Hybrid integrated multi-lane erbium-doped Si_3N_4 waveguide amplifiers

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Abstract: We present the integration of four individual erbium-doped waveguide optical amplifiers on a Si_3N_4 photonic integrated circuit hybrid integrated with a four-lane semiconductor pump laser diode chip. Each amplifier achieves 15 dB on-chip gain.

1. Introduction

Erbium-doped fiber amplifiers (EDFAs) [1] are ubiquitously used to serve as power boosters and pre-amplifiers in long-haul coherent optical communications. EDFAs have the advantages of a lower noise figure and the absence of transient gain nonlinearity that can cause signal distortions, in comparison to semiconductor optical amplifiers (SOAs). Therefore, EDFAs are favored in contemporary wavelength-division multiplexed (WDM) optical communications. In contrast to the rapid development of integrated III-V semiconductor lasers and silicon photonic devices such as modulators and photodetectors, the development of on-chip low-noise, high-gain erbium-doped waveguide amplifiers (EDWAs) — the integrated counterpart of the EDFAs — is lagging far behind, which is arguably a long-anticipated building block for silicon-based photonic integrated circuits (PICs). Miniaturized PIC-based EDWAs hold the great potential for emerging applications that require high-density, channel-scalable optical transmission, in particular for the next-generation data center interconnect (DCI), submarine optical cables, and the future large-scale on-chip photonic meshes for optical computing [2, 3].

Chip-scale EDWAs have been compounded by the waveguide loss and the erbium gain coefficient. Recently this was overcome by using low-loss Si_3N_4 waveguides [4] and erbium ion implantation. We demonstrated an erbium-doped silicon nitride (Si_3N_4) photonic integrated circuit-based amplifier by applying high-energy (2 MeV) erbium ion implantation to 700 nm Si_3N_4 photonic chips, achieving 30 dB small signal gain and > 100 mW power, comparable with the performance level of commercial EDFAs [5]. This high-performance EDWAs allows to find immediate applications in photonic generation of microwaves, and multi-Tb/s coherent optical communications [6]. However, the realization of fully-integrated, multi-lane EDWAs have so far remained elusive, which are expected to take the full advantages of the scalability and high integration density of the Si_3N_4 PICs.

In this work, we report a hybrid-integrated waveguide amplifier module that integrates four independent EDWAs on a single Si_3N_4 PIC chip, achieved by 4-inch wafer-scale thin-Si_3N_4 PIC fabrication and ion-implantation. The adoption of 200-nm Si_3N_4 waveguides allows for the reduction of the ion beam energy to 500 keV, thus better availability of implanters, and the increase of amplifier saturation power. We demonstrated an on-chip net gain of up to 15 dB and an output power of 22 mW for individual EDWA lanes.

2. Design and fabrication of multi-lane erbium-doped waveguide amplifiers

Figure 1 (a) shows the layout of a four-lane Er:Si_3N_4 waveguide optical amplifier chip that accommodates four individual EDWAs, each of which consists of a 17-cm-long Archimedean spiral gain section and an on-chip WDM coupler for pump injection. This amplifier device is implemented using 200 nm thick, 5 µm wide Si_3N_4 strip waveguides. The outer diameter of each gain spiral is ~ 2.6 mm ($< 30\,\mathrm{mm}^2$ area) with a > 2.5 µm waveguide section in the S-bend to strip higher order optical modes. We design the on-chip WDMs based on directional couplers [7] to combine the optical signal near 1550 nm and hybrid-integrated 1480 nm pump sources. The input and output ports of all the EDWAs are arranged in an arrayed fashion with a pitch of 250 µm along one chip edge, while the input ports of the pump light are located at the other side of the chip (Fig. 1 (b)). The thin and wide waveguide enables a large mode area of $> 10\,\mu\mathrm{m}^2$, beneficial for higher saturation power and reduced nonlinearity-induced impairment, which is demanded by high power waveguide amplifiers, compared to those

