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# Electro-optically tunable microdisk laser on $Er^{3+}$-doped lithium niobate thin film

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**We report an electro-optically (EO) tunable microdisk laser fabricated on the erbium ($Er^{3+}$)-doped lithium niobate on insulator (LNOI) substrate. By applying a variable voltage on a pair of integrated chromium (Cr) microelectrodes fabricated near the LNOI microdisk, electro-optic modulation with an effective resonance-frequency tuning rate of 2.6 GHz/100 V has been achieved. This gives rise to a tuning range of 45 pm when the electric voltage is varied between −200 V and 200 V.**

**Keywords:** electro-optically tunable microlaser; $Er^{3+}$ doping; lithium niobate; microdisk.

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## 1. Introduction

Thin film lithium niobate on insulator (LNOI) is emerging as a promising platform for integrated photonic technologies because of its small footprint, broadband ultra-low propagation loss, high optical nonlinear coefficient, and large electro-optical effect[1–4]. Furthermore, rare-earth ions such as erbium ($Er^{3+}$) and $Yb^{3+}$ can be conveniently doped into the LNOI to realize an active material platform[5,6]. The on-chip waveguide amplifier and microlaser based on the $Er^{3+}$-doped LNOI have stimulated growing interest in recent years, owing to the excellent optical properties of the host crystal material together with the gain performance provided by the $Er^{3+}$ ions[7–14]. Recent advances in LNOI and its micro- to nano-fabrication technologies permit the hybrid integration of LNOI circuits, where the on-chip microresonator modulator or microlaser can be controlled by the passive circuitry. The passive electro-optically (EO) tunable devices on LNOI such as high-speed EO modulators have been broadly investigated[15–18], while the active counterparts on LNOI are only studied very recently, owing to the advent of the $Er^{3+}$-doped LNOI in the last year. Benefited from the large electro-optical coefficient of the crystalline lithium niobate (LN), a high $Q$ factor of the microdisk resonator, and the gain performance provided by the rare-earth ions, the EO tunable microdisk laser on $Er^{3+}$-doped LNOI has been realized with fascinating perspectives in emerging fields including photonic chip, high-speed optical communication, precision metrology, and artificial intelligence.

In this Letter, we demonstrate an EO tunable microlaser based on an $Er^{3+}$-doped high-quality ($\sim 2.13 \times 10^6$) LN microdisk resonator fabricated by photolithography assisted chemo-mechanical etching (PLACE). By applying voltage on the integrated Cr thin film microelectrodes beside the $Er^{3+}$-doped LN microdisk resonator, the electro-optic modulation with an effective resonance-frequency tuning rate of 2.6 GHz/100 V was achieved. Furthermore, the lasing wavelength of $Er^{3+}$-doped LN microdisk laser can be tuned by 45 pm when the voltage is raised from −200 V to 200 V.

## 2. Device Characterization

In our experiment, the on-chip LN microdisk resonator integrated with Cr film electrodes was fabricated on a 600-nm-thick

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$Z$-cut $Er^{3+}$-doped LNOI with a doping concentration of 1% (molar fraction). The $Er^{3+}$-doped LN thin film is bonded by a 2-μm-thick $SiO_2$ isolation layer on a 0.5-mm-thick undoped LN substrate, which was fabricated by the smart-cut method[19]. A 600-nm-thick Cr film layer was deposited on the surface of the $Er^{3+}$-doped LNOI by the magnetron sputtering method. The on-chip $Er^{3+}$-doped LN microdisk resonator integrated with Cr film electrodes was fabricated by PLACE, and more fabrication details can be found in Refs. [20–22]. Figure 1(a) presents the schematic of the on-chip $Er^{3+}$-doped LN microdisk resonator integrated with Cr film electrodes. Figure 1(b) presents the top view of the 200-μm-diameter $Er^{3+}$-doped LN microdisk from the optical microscope. The $SiO_2$ pedestal underneath the microdisk has a diameter of ~150 μm. The anode is fabricated into a circular pad of a comparable diameter to overlap the area supported by the $SiO_2$ pedestal, while the cathode has a concave semicircle pattern with a diameter of ~230 μm surrounding the $Er^{3+}$-doped LN microdisk. The Cr microelectrodes are clearly visible in the optical micrograph under reflected illumination in Fig. 1(b), which appear bright white in contrast to the green $Er^{3+}$-doped LN microdisk. Figure 1(c) shows the enlarged image of the rim of the $Er^{3+}$-doped LN microdisk by a 100× microscope objective; it displays interference patterns under reflected illumination, indicating the varying thickness at the edge of the $Er^{3+}$-doped LN disk.

