On-chip integrated waveguide amplifiers on Erbium-doped thin film lithium niobate on insulator

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We demonstrate on-chip light amplification with integrated optical waveguide fabricated on erbium-doped thin film lithium niobate on insulator (TFLNOI) using the photolithography assisted chemo-mechanical etching (PLACE) technique. A maximum internal net gain of 18 dB in the small-signal-gain regime is measured at the peak emission wavelength of 1530 nm for a waveguide length of 3.6 cm, indicating a differential gain per unit length of 5 dB/cm. This work paves the way to the monolithic integration of diverse active and passive photonic components on the TFLNOI platform.

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1. INTRODUCTION
The establishment of erbium-doped fiber amplifier (EDFA), featuring a low-nonlinearity and low-noise amplification with a broad gain covering the telecom C- and L-bands, underpins the current long-haul fiber lightwave systems. The essential advantages of rare-earth-ion-doped materials at longer excited-state lifetimes and less refractive index changes induced by excitations of doped ions compared to the electron-hole pairs in III-V semiconductors, also boost deep and extensive researches on the photonic integration of erbium-doped waveguide amplifiers and lasers with a variety of passive components on a single chip [1, 2]. An abundant of host materials including crystalline materials like lithium niobate and amorphous materials like aluminum oxides, are widely investigated to provide spatially and temporally stable gain by erbium doping for high-bit-rate optical communication and narrow-linewidth laser source [2-7].

Recently, the thin film lithium niobate on insulator (TFLNOI) platform has attracted increasing interests in photonic integrated circuits (PIC) owing to its broad optical transparency window (0.35-5 μm), high nonlinear coefficient (d33 = −41.7 ± 7.8 pm/V@λ = 1.058 μm), high refractive index (~2.2), and large electro-optical effect (r33 = 30.9 pm/V@λ = 632.8 nm). Significant progresses in the design and fabrication of passive photonic components based on TFLNOI have been made towards both scientific and technical applications including nonlinear frequency conversion, high-speed integrated modulator, quantum information technology, microwave photonics, frequency microcomb and precision metrology [8-14]. A growing impetus on integration of active components such as lasers and amplifiers based on the erbium-doped TFLNOI platform emerges, though the microchip lasers on the erbium-doped TFLNOI are only demonstrated very recently, showing great potentials for high-performance scalable light sources on the TFLNOI platform [15, 16].
Here, we demonstrate the first monolithically integrated erbium-doped TFLNOI waveguide amplifier, to the best of our knowledge, fabricated by photolithography assisted chemo-mechanical etching (PLACE). The on-chip integrated device exhibits more than 40 nm bandwidth of internal net gain around the C-band, with the peak gain of 18 dB in the small-signal gain regime at ~1530 nm for a 3.6 cm long waveguide. This work demonstrates the efficient broadband amplifications by erbium-doped TFLNOI waveguide amplifiers, paving the way to the monolithic integration of diverse active and passive photonic components on the TFLNOI platform.

2. EXPERIMENTAL RESULTS

Fig. 1(a) shows the schematic of the monolithic Er$^{3+}$-doped lithium niobate (LN) waveguide amplifier chip. The 600-nm-thick Er$^{3+}$-doped Z-cut LN waveguides with a top-width of ~1.2 μm and a bottom-width of ~4 μm are located on the top of a 2-μm-thick silica layer, which is further bonded onto a 0.5-mm-thick undoped crystalline LN wafer. The monolithic Er$^{3+}$-doped LN waveguide amplifier chip was fabricated using PLACE technique, and details about the fabrication process can be found in Refs. 17-20. The concentration of Er$^{3+}$ ions in the LN waveguides is 1 mol%, Fig. 1(b) and (c) presents the zoom-in images of the curved and straight waveguides of the on-chip Er$^{3+}$-doped LN waveguide amplifier, respectively. The rim of the LN waveguide displays interference patterns under illumination, indicating the varying thickness at the edge of the LN waveguide. The spiral design reduces the overall footprint of the amplifier, providing a total gain length of 3.6 cm with a minimum bending radius of 800 μm. Fig. 1 (d) presents the scanning electron microscope (SEM) image of the cross-section of the fabricated Er$^{3+}$-doped LN waveguide, the tilt angle of SEM image is about 52°. The LN waveguide is coated with a thin layer of metal film for the sake of imaging in the SEM process, thus both the top surface and sidewall appear a little bit rough. Fig. 1 (e) shows the simulated electric field distribution of the fundamental mode in the LN waveguide at λ=1550 nm.