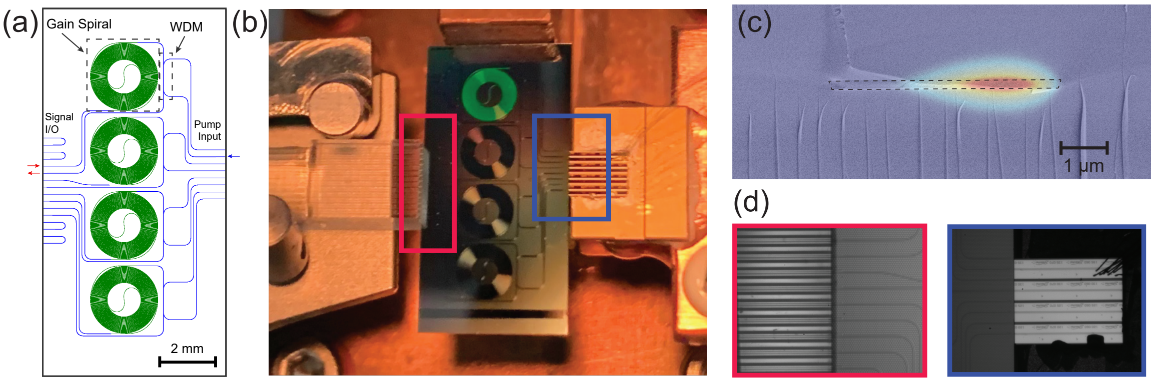

Fig. 1. **The four-lane Er-doped waveguide amplifiers**. (a) Layout of the Er:Si_3N_4 PIC chip. (b) Photo of the hybrid coupled four-lane amplifier under test. (c) Scanning electron microscopy image of the Er:Si_3N_4 waveguide, overlaid with the simulated optical mode. (d) Red: Zoomed-in view of the coupling between the Er:Si_3N_4 chip and the fiber array for signal input and output. Blue: Zoomed in view of the coupling with the hybrid-integrated four-channel pump laser diode.

using thick waveguides with tight optical confinement. The hybrid integration of the multi-lane amplifier device is implemented using with an optical fiber array (PHIX) (Fig. 1 (c)) and a multi-lane pump laser diode chip (Seminex) (Fig. 1 (d)). The pump diodes are single transverse mode Fabré -Pérot diodes delivering up to 400 mW.

The use of 200 nm waveguides—compared to the 700 nm in [5]—allows for lowering implantation energy for erbium ions from 2 MeV to less than 500 keV, as the required ion energy scales approximately linearly with the ion range. The reduced implantation energy greatly relieves the requirement of the ion implanter in terms of terminal voltage and beam current [8], allowing implantation at wafer scale within a reasonable time using commercial tools and mass production at lower cost. However, conversely, using thinner waveguides leads to a lower gain coefficient (in dB/m) at the same doping concentration, as the overlap factor between ion density and optical mode is reduced due to the weaker optical mode confinement. For examples, when using the maximum implantation energy of 500 keV (350 keV), the overlap factor is typically 30% (20%). This trade-off can be alleviated using higher doping concentrations or longer waveguides to reach sufficient total gain.

The waveguides were fabricated by low-pressure chemical vapor deposition, deep ultra-violet lithography, and reactive ion etching. The passive sections were masked by 3 μm-thick photoresist. Erbium ion implantation was carried out at Friedrich Schiller University Jena with maximum beam energy of 350 keV and total implantation dose of $2.4 \times 10^{15}\,\mathrm{cm}^{-2}$. After implantation, we annealed the samples at 1000 °C (1 h, in O_2) and deposited a 3 μm SiO_2 cladding by plasma-enhanced chemical vapor deposition with $SiCl_4$ as precursor [9]. The background loss of the annealed waveguides ranges from 5 dB/m to 10 dB/m at 1.3 μm (outside the erbium absorption bands).

3. Performance characterization of the EDWA

Figure 2 (a) shows the experimental setup for characterization of the multi-lane EDWA. The signal input and output were coupled with a 250-μm pitch fiber array with twelve UHNA7 fibers that have matched optical mode area with the waveguide tapers. The coupling loss was characterized to be $\sim$ 4.9dB per facet, which is subject to further optimization. An 1550 nm external cavity diode laser (Toptica) is used as input signal after attenuation (ATT) and polarization controller (FPC). Signal output is measured with a power meter (PM) and an optical spectrum analyzer (OSA) after a 1500 nm low-pass filter (LPF) to reject the residual pump. Figure 2 (b) shows the small signal on-chip net gain of two channels, both channels have comparable maximum gain of 13 dB to 15 dB. The achieved gain is so far constrained by the estimated $\sim$ 20% overlap factor, which leads to a limited gain coefficient. This can be overcome by increasing the implantation fluence and the overlap factor. Benefiting from the larger mode area, the saturation input power was increased to around -5 dBm (Fig. 2 (c)). Figure 2 (d) shows the on-chip output power in typical large signal operation. An output power of up to 22 mW is achieved at 278 mW off-chip pump power. This corresponds to a 12% on-chip power conversion efficiency considering a pump coupling loss of 2.5 dB. Both channels show comparable gain performance in characterization. We note that we operated the EDWA lanes individually, considering thermal management in this proof-of-concept demonstration.

