Influence of waveguide taper length on the total loss of an $Al_2O_3:Er^{3+}$ – Si_3N_4 vertical coupler

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Erbium-doped waveguide amplifiers (EDWAs) play a crucial role in modern telecommunications systems, serving as indispensable components for enhancing signal strength and enabling long-distance data transmission. However, there is a challenge to decrease the size and cost of EDWAs to boost their commercialization. Erbium-doped Aluminium Oxide ($Al_2O_3:Er^{3+}$) has attracted significant interest from the research community due to its high solubility for rare-earth ions, wide optical transparency, and capability to be integrated monolithically onto passive photonic platforms, such as Si_3N_4. Short and low-loss transitions between the active-passive platforms are required to maximize the optical gain of the amplifiers and increase on-chip functionality. In this work, $Al_2O_3:Er^{3+}$ waveguide tapers are fabricated via reactive sputtering, electron beam lithography, and reactive ion etching, which are vertically integrated onto the asymmetric double stripe (ADS) Si_3N_4 TriPleX technology. A systematic study is performed to investigate the influence of the waveguide taper length on the total loss of the vertical couplers.

Introduction

Photonic integrated circuits (PICs) are vital components in contemporary information processing [1], communication systems [2], and sensing applications [3]. As the demand for higher data rates, reduced power consumption, and increased functionality grows, the imperative to seamlessly integrate diverse photonic elements becomes increasingly pronounced. The importance of monolithic integration lies in its ability to consolidate multiple optical functions onto a single chip, offering enhanced compactness, improved performance, and cost-effective production. Furthermore, it involves the co-fabrication of diverse elements on a single substrate, streamlining the manufacturing process and enabling unprecedented levels of miniaturization.

Silicon nitride (Si_3N_4) and aluminum oxide (Al_2O_3) emerge as pivotal materials in this integration landscape due to their unique optical properties and compatibility with existing semiconductor fabrication technologies. Silicon nitride, characterized by its low propagation loss and broad transparency window [4], serves as an excellent medium for guiding and manipulating light. Meanwhile, Al_2O_3 complements Si_3N_4 with its high thermal stability, low propagation losses, and high rare-earth ion solubility, enabling optical gain at a variety of wavelengths [5], C-band for the case of $Al_2O_3:Er^{3+}$ waveguides. For the commercialization of devices, such as EDWAs, the transition between both material platforms should be compact and with minimum optical losses.

Coupler design

The $Al_2O_3:Er^{3+}$ – Si_3N_4 vertical coupler design described in [6] was used for this study. In other words, a Si_3N_4 core with a width of 1.1 µm was laterally tapered to a width of 300 nm while the $Al_2O_3:Er^{3+}$ taper tip was tapered from 150 nm to a waveguide width of 1.75 µm. The tapered length varies from 200 – 800 µm. The $Al_2O_3:Er^{3+}$ core width was chosen to maximize the gain of an EDWA [7]. A schematic of the vertical coupler is presented in Fig 1.

