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Photonic integration on rare earth ion-doped thin-film lithium niobate

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The modulation bandwidth of silicon-based photonics is limited to approximately 60 GHz because of the maximum carrier mobility, which limits its development in high-capacity and high-speed information processing. Lithium niobate has received much attention due to its excellent electro-optic properties. With its remarkable electro-optic, acousto-optic, nonlinear, and piezoelectric nature, etc. [1,2], lithium niobate (LN) is also praised as the "silicon of photonics". Along with the realization of the CMOS-compatible 100 GHz modulation bandwidth electro-optical modulator based on lithium niobate on insulator (LNOI) [3,4], optoelectronic integration on LNOI has become a research hotspot.

Since its commercialization in 2014, LNOI has sparked many photonic devices, such as the frequency converter, signal modulator, and filter, because of its high refractive index contrast, low propagation loss, and rapid advances in processing technique. However, as important components of photonic chips, the light sources and amplifier on LNOI have not been developed because lithium niobate is not a gain medium. Rare earth ions doped by ion implantation or high-temperature ion diffusion in LN can achieve gain, but the concentration, depth, and uniformity of doped rare earth ions are difficult to control. Therefore, for a long time, various studies on erbium ion-doped LNOI have only obtained fluorescence [5] rather than laser output. To solve the above problems, Liu et al. [6] chose doping erbium ions in the growth process of an LN single crystal so that it can become a uniform gain medium. Using the erbium-doped LN single crystal and the smart-cut process, an erbium-doped LN thin film was obtained.

On the basis of the erbium-doped LNOI, Liu et al. [6] achieved the low threshold on-chip microcavity laser output at the C-band in a whispering gallery mode microdisk with a 150-μm diameter. The vernier effect [7] and thermal-optic effect were also used to realize the on-chip adjustable single-mode laser sources. On-chip multi-mode and single-mode lasers at different wavelengths doped with different ions in LN have also been demonstrated. However, the outputs and linewidths of these on-chip microcavity lasers based on rare earth ion-doped LNOI are not ideal and need further improvement.

An on-chip amplifier can also be achieved by erbium-doped LNOI, which would be a key device in photonic integrated circuits (PICs). Many studies on on-chip amplifiers [8-11] based on erbium-doped LNOI have been reported soon after the laser was developed. However, the saturated output of the LNOI waveguide amplifier is still low. A small signal gain of 30 dB was achieved in the erbium-doped silicon nitride waveguide amplifier [12]. Optimizing the doping concentration to improve the quantum luminescence efficiency and reducing the waveguide loss can increase the saturated output gain to meet practical requirements.

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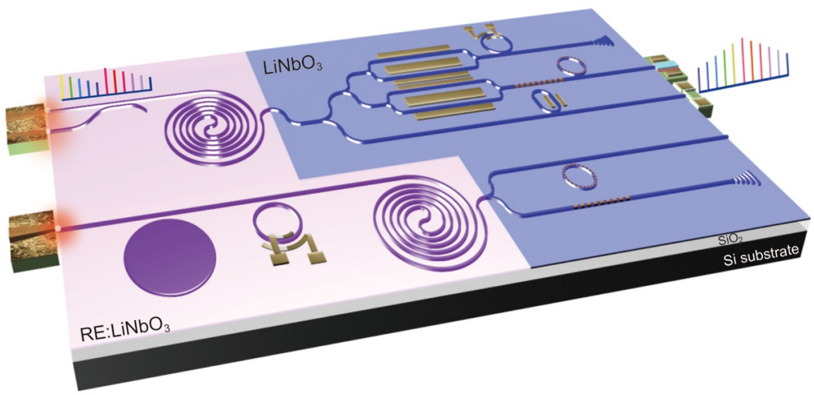

Figure 1 (Color online) Integrated photonic devices on a thin-film lithium niobate with rare earth ions in the doped and undoped regions. The illustrated components include an electro-optic frequency comb source, heterogeneously bonded laser source, spiral waveguide amplifier, periodically poled waveguide and ring, Mach-Zehnder electro-optic modulators, single-ring modulators, microdisks, and photodetectors. A visual illustration of the LNOI platform with hybrid rare earth ion doping can support more photonic devices on one chip.

In addition to erbium ions, other rare earth ions, such as thulium (Tm^{3+}), neodymium (Nd^{3+}), and ytterbium (Yb^{3+}) ions [13], can also be doped in LN or LNOI, which can further broaden its applications as mid-infrared lasers, high-performance quantum photonic components, etc.

On the basis of LNOI, recent studies have also paid much attention to the heterogeneous integration scheme with semiconductor lasers, such as heterogeneous light sources [14] and detection [15] using an electric pump. Notably, if we use the other two doping technologies, ion implantation or ion diffusion technology, assisted by semiconductor mask technology, chemical mechanical polishing, and annealing, we may optimize and achieve a hybrid rare earth-doped LNOI (RE:LNOI) chip with gain and non-gain areas in Figure 1, which can be constructed to the functional integration of active and passive devices for LNOI PICs. For example, we can make a microcavity (undoped region) to generate frequency comb sources, then combine the amplifier (doped region) to increase the intensity; the amplified laser sources selected and modulated can benefit from an efficient nonlinear output based on a spontaneous quasi-phase-matched micro-racetrack resonator (undoped region) [16].

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