![Fig. 1](image1)

![Fig. 1](image2)

![Fig. 1](image3)

![Fig. 1](image4)

![Fig. 1](image5)

The pump-and-signal method was applied to measure the internal net gain in the Er$^{3+}$-doped LN waveguides as shown in Fig. 2. The pump light at 980 nm is provided by a diode laser (CM97-1000-76PM, Wuhan Fredlink Opto-electronics Co., Ltd.), while a continuous-wave C-band tunable laser (TLB 6728, New Focus Inc) with the wavelength range from 1520 nm to 1570 nm was used as the signal. The polarization states of both the pump and signal lasers are adjusted using several inline fiber polarization controllers. The pump and signal light waves were combined (separated) by the fiber-based wavelength division multiplexers (WDM) at the input (output) port of the integrated amplifier. Bidirectional pumping scheme was employed to invert the erbium ions more uniformly along the full length of the amplifier. The polarization states of the pump and signal lasers were adjusted by an commercialized fiber polarization controller. Both the output amplified signals and amplified spontaneous emissions (ASE) were measured by an optical spectrum analyzer (OSA: AQ6370D, YOKOGAWA Inc.). Since the launching and collecting lensed fibers have exactly the same characteristics in all the experiments, individual coupling efficiencies were assumed for both the input and output ports. The photograph of a pumped (λp = 980 nm) Er$^{3+}$-doped LN waveguide spiral amplifier chip in Fig. 2 displays the strong green upconversion fluorescence along the Er$^{3+}$-doped LN waveguide.

![Fig. 2](image6)

![Fig. 2](image7)

![Fig. 2](image8)

![Fig. 2](image9)

![Fig. 2](image10)

Fig. 3 Propagation losses measurement, (a) Transmission spectrum of the Er$^{3+}$-doped LN microring, the inset displays a 400-μm-diameter Er$^{3+}$-doped LN microring integrated with a undoped LN waveguide, (b) The Lorentzian fitting indicating the Q-factors of $2.6 \times 10^6$ of the microring as measured at 1554.13 nm wavelength, (c) Top-view microscope Image of a 300-μm-long straight waveguide, (d) Intensity distribution along the propagation direction in the 300-μm-long straight waveguide.

The optical propagation losses of the Er$^{3+}$-doped LN waveguides around the signal wavelength (~1550 nm) were first characterized using whispering-gallery-resonator-loss measurements [17]. An Er$^{3+}$-doped LN microring resonator with the diameter of 400 μm was fabricated using the same waveguide parameters shown in Fig. 1. The measured transmission spectrum of the micro-ring resonator around 1550 nm is depicted in Fig. 3(a), featuring a free spectral range (FSR) of 8 nm which is well consistent with the 400 μm diameter of the
microring resonator. The regularly spaced resonance lines indicate the dominant excitations of the fundamental modes in the microring resonator. As shown in Fig.3(b), one of the whispering-gallery modes at the resonance wavelength of 1554.13 nm was chosen for the measurement of the loaded Q-factor by fitting the transmission curve with a Lorentz function, giving $Q_s = 2.6 \times 10^4$. Meanwhile, the group index at the wavelength of 1554.13 nm was calculated by group index $n_g = \lambda^2 / (\pi D \cdot FSR)$ to be 2.4, where $D$ is the diameter of the microring resonator. Consequently, the propagation loss of the Er$^{3+}$-doped LN waveguide was deduced to be 0.16 dB/cm using the expression $\omega = 2\pi n_g / (Q_s)$. It should be noted that the retrieved propagation loss includes both the waveguide scattering loss due to the sidewall roughness and the absorption loss induced by ground-state erbium ions.