To characterize the electro-optical tunability of the $Er^{3+}$-doped LN microdisk laser, we used an experimental setup, as shown in Fig. 2(a). Here, a continuous-wave C-band tunable laser (CTL 1550, TOPTICA Photonics Inc.) was used for characterizing the $Q$ factor of the $Er^{3+}$-doped microdisk. Alternatively, a diode laser (CM97-1000-76PM, Wuhan Freelink Opto-electronics Co., Ltd.) operating at the wavelength ~976 nm was chosen to pump the $Er^{3+}$-doped LN microdisk. The polarization states of the tunable laser and pump laser are adjusted using the in-line fiber polarization controller

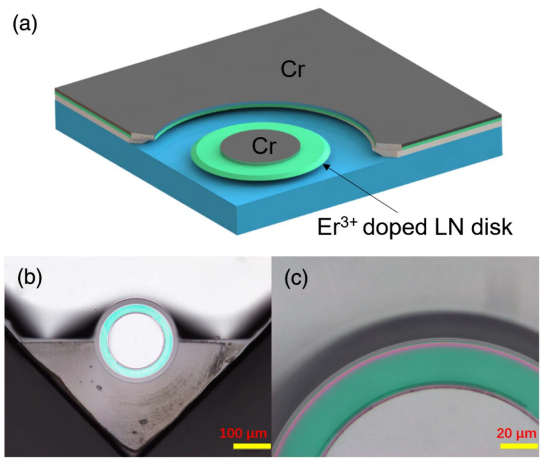


**Fig. 1.** (a) Schematic of the on-chip $Er^{3+}$-doped LN microdisk resonator integrated with Cr film electrodes. (b) The top view of the 200-μm-diameter $Er^{3+}$-doped LN microdisk from the optical microscope. (c) The enlarged image of the rim of the $Er^{3+}$-doped LN microdisk by a 100× microscope objective.

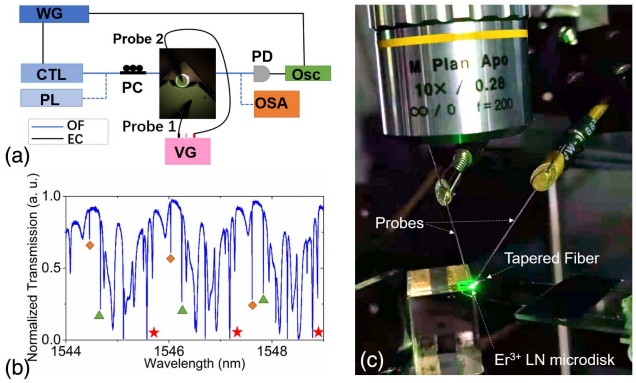


**Fig. 2.** (a) Schematic of the experimental setup for tunable $Er^{3+}$-doped LN microdisk laser. (WG, waveform generator; CTL, C-band tunable laser; PL, pump laser; PC, polarization controller; PD, photodetector; Osc, oscilloscope; OSA, optical spectrum analyzer; VG, voltage generator; OF, optical fiber; EC, electric cable.) (b) The measured transmission spectrum for the wavelength of the $Er^{3+}$-doped LN microdisk laser. (c) The experimental setup photographed by a cell phone.

(FPC561, Thorlabs Inc.). The light into and out of the fabricated $Er^{3+}$-doped LN microdisk was coupled by a tapered fiber with a waist of 1 μm. A photodetector (New Focus 1811-FC-AC, Newport Inc.) was directed in the fiber path to measure the transmission spectrum and $Q$ factor of resonant modes of the microdisk. The signal in the output of the fiber was captured by an optical spectrum analyzer (OSA, AQ6370D, Yokogawa Inc.). A direct current (DC) stabilized power source (CE1500002T, Rainworm Co., Ltd.) was used as the voltage generator for Cr electrodes, which provided a variable voltage ranging from 0 V to 500 V. Two probes (ST-20-0.5, GGB Industries Inc.) were used to apply DC voltage on Cr electrodes, respectively. Figure 2(b) illustrates the measured transmission spectrum for the wavelength range from 1540 nm to 1550 nm. Both the fundamental mode and higher-order modes of the $Er^{3+}$-doped LN microdisk are excited, which are labeled with different markers (star, triangle, and square), and the free spectrum range (FSR) of the 200-μm-diameter $Er^{3+}$-doped LN microdisk is measured to be about 1.6 nm. Figure 2(c) is the experimental setup photographed by a cell phone, and the strong green upconversion fluorescence in the $Er^{3+}$-doped LN microdisk pumped by a 976 nm laser can be easily noticed.

The intrinsic $Q$ factors of 80 resonant modes on the $Er^{3+}$-doped LN microdisk produced in a batch were plotted statistically in Fig. 3(a), which displays the distribution of $Q$ factors with different resonant modes. The loaded $Q$ factor was measured at low laser power to avoid thermal broadening effects. The highest intrinsic $Q$ factor of our $Er^{3+}$-doped LN microdisk was measured to be $2.13 \times 10^6$ through a double Lorentzian fitting at the wavelength of 1542.39 nm, as shown in Fig. 3(b).