4. Conclusion

We demonstrated a four-channel erbium-doped waveguide amplifier with a hybrid integrated pump laser diode array. The four gain spirals and the WDMs are integrated within a 6.5 mm$\times$13 mm chip. The amplifier lanes

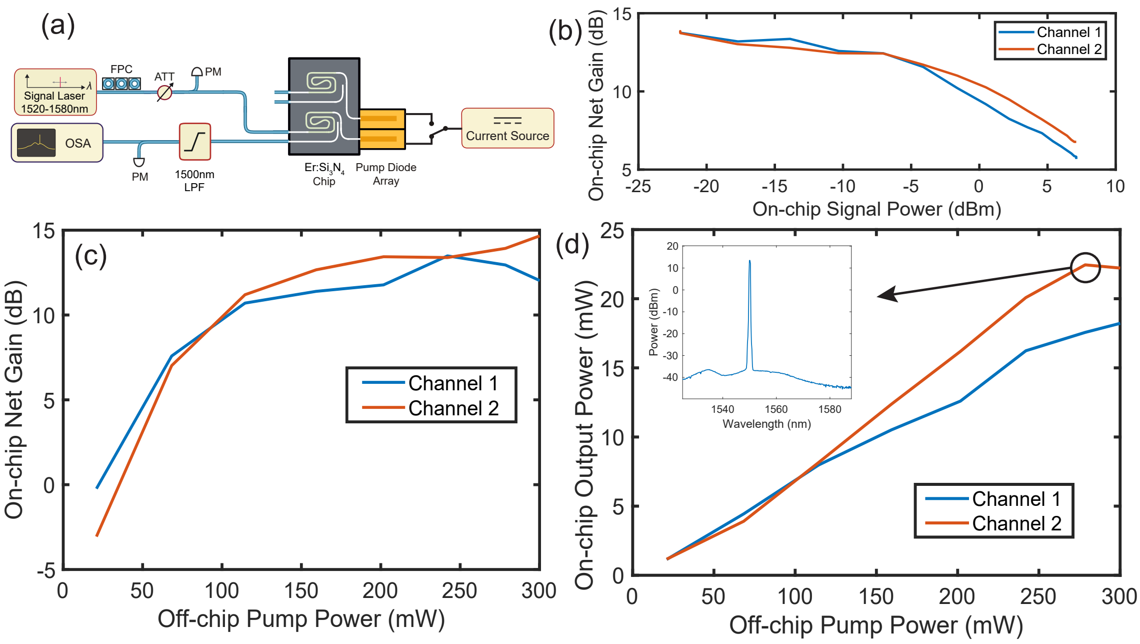

Fig. 2. **Multilane-EDWA performance characterization**. (a) Device characterization setup. For simplicity, only two channels are shown. (b) Measured on-chip net gain at different 1550 nm signal power level, where off-chip pump power is around 242 mW. (c) On-chip net gain at different diode pump power. Measured at -19.9 dBm on-chip signal power. (d) On-chip output power at different Off-chip pump power. Measured at 5.4 dBm on-chip signal power. Inset: output optical spectrum.

achieved maximum 15 dB on-chip gain and up to 22 mW on-chip output power. We envisage that such high-density multi-channel amplifiers have great potential for applications requiring scalability such as compact, pluggable optical line systems for inter-datacenter communications, integrated microwave photonics, phased array systems, space-division multiplexing transmission, and submarine optical cables.

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References

1. Robert J. Mears, et al. ”Low-noise erbium-doped fibre amplifier operating at 1.54 μm,” Electronics Letters **19**, 1026-1028 (1987).
2. Peter J. Winzer, and David T. Neilson., ”From scaling disparities to integrated parallelism: A decathlon for a decade,” IEEE J. Lightwave Technol. **35**, 1099-1115 (2017).
3. Johannes Feldmann, et al., ”Parallel convolutional processing using an integrated photonic tensor core” Nature **589**, 52-58 (2021).
4. Junqiu Liu, et al. ”High-yield, wafer-scale fabrication of ultralow-loss, dispersion-engineered silicon nitride photonic circuits,” Nature communications **12** 2236 (2021).
5. Yang Liu, et al. ”A photonic integrated circuit–based erbium-doped amplifier,” Science **376**, 1309-1313 (2022).
6. D. Che, et al., ”First Demonstration of Erbium-Doped Waveguide Amplifier Enabled Multi-Tb/s (16×1.6T) Coherent Transmission,” in Optical Fiber Communication Conference (OFC) 2023, Technical Digest Series (Optica Publishing Group, 2023), paper Th4B.3.
7. H. C. Cheng and R. V. Ramaswamy, ”Symmetrical directional coupler as a wavelength multiplexer-demultiplexer: theory and experiment,” IEEE Journal of Quantum Electronics **27**, 567-574 (1991).
8. S. B. Felch et al., Proceedings of the North American Particle Accelerator Conference. Vol. 9. 2013. Felch, S. B. et al., ”Ion implantation for semiconductor devices: The largest use of industrial accelerators,” in Proceedings of the North American Particle Accelerator Conference, (JACoW, 2013), Vol. 9, pp. 740-744.
9. Zheru Qiu, et al., ”Low-temperature and hydrogen-free silicon dioxide cladding for integrated photonics,” in CLEO 2023, Technical Digest Series (Optica Publishing Group, 2023), paper SM2H.2.