Integrated lithium niobate single-mode lasers by the Vernier effect

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Received June 14, 2021; accepted July 15, 2021; published online July 30, 2021

Microcavity lasers based on erbium-doped lithium niobate on insulator (LNOI), which are key devices for LNOI integrated photonics, have attracted significant attention recently. In this study, we report the realization of a C-band single-mode laser using the Vernier effect in two coupled erbium-doped LNOI microrings with different radii under the pump of a 980-nm continuous laser. The laser, operating stably over a large range of pumping power, has a pump threshold of about 200 μW and a side-mode suppression ratio exceeding 26 dB. The high-performance LNOI single-mode laser will promote the development of lithium niobate integrated photonics.

lithium niobate, LNOI, microcavities, single-mode laser

PACS number(s): 42.55.Sa, 42.55.Rz, 77.84.Bw, 77.55.+f

Citation: R. Zhang, C. Yang, Z. Z. Hao, D. Jia, Q. Luo, D. H. Zheng, H. D. Liu, X. Y. Yu, F. Gao, F. Bo, Y. F. Kong, G. Q. Zhang, and J. J. Xu, Integrated lithium niobate single-mode lasers by the Vernier effect, Sci. China-Phys. Mech. Astron. 64, 294216 (2021), https://doi.org/10.1007/s11433-021-1749-x

1 Introduction

Recently, lithium niobate (LN) integrated optical devices have attracted significant attention [1,2]. On the one hand, it is because of the excellent optical properties of LN, such as wide transparent window (0.35-5 μm), low intrinsic absorption, extraordinary second-order nonlinear ($d_{33}$= −41.7 pm/V), electro-optic ($r_{33}$=30.9 pm/V), acousto-optic effects, and marked photorefractive, piezoelectric, pyroelectric effects. On the other hand, the presence of lithium niobate on insulator (LNOI) offers an improvement in optical confinement in time and space compared with traditional LN devices fabricated through proton exchange or the indiffusion of titanium. Moreover, the commercialization of LNOI has promoted the development of integrated LN devices. A large number of passive integrated optical devices, such as nonlinear frequency converters [3-6], optical parametric oscillators [7