Figure 4(a) shows that the resonant wavelength continuously shifts with the increase of the applied DC voltage; the measurement was performed around the resonant wavelength of

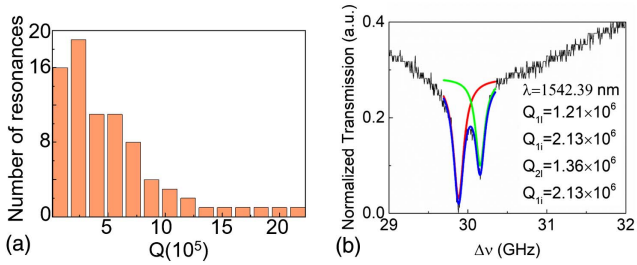


**Fig. 3.** (a) Histogram showing the statistic results of 80 resonant modes in $Er^{3+}$-doped LN microdisk. (b) The double Lorentzian fitting showing a mode splitting, indicating both intrinsic $Q$ factors of $2.13 \times 10^6$ as measured at $\lambda$ = 1544 nm.

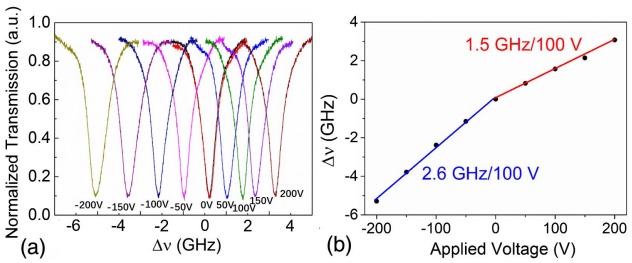


**Fig. 4.** Electro-optic modulation in $Er^{3+}$-doped LN microdisk resonator. (a) Normalized transmission measured when −200 V, −150 V, −100 V, −50 V, 0 V, +50 V, +100 V, +150 V, and +200 V voltages were applied on the electrodes. (b) The linear fitting of resonance wavelength shift in the $Er^{3+}$-doped LN microdisk resonator with the applied negative and positive voltages.

1551.12 nm. Benefiting from the large electro-optical coefficient of LN crystal and a high $Q$ factor of our microdisk resonators, we observe that by changing the electric voltage from −200 V to 200 V, a linear dependence of the resonant wavelength on the pump power is observed, showing that the resonant wavelength shifts with ~8.4 GHz, as shown in Fig. 4(a). The linear fitting in Fig. 4(b) confirms that the resonant wavelengths move linearly with the applied negative and positive voltages across the $Er^{3+}$-doped LN microdisk, and the tuning rates of the applied negative and positive voltages are 2.6 GHz/100 V and 1.5 GHz/100 V.

The lasing mode of the $Er^{3+}$-doped LN microdisk shows a strong dependence on the applied voltage. As shown in Fig. 5(a), at the pump laser power of 18 mW, the laser is a single-frequency

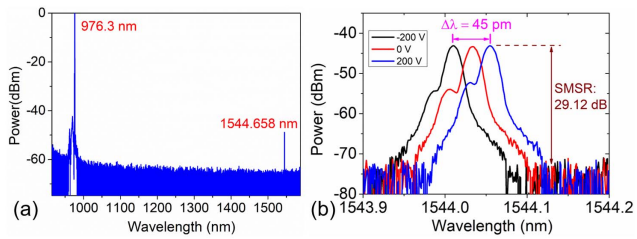


**Fig. 5.** (a) Spectrum of the $Er^{3+}$-doped LN microdisk laser with the pump power at 18 mW. (b) Recorded lasing spectra of the microdisk with the increasing voltage applied on electrodes.

lasing emission at the wavelength around 1544.658 nm, and with a side mode suppression ratio (SMSR) of 29.12 dB. This should be a result of the strong competition between the lasing modes of different gain efficiencies. Benefiting from the large electro-optical coefficient of the LN crystal, we are able to continuously red-shift the resonant wavelength by ~45 pm by increasing the electric voltage from −200 V to 200 V, as shown in Fig. 5(b). This observation indicates that the $Er^{3+}$-doped LN microdisk laser provides an efficient and convenient method for all optical tuning of the on-chip laser wavelength.

## 3. Conclusions

To conclude, we have demonstrated an EO tunable microlaser based on an $Er^{3+}$-doped high-quality ($\sim 2.13 \times 10^6$) LN microdisk resonator. The lasing wavelength of the $Er^{3+}$-doped LN microdisk laser can be tuned by 45 pm when the voltage is changed from −200 V to 200 V. This device can find interesting applications in emerging fields including photonic chip, high-speed optical communication, precision metrology, and artificial intelligence. Future investigations will focus on the physical mechanism of single-mode lasing and improving the lasing wavelength electro-optical tuning range by systematical optimizations of the geometries of the microdisk and the microelectrodes.

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