Integrated spiral waveguide amplifiers on erbium-doped thin-film lithium niobate

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Integrated optical amplifiers and light sources are of great significance for photonic integrated circuits (PICs) and have attracted many research interests. Doping rare-earth ions in materials as a solution to realize efficient optical amplifiers and lasing has been investigated a lot. We investigate the erbium-doped lithium niobate on insulator (LNOI). Here, spiral waveguide amplifiers were fabricated on a 1-mol% erbium-doped LNOI by CMOS-compatible technique. We demonstrated a maximum internal net gain of 8.3 dB at 1530 nm indicating a net gain per unit length of 15.6 dB/cm with a compact spiral waveguide of 5.3 mm length and ~0.06 mm² footprint. The erbium-doped integrated lithium niobate spiral waveguide amplifiers would pave the way in the PICs of the lithium niobate platform, especially in achieving efficient integration of active and passive devices on a lithium niobate thin film, which will make full use of its excellent physical properties such as remarkable photoacoustic, electro-optic, and piezoelectric characteristics.

Integration is of great significance in device miniaturization and improving energy efficiency. Photonic integrated circuits as one of important goals for the development of photonics have attracted enormous attentions and became one of the most inveetigated research fields. Lithium niobate (LN) as an emerging integrated photonic platform material is widely used in optical and microwave fields, due to its rich properties as wide transparent wavelength range, excellent electro-optic, acousto-optic characteristics and large second-order nonlinear susceptibility. In particular, with the lithium niobate on insulator (LNOI) commercializing, more compact and low-cost photonic devices with high-performance can be achieved on LNOI, which is very important for the Photonic integrated circuits, especially for the development of a large number of integrated functional devices. Many on-chip optical devices based on LNOI have been demonstrated, such as efficient frequency converters, electro-optical modulators, frequency comb sources. However, for a complete photonic integrated circuits, integrated waveguide amplifiers and light sources are essential elements to realize on-chip various functionalities. Due to the LN is not an efficient gain medium, we can not achieve waveguide amplifier and lasing directly on a LNOI. In order to overcome this shortage, the most straightforward approaches is to doping rare earth ions into the LNOI, which is similar to the erbium doped fiber amplifier. Actually, erbium-doped laser and waveguide amplifier have been realized in many host materials and show great potential for integrated waveguide amplifiers and light sources. The on-chip whispering gallery mode lasers based on the LNOI also have been demonstrated, recently. But, there are still less research works about the on-chip spiral waveguide amplifiers based on the LNOI. It’s worth noting that a efficient waveguide amplifier based on erbium-doped thin film LN has been realized recently. However, this straight waveguide amplifier with a length of 5-mm is still too long to realize a more compact on-chip photonic integration, especially for a chip with a large number of functional devices.

Here, we demonstrated a spiral waveguide amplifier with a maximum net gain of 8.3 dB on a 1-mol% erbium-doped LNOI, with a 15.6 dB/cm net gain per unit length. The spiral waveguide amplifiers with total 5.3-mm-long and ~0.06 mm² of footprint based on the CMOS compatible process, presents strong light confinement for the signal and pump light and have great significance on photonic integrated circuits. We shows that it is possible to achieve efficient on-chip amplifiers with a small footprint spiral waveguides, which would pave the way for the active and passive photonic devices integration of various functionalities on the erbium-doped LNOI platform.

The spiral waveguide amplifiers were fabricated on a 1-mol % Z-cut erbium-doped LNOI, with 600-µm-thick erbium-doped lithium niobate (LN), 2-µm-thick silica (SiO₂) and 500-µm-thick silicon (Si) substrate [Fig. 1(a)]. Here, we select the lithium niobate (LiNbO₃) as a host materials due to its excellent physical properties compared to other materials. In order to obtain uniform erbium ions doping concentration and achieve a better gain effect, we doped erbium ions into LN during the crystal growth processes.

