via Si_3N_4 waveguides with a 3.19 cm long Al_2O_3:Er^{3+} waveguide amplifier for a variety of signal powers. Gain saturation shown not to occur at high signal powers up to 7.1 dBm for 1532 and 1550 nm for a launched pump power of ~150 mW. Sample shown during pumping of a ~17 cm Al_2O_3:Er^{3+} waveguide amplifier (inset).

Figure 2 a) shows the measured transmission data used to extract the amplifier gain performance. The relation between the reference branch (i.e., in Si_3N_4) and the amplifier when the 1480 nm pumps are on and off. In this manner, the internal net gain of the amplifier (i.e., from Si_3N_4 to Si_3N_4) can be directly obtained by the ratio of the measured power at the output of the amplifier and reference branches [4]. The measured internal net gain at both 1532 and 1550 nm is shown in Figure 2 b), for a 3.19 cm long amplifier section, with a launched pump power of ~150 mW for launched signal powers up to 5.15 mW. Peak on-chip power is estimated to be 8.25 mW at 1550 nm. Shown in the inset is a ~17 cm chip during 1480 nm pumping where the transfer between layers can be seen visually by the up conversion in the Al_2O_3:Er^{3+}.

DISCUSSION

Gain demonstrated in the high-power regime shows a promising step towards high power amplifiers for LIDAR and other applications that require large amounts of off-chip power. Although the gain is low compared to other demonstrations [6-8], the presented results are preliminary. Many optimization steps can be taken, including the optimization of the amplifier length (i.e., in this work 3.19 cm), the annealing temperature, erbium concentration as well as features and alignment of the amplifier taper coupling sections. Scanning electron microscopy will be used to investigate any misalignment and further characterization can be done to ascertain the additional losses that may be impacting amplifier performance, such as losses at the signal wavelengths. Using the same processes in bulk $Al_2O_3:Er^{3+}$ to define a single layer strip waveguide amplifier has lead to internal gain of up to ~20 dB in similar and higher concentrations (~3.0×10^{20} ions/cm^3) with identical annealing steps and process parameters [9]. There however, uncertainties such as the waveguide absorption and propagation losses are included in the measurement, as well as increased coupling losses to the chip. This discrepancy suggests further characterization of vertical multi-layer coupling losses should be investigated to validate results for the gain medium. It is also possible that higher concentrations could provide increased gain, which can be optimized for shorter or medium (1-10 cm) length amplifiers, whereas lower concentrations here will enable longer devices (20+ cm), which were unfortunately unavailable on the measured sample due to waveguide defects in the gain layer. Future work includes the further annealing and characterization of chips from this same wafer and amplifier sections of varying cross section and length.

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References

[1] W. A. P. M. Hendriks et al., *"Rare-earth ion doped Al_2O_3 for active integrated photonics,"* Advances in Physics X, vol. 6, no. 1, 2021.

[2] J. D. B. Bradley *et al.*, *"Monolithic erbium- and ytterbium-doped microring lasers on silicon chips,"* in *Optics Express,* vol. 22, no. 10, 2014.

[3] Y. Liu, et al., *"A photonic integrated circuit–based erbium-doped amplifier,"* Science, vol. 376, 2022.

[4] J. Mu, et al., *"High-gain waveguide amplifiers in Si_3N_4 technology via double-layer monolithic integration,"* Photonics Research, vol. 10, no. 8, 2020.

[5] C. I. Emmerik et al., *"Relative oxidation state of the target as guide line for depositing optical quality RF reactive magnetron sputtered Al2O3 layers,"* Optical Materials Express, vol. 10, no. 6, 2020.

[6] S. A. Vázquez-Córdova et al., *"Erbium-doped spiral amplifiers with 20 dB of net gain on silicon,"* Optics Express, vol. 22, no. 21, 2014.

[7] T. Chrysostomidis *et al.*, *"8×40 Gbps WDM Amplification in a Monolithically Integrated $Al_2O_3:Er^{3+}$-Si_3N_4 Waveguide Amplifier,"* in *IEEE Photonics Technology Letters*, vol. 33, no. 21, 2021.

[8] J. D. B. Bradley et al., *"Gain bandwidth of 80 nm and 2 dB/cm peak gain in $Al_2O_3:Er^{3+}$ optical amplifiers on silicon,"* Journal of Optical Sciences America B, vol. 27, no. 2, 2010.

[9] D.B. Bonneville et al., *"Material optimization via optical and spectroscopic parameters of $Al_2O_3:Er^{3+}$ for the development of amplifiers and lasers,"* in Proceedings of IEEE Benelux Photonics Chapter, 2022