PHOTONICS

A photonic integrated circuit–based erbium-doped amplifier

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Erbium-doped fiber amplifiers revolutionized long-haul optical communications and laser technology. Erbium ions could provide a basis for efficient optical amplification in photonic integrated circuits but their use remains impractical as a result of insufficient output power. We demonstrate a photonic integrated circuit–based erbium amplifier reaching 145 milliwatts of output power and more than 30 decibels of small-signal gain—on par with commercial fiber amplifiers and surpassing state-of-the-art III–V heterogeneously integrated semiconductor amplifiers. We apply ion implantation to ultralow-loss silicon nitride (Si3N4) photonic integrated circuits, which are able to increase the soliton microcomb output power by 100 times, achieving power requirements for low-noise photonic microwave generation and wavelength-division multiplexing optical communications. Endowing Si3N4 photonic integrated circuits with gain enables the miniaturization of various fiber-based devices such as high–pulse-energy femtosecond mode-locked lasers.

The invention of erbium-doped fiber amplifiers (EDFAs) in the 1980s (1, 2) revolutionized long-haul optical communications, profoundly affecting the transmission of information in society. EDFAs have replaced complex and bandwidth-limited electrical repeaters, enabling transatlantic fiber-based optical communication networks (3). Erbium amplifiers have a number of properties highly suitable for optical communications, such as a broadband gain of ~1550 nm-wavelength that coincides with the lowest optical fiber propagation loss band, a long millisecond (ms)-lifetime of the parity forbidden intra–4f shell \(^{4}I_{13/2} \leftrightarrow ^{4}I_{15/2}\) transition that leads to slow gain dynamics and negligible interchannel cross-talk in multiwavelength amplification, high-temperature stability, and a low-noise figure approaching the quantum mechanical limit of 3 decibels (dB) for phase-insensitive amplification (4). Today, EDFAs have underpinned the development of narrow-linewidth and mode-locked lasers that are widely deployed in applications such as coherent communications (5), interferometric sensing, and optical frequency metrology (6). Rare-earth ion doping (6, 7) can provide the basis for compact erbium-doped waveguide amplifiers (EDWAs) (8). In the 1990s efforts were made to implement EDWAs on the basis of oxide glass waveguides (9, 10), but these were hindered by large waveguide background losses, large device footprints, and incompatibility with contemporary photonic integrated circuits, and thus were ultimately abandoned. Interest in EDWAs re-emerged with the Si3N4 complementary metal-oxide-semiconductor–compatible photonic integrated circuit platform, with advantages over silicon including a wider transparency window (11), absence of two-photon absorption in telecommunication bands, lower temperature sensitivity, high power handling of >10 watts (12), and most crucially, low propagation losses of <3 dB/m, maintained over meter-scale lengths (13).

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Fig. 1. Integrated erbium-implanted Si3N4 waveguide amplifier. (A) A Si3N4 waveguide amplifier with erbium ions optically excited by a 1480-nm pump. (B) Optical image of a 0.5-m-long Er: Si3N4 waveguide coil. (C) Schematics of key fabrication processes and SEM images of waveguide cross sections overlaid with the simulated optical transverse electric (TE) mode before and (D) after ion implantation. (E) Vertical profiles of calculated erbium concentration (green), simulated optical TE mode intensity (red), and measured concentration (blue) by Rutherford backscattering spectrometry (RBS) across the waveguide center. (F) Measured optical losses before ion implantation, as-implanted, and after annealing. (G) Optical image of an intensely pumped Er: Si3N4 chip butt-coupled with optical fibers.
One challenge in realizing photonic integrated circuit–based erbium amplifiers is the limited achievable gain stemming from constraints in doping concentration due to cooperative upconversion (14). This limitation necessitates waveguides with low propagation losses and long waveguides with lengths ranging from tens of centimeters to meters, to achieve large gain and high output power. Although net gain has been shown, all prior work using erbium-doped Al2O3 (15, 16), TeO2 (17), and erbium chloride silicate nanowires (18) typically achieved low output power of <1 mW, below the level demanded by many applications and below that achieved with heterogeneous III-V integration in silicon photonics (19, 20).