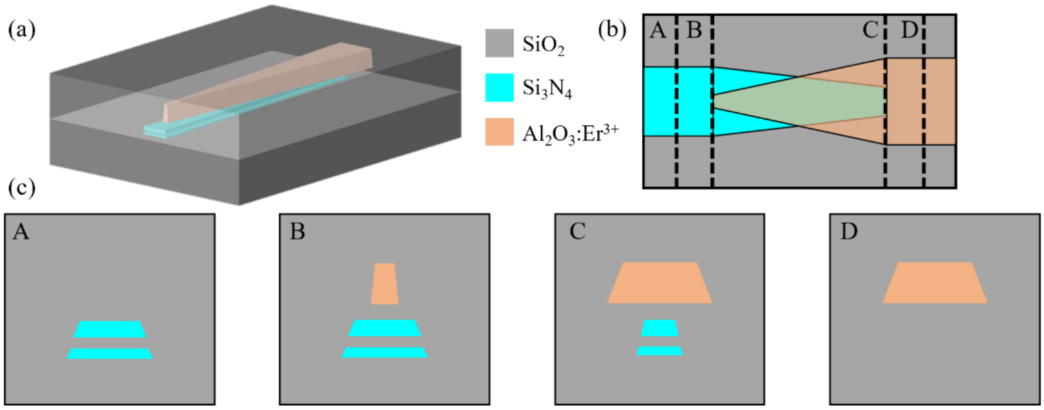

Fig 1. Schematic of vertical coupler. (a) 3D view. (b) Top view. (c) Cross-section at different locations (A: Si_3N_4 core, B: Si_3N_4 core and $Al_2O_3:Er^{3+}$ tip, C: Si_3N_4 tip and $Al_2O_3:Er^{3+}$ core, D: $Al_2O_3:Er^{3+}$ core).

Fabrication

Silicon nitride waveguides were fabricated by LioniX International to achieve low-loss underlying circuits using their standard Asymmetric Double Stripe (ADS) TriPleX platform [4]. A 220 nm buffer SiO_2 separates the Si_3N_4 from the Al_2O_3 waveguides. Reactive magnetron co-sputtering was used with purity controlled solid target precursors in oxygen ambient with a flow of 3.0 sccm following procedures outlined in [8]. A ~770 nm thick layer of $Al_2O_3:Er^{3+}$ with a dopant concentration of approximately 2.5×10^{20} ions/cm^3 was chosen to maximize the overlap with the waveguide while maintaining compact bending radii and increase the gain with as much erbium as the etching process would allow. Electron beam lithography was used to align to a Si_3N_4 marker to define the waveguides on top of the vertical couplers using a dose of 1100 μC/cm^2. Reactive ion-etching (RIE) was performed to define the waveguides. Plasma-enhanced chemical vapour deposition (PECVD) was used to deposit a 6 μm thick SiO_2 cladding 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 550 °C.

Characterization

The experimental setup used to characterize the PIC with a number of cascaded vertical couplers is shown in Fig. 2a. Piezo controlled stages were used to couple the signal from

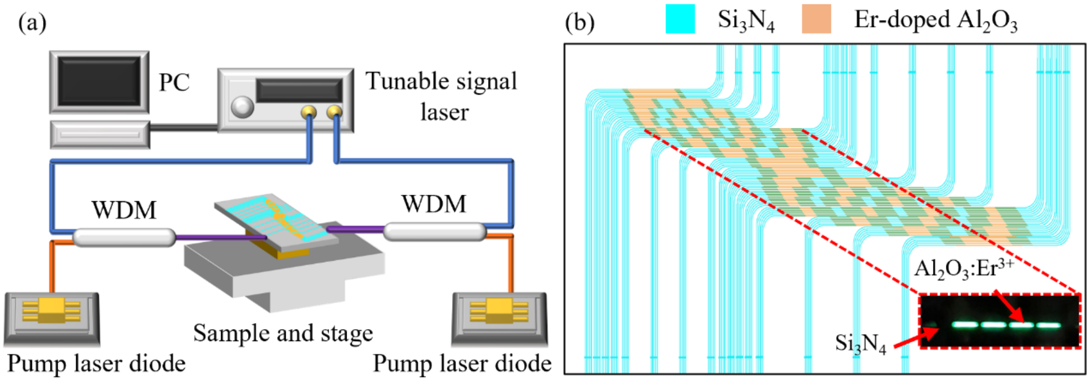

Fig 2. (a) Schematic of the experimental setup. (b) PIC layout. Inset shows sample during alignment with a 1480 nm pump laser to 4 transition waveguide (8 couplers).