The optical losses at the pump wavelength of 980 nm were further estimated by measuring the green fluorescence from the energy-transfer-upconversion (ETU) of Er$^{3+}$ ions excited by the pump light [2]. Top-view microscope images of the scattered fluorescence ($\sim 530$ nm) in a 300-μm-long straight waveguide under the dark-field and bright-field conditions captured by an COMS camera (DCC32-40C, Thorlabs Inc.) were shown in Fig. 3(c). Assuming that in average the intensity of scattered fluorescence is proportional to the local intensity of the pump travelling through the waveguide, a Lambert-Beer law for the decay of the fluorescence along the waveguide path is observed and fitted as plotted in Fig. 3(d), indicating a propagation loss of 6.28 dB/cm around 980 nm. Besides, the fiber-to-chip coupling losses for the integrated amplifier were measured to be 10 dB and 73 dB per facet at the wavelengths of 980 nm and 1550 nm, respectively. The high coupling losses are due to the unoptimized mode field profiles in both of the LN waveguide and lensed fibers.

The internal net gain of the Er$^{3+}$-doped LN waveguide amplifier was measured by the signal enhancement method and defined by the following equation

$$g = 10 \log \frac{P_{\text{on}}}{P_{\text{off}}} - \alpha_1 L$$

where $P_{\text{on}}$ and $P_{\text{off}}$ are the collected signal powers with and without the pump laser measured at the output fiber respectively, and $\alpha_1$ is the optical propagation loss of Er$^{3+}$-doped LN waveguide in dB/cm. Figs. 4(a) and 4(c) demonstrate the measured spectra with different pump powers for the signal wavelength of 1530 nm and 1550 nm, respectively. Figs. 4(b) and 4(d) shows the net gain of the integrated amplifier as a function of the launched pump power for the signal wavelengths at 1530 nm and 1550 nm, respectively. In both cases a rapid rising of gain values following the growing pump power is first observed, which is followed by a slow gain saturation at the higher pump powers (>20 mW). Specifically, the internal net gain for the 1530 nm signal approaches the maximum gain of ~18 dB at the launched pump power of ~40 mW.

The gain dependence of the amplifier on the signal powers was also investigated. By setting the launched pump power to ~20 mW, the net gains provided by the amplifier were measured at different signal powers with the results shown in Fig. 5. It can be clearly seen that the small-signal gain was gradually decreased at increasing signal powers due to the depletion of excited-state population of erbium ions.

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without injection of the signal laser was shown in the inset of Fig. 6 for comparison. The good agreement between the gain spectrum and the ASE spectrum corroborates the reliable population inversion of erbium ions excited within the Er\(^{3+}\)-doped LN waveguide amplifier.

3. CONCLUSION

Erbium-doped Ti-diffused lithium niobate channel waveguides have been previously employed for integrated amplifiers and lasers, allowing versatile functionalities due to the excellent electrooptical, acoustooptic, and nonlinear optical properties of the LN substrate [21–23]. However, the large mode size and inhomogeneous distribution of erbium ions in the Er\(^{3+}\)/Ti:LiNbO\(_3\) waveguides limit the attainable gain coefficients to ~2 dB/cm. In contrary, the Er\(^{3+}\)-doped LN ridge waveguides realized in the current work enable a tight confinement of the guided modes as well as a uniform concentration across the waveguide, facilitating a good spatial overlap between the pump and signal fields with the erbium gain volume and achieving the record-high differential gain of ~5 dB/cm with ~40 mW in-coupled pump power at ~980 nm. Further optimizations concerning the erbium doping concentration to suppress the quenching of excited ions by energy transfer and diffusion processes, the waveguide geometric design to allow for high-power amplifications, and the pumping condition to promote excited-state population, are anticipated to increase the waveguide gain to even higher values comparable with other erbium-doped waveguide amplifiers, holding broad perspectives in sophisticated designs of photonic integrated circuits.

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