We demonstrate a photonic integrated circuit–based erbium-implanted Si3N4 (Er:Si3N4) amplifier based on meter scale ultralow-loss Si3N4 waveguides (Fig. 1A). We fabricate densely-packed Si3N4 spiral waveguides of 0.5 m in length (Fig. 1B) with 3-μm gap spacing and cross sections measuring 0.7 × 2.1 μm², achieving a compact footprint of only 1.2 × 3.6 mm² and a propagation loss of <5 dB/m through the photonic damascene process (13) (Fig. 1C and fig. S1). We use devices without top cladding to enable direct ion implantation into the waveguide core (Fig. 1D). Next, we apply ion implantation (6)—a wafer-scale process that benefits from much lower cooperative upconversion compared with cosputtered films (14)—to the Si3N4 integrated circuits (fig. S1). To achieve a large overlap of Γ = 50% between embedded ions with the fundamental optical waveguide mode, we use three successive implantation steps with ion energies of 2.0, 1.416, and 0.966 mega–electron volts (MeV) and corresponding ion fluences of 4.50 × 10^15, 3.17 × 10^15, and 2.34 × 10^15 cm⁻², respectively. The simulated concentration profile (Fig. 1E, green) with a maximum depth of 400 nm in Si3N4 (21) matches well with Rutherford backscattering spectrometry (RBS) measurement (fig. S2).

Upon implantation the waveguide background loss increases from <5 to 100 dB/m because of implantation defects (Fig. 1F). The background loss outside the erbium absorption band is reduced after annealing at 1000°C in oxygen for 1 hour and approaches the same level as undoped waveguides (21). Green luminescence is observed stemming from cooperative upconversion (Fig. 1G). Notably, such a loss only contributes <2.5 dB of background attenuation for a 0.5-m-long waveguide, appreciably lower than the 30 dB passive loss for waveguides of equal lengths in prior work (15, 16), which depletes the pump early and prevents efficient amplification. Moreover, we investigate selective masking (using a photoresist) during ion implantation (figs. S4 and S5). Crucially, lateral claddings can provide mechanical support to mitigate severe cross section deformations observed in the waveguides without lateral claddings (figs. S1 and S6).

The emission and absorption cross sections [σₐ(λ) and σₐ(λ)] are important parameters for modelling gain performance and extracting cooperative upconversion coefficients. Figure 2A shows the emission spectrum when pumping the 4I13/2 state (980 nm) in a 0.46-cm-long Er:Si3N4 waveguide, from which the emission cross section (Fig. 2C) can be derived (22) through \( \sigma_\text{em} = 8\pi n^2 c \frac{\sigma_a(\lambda)}{\lambda^2} d\lambda \), in which \( n \) is the waveguide refractive index and \( \tau = 3.4 \text{ ms} \).
is the photoluminescence lifetime fitted from temporal measurement (Fig. 2, D and E), assuming the modification (~0.93) of the density of states has limited effects on the emission rate (27). The wavelength-dependent erbium absorption loss $\alpha_s(\lambda)$ is derived from the intrinsic resonance linewidths of an Er:Si$_3$N$_4$ micro-ring resonator and is calibrated by optical frequency domain reflectometry measurements (fig. S3). The loss is proportional to the erbium absorption cross section given by $\sigma_s = N_0 \sigma_{ls}(\lambda)$, in which $N_0$ is the effective peak erbium ion concentration and $\Gamma$ is the overlap factor (23). The absorption cross section $\sigma_0(\lambda)$ is obtained by scaling its peak value to approximately that of the derived $\sigma_s(\lambda)$, which in turn gives $N_0 = 1.35 \times 10^{20} \text{ cm}^{-3}$, indicating that almost all the incorporated erbium ions are optically active compared with the RBS measurement (Fig. 1E). Comparisons of measured gain coefficients are made under different ion concentrations (Fig. 2F), pump wavelengths, and waveguide widths (fig. S7).