a tunable laser (1460 nm – 1640 nm) to the PIC using PANDA single-mode polarization maintaining fibers. Si_3N_4 mode converters were used for optimal coupling at 1550 nm wavelength. The length of the Si_3N_4 and the Al_2O_3:Er^{3+} was fixed for all the waveguides but the number and length of transitions was changed. A total of 12 different designs were characterized, varying the number of cascaded couplers (2, 4, 6, and 8) and the length of the tapered region (200, 400, and 800 µm). The schematic design of the PIC is shown in Fig 2b. A 1480 nm pump laser diode was used to align to the waveguides, since it was easier to distinguish between the number of transitions (Fig. 2b inset).
The coupler loss as a function of wavelength is shown in Fig. 3a. The coupler loss was extracted by fitting the transmitted power as a function of the number of cascaded couplers in the waveguide as illustrated in Fig. 3b. A signal power of 0 dBm was used for all the measurements. For some cases the facet of the waveguides was not optimal, which resulted in an inadequate coupling and the data for such waveguides was excluded from the fitting of the losses (red circle in Fig. 3b).
From Fig. 3a is observed that for longer tapers the total coupler loss is higher. This does not match to the simulated losses in [6], where a value below 0.05 dB per coupler was calculated for an 800 µm long taper. The experimental data indicates that a coupler with a taper length of 800 µm resulted in a loss of 0.25 ± 0.07 dB per coupler in the range of 1530 nm –1640 nm while the 200 µm long taper showed losses of 0.04 ± 0.03 dB per coupler.

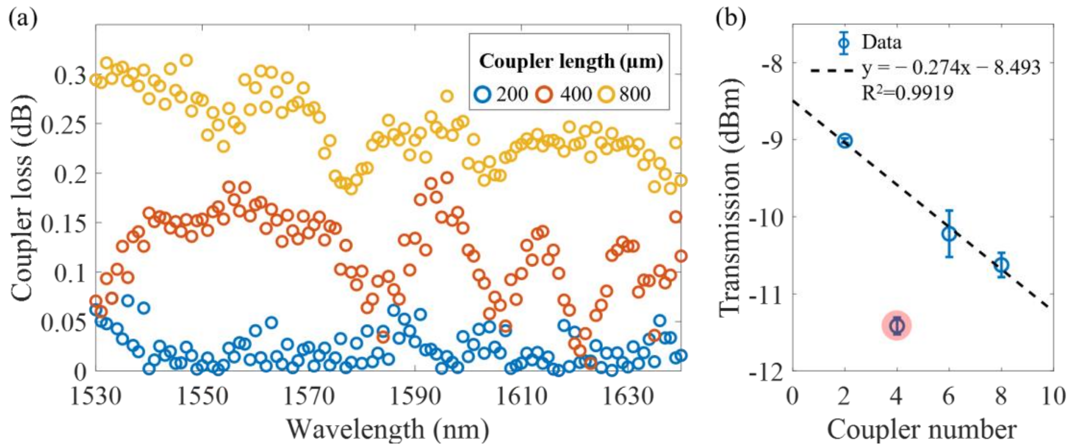

Fig 3. (a) Coupler loss as a function of wavelength for different taper lengths. (b) Transmitted power as a function of number of Al_2O_3:Er^{3+} – Si_3N_4 vertical couplers with a length of 800 µm at the wavelength of 1550 nm.

The waveguides with an 800 µm long taper were further measured at a smaller signal power to investigate the reason of higher loss compared to the shorter tapers. The results are displayed in Fig. 4a. It is visible that for a smaller signal power the coupler loss increases for the wavelength range where the erbium ions have an absorption peak (i.e. 1530 nm – 1560 nm). This trend might indicate that the source of extra losses in the Al_2O_3:Er^{3+} – Si_3N_4 vertical coupler is related to an absorption process. The cross-section depicted in Fig.1c-B was simulated using the FDE solver of Lumerical Mode Solutions software. The E-field intensity of the fundamental TE mode is depicted in Fig. 4b. The fraction of power integrated in the Al_2O_3:Er^{3+} tip (red outline in Fig. 4b) is below 5%. Therefore, it is expected that this section acts as an absorption region in the vertical coupler. The longer the taper is, the more gradual the transition of the Al_2O_3:Er^{3+} cross-section from a 150 nm tip to a 1.75 waveguide core is. In addition, it is possible that there are additional losses in the tapered region due to the interaction of the mode with the sidewall roughness that results from the fabrication process. In this regard, longer tapers means there is a longer interaction section with the narrow Al_2O_3:Er^{3+} waveguide resulting in a higher absorption and interaction with the sidewall roughness and thus increasing the total losses of the Al_2O_3:Er^{3+} – Si_3N_4 vertical coupler. The influence of the absorption and sidewall roughness of the Al_2O_3:Er^{3+} tapered section was not considered in the design optimization presented in [6].