Figure 1(b) shows the scanning electron microscope (SEM) image of the spiral waveguide amplifier. The total length of the spiral waveguide amplifier is 5.3 mm with a minimum radius of 25 µm in the bend part of the spiral waveguides. The footprint of the whole spiral waveguide is ~0.06 mm², which is the smallest among all erbium-doped LNOI waveguide amplifiers, to the best of our knowledge. Since it will be more suitable for the compact on-chip integration. Insets in Fig. 1(b) are
the magnified grating and spiral waveguides part SEM image with false color. In order to obtain high coupling efficiency for pump and signal light. The coupling grating is designed to be two part with periods as 900nm for 1550 nm, which exhibits the loaded and intrinsic Q factor of 5 × 10^4 and 5.4 × 10^4, respectively. We can estimate the propagation loss α of the spiral waveguide based on the equation α = 2πn_{eff}/λ_0Q_f, where n_{eff} is the effective index of the waveguide and λ_0 is the target wavelength. The calculated propagation loss at 1550 nm is ~ 6.86dB/cm, which lead to a loss about 3.64 dB for our 5.3-mm spiral waveguide amplifiers. We also measured the coupling losess of our coupling grating at 980 nm and 1550 nm, which are 16 dB and 13.4 dB, respectively. The launched pump and signal powers into the spiral waveguide have been calibrated by using the above measurement results.

Figure 5(a) presents the measured signal spectra at 1530 nm with the increasing pump power, which shows the apparently signal enhancement. Figure 5(b) is the amplifier net gain as a function of the launched pump power with different signal powers at 1530 nm. As expected, the spiral waveguide optical gain increases rapidly at the small pump powers. Then, we can observed the gain approaching saturation with the launched pump power increasing around 10 mW. A maximum net internal gain of 8.3 dB is achieved with the signal power at -10.7dBm and pump power at 10.78 mW, which corresponding to a net gain per unit length of ~ 15.6 dB/cm.

It is higher than other erbium-doped LNOI and bulk LN.23-33. What’s more, a small gain saturation is also found when the launched signal power increasing, shown as Fig. 5(c). The net gain at other wavelengths of telecommunication bands is characterized as shown in Fig. 5(d), with a launched signal power at -10.7 dbm. The pink area of Fig. 5(d) shows the net gain over 3 dB and we can find that the spiral waveguide amplifier exhibits a net gain bandwidth of 1530-1570 nm. These re-
FIG. 3. The net gain measurement setup. Insets are the microscope photograph of the spiral waveguide amplifiers pumped by 974 nm light with strong up-conversion induced green photoluminescence (Top) and the optical microscope image of the spiral waveguide amplifier comparing with a single-mode optical fiber (Coning SMF-28) (bottom).

FIG. 4. Propagation loss measurement with a micro-ring. (a) The false-color SEM image of microring with the radius of 30 μm. (b) The Lorenztian fitting exhibiting the microring with a loaded Q factor of $Q_L = 5 \times 10^4$ and intrinsic Q factor of $Q_I = 5.4 \times 10^4$.

results show the potential for on-chip integration with high optical gain amplifier in erbium-doped LNOI platform.

In conclusion, we fabricated high-gain optical spiral waveguide amplifiers with total 5.3-mm-long and $\sim 0.06$ mm$^2$ of areas on a 1-mol% erbium-doped LNOI. A maximum internal net gain of 8.3 dB at 1530 nm and a broad gain band (1530-1570 nm) have been demonstrated. A maximum net gain per unit length can reach up to 15.6 dB/cm. The strong confinement to the pump and signal light, small footprint and relative high signal enhancement of the spiral waveguide amplifier are of great significance for the LN on-chip photonic integrated circuits, which would pave the way in the photonic integrated circuits of lithium niobate platform or the hybrid integration.

It is worth noting that another two erbium-doped waveguide amplifiers works were posted on arXiv [30,31], during the preparation of this article. Comparing to these two works, our spiral waveguide amplifiers have a narrower top width and smallest footprint, which means the spiral waveguide amplifiers are integrated and can support more compact on-chip integration. Spiral waveguide amplifiers should be better for a large number of photonic devices integration.

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