Next, we demonstrate high output power and large net gain upon 1480 nm pumping in a 0.21-meter-long Er:Si$_3$N$_4$ waveguide with an erbium concentration of $3.25 \times 10^{20} \text{ cm}^{-3}$ (Fig. 3A), showing a broadband on-chip net gain of 30 dB (Fig. 3B). Figure 3C shows measured net gain at 1550 nm along with simulations reproduced for parameter fitting. The on-chip output power reaches 60 mW for 0.07 mW input, indicating an off-chip net gain of 24 dB considering ~5.8-dB coupling loss. The on-chip output power reaches 145 mW for an increased input power of 2.61 mW at 245 mW coupled pump power (Fig. 3D, inset), indicating an on-chip power conversion efficiency approaching 60% (signal power increment divided by pump power). Similar gain performance is achieved in a 0.5-meter-long Er:Si$_3$N$_4$ waveguide with a lower erbium concentration of $1.35 \times 10^{20} \text{ cm}^{-3}$ (figs. S9 and S10). A noise figure of ~7 dB is measured at a net gain of ~20 dB (fig. S11) and the excess EDWA RIN approaches the same level (ca. ~18 cm$^2$s$^{-1}$) as the EDFA for >10 MHz offset Fourier frequency (fig. S12). Simulations suggest that the low cooperative upconversion $(C_{24} = 3.0 \times 10^{-18} \text{ cm}^3 \text{s}^{-1}$ and $13.0 \times 10^{-18} \text{ cm}^3 \text{s}^{-1}$ fitted for low and high concentrations, respectively) does not impose limitation on the EDWA gain performance at high pump power >245 mW (27). The observed fluctuations in measured gain are caused by the gain clamping effect when parasitic lasing occurs in an optical Fabry-Pérot cavity formed by waveguide facets (fig. S13).

As an example of the utility, we apply the Er:Si$_3$N$_4$ EDWA to the amplification of soliton microcombs (Fig. 4A) (24), which typically exhibit low conversion (~1%) efficiency (25) and require amplification in virtually all applications. First, a 19.8-GHz single-soliton microcomb generated in a Si$_3$N$_4$ Euler-bend racetrack microresonator (26) with 0.08 mW output power (Fig. 4B, panel (i)), is amplified to 8.4 mW of off-chip power by the EDWA (panel (ii)). This leads to a reduction in single-sideband phase noise of a soliton repetition rate to ca. ~14 dBc/Hz at >1 MHz offset Fourier frequency, compared with ~104 dBc/Hz (before amplification) limited by photon shot noise (Fig. 4C). Comb line spikes [panel (iii)] are induced by the regenerative feedback from EDWA chip facets. A commercial EDFA is deployed to amplify the same soliton microcomb to a similar power level [panel (iii)], giving identical performance.

Second, we demonstrate a telecommunication experiment using an amplified soliton

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**Fig. 3. Intense optical amplification in an Er:Si$_3$N$_4$ waveguide amplifier.** (A) Experimental setup for optical amplification with a free-space filter for pump suppression. ATT, tunable optical attenuator; PM, power meter; OSA, optical spectrum analyzer. (B) Measured gain spectrum. (C) Measured (scatters) and simulated (curves) gain at 1550 nm. The color-shaded areas indicate the region of off-chip net gain and sources of loss. (D) Measured output power at 1550 nm. The inset shows the calibrated optical spectrum at 145 mW signal output.
Soliton microcomb amplification

(A) Experimental setup for soliton amplification, microwave generation, and wavelength-division multiplexing optical communication. FBG, fiber Bragg grating; DEMUX, demultiplexer; LO, local oscillator. (B) Amplification of 19.8 GHz microcomb. (i) Generated single-soliton state microcomb, (ii) amplified microcomb by the EDWA (inset), and (iii) amplified microcomb by a commercial EDFA (inset). The EDWA output power is measured with ~3.5 dB insertion loss of fiber couplers and filters. (C) Measured single-sideband phase noises of generated microwave signals. (D) Optical spectra of amplified 100 GHz soliton microcomb and input. (E) Measured bit error ratio (BER). Blue (red) dashed line corresponds to 7% soft decision (20% hard decision) forward error correction overhead. (F) Reconstructed QPSK constellation diagrams.

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**Fig. 4.** On-chip amplification of soliton microcombs. (A) Experimental setup for soliton amplification, microwave generation, and wavelength-division multiplexing optical communication. FBG, fiber Bragg grating; DEMUX, demultiplexer; LO, local oscillator. (B) Amplification of 19.8 GHz microcomb. (i) Generated single-soliton state microcomb, (ii) amplified microcomb by the EDWA (inset), and (iii) amplified microcomb by a commercial EDFA (inset). The EDWA output power is measured with ~3.5 dB insertion loss of fiber couplers and filters. (C) Measured single-sideband phase noises of generated microwave signals. (D) Optical spectra of amplified 100 GHz soliton microcomb and input. (E) Measured bit error ratio (BER). Blue (red) dashed line corresponds to 7% soft decision (20% hard decision) forward error correction overhead. (F) Reconstructed QPSK constellation diagrams.
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SUPPLEMENTARY MATERIALS

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Materials and Methods

Supplementary Text

Tables S1 to S3

References (32–65)

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