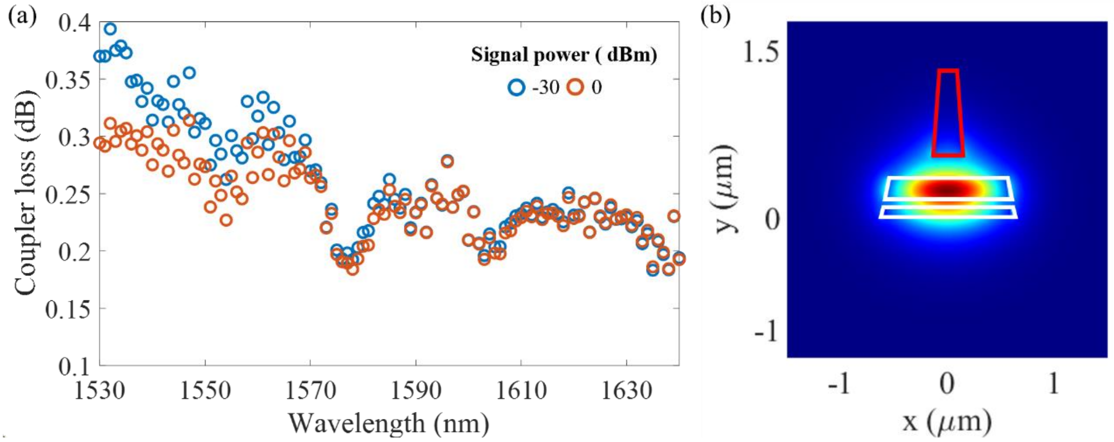

Fig 4. (a) Coupler loss of an 800 µm long taper as a function of wavelength for different signal powers. (b) E-field intensity of the fundamental TE mode for the Al_2O_3:Er^{3+} – Si_3N_4 vertical coupler at a location illustrated in Fig. 1c–B.

Conclusion

In conclusion, the influence of the length on the total losses of an Al_2O_3:Er^{3+} – Si_3N_4 vertical coupler has been investigated. The experimental results showed losses of 0.25 ± 0.07, 0.10 ± 0.09 and 0.04 ± 0.03 dB per coupler for taper lengths of 200, 400 and 800 µm, respectively. In contrast to what was expected from simulations, higher losses were observed for longer tapers. A possible explanation for this behavior are the induced absorption losses in the tapered region due to the small overlap of the signal with the gain medium, this is supported by additional power dependency in the longer tapers.

Passive Al_2O_3 – Si_3N_4 vertical couplers could be fabricated and characterized to see if the absorption losses of the material are increasing the total losses of the couplers. In such case, future work will be focused on the design and optimization of the Al_2O_3:Er^{3+} – Si_3N_4 vertical couplers taking into account the absorption in the tapered region. In addition, it is expected that the coupler losses are dependent on the erbium ion concentration, so it is also an important parameter to consider in future designs, especially for applications such as on-chip booster amplifiers were it is expected to have a high erbium ion concentration. A reliable gain simulation model will be essential for such designs. Therefore, it is important to characterize the spectroscopic parameters of the Al_2O_3:Er^{3+} material.

Furthermore, the cross-section characterization of the fabricated Al_2O_3:Er^{3+} – Si_3N_4 vertical couplers, e.g. using a FIB tool, could reveal additional information regarding the misalignment between the Al_2O_3:Er^{3+} and Si_3N_4 structures, which could increase the coupling losses. Likewise, the quality of the SiO_2 cladding should be investigated since it is possible that some light is leaking through the cladding, which could result in higher losses for longer tapered regions, since in these regions the mode is less confined to the waveguides and has more interaction with the cladding. Finally, the optimization of the fabrication process, e.g. EBL and RIE, will reduce the sidewall roughness of the waveguides, reducing the overall losses of the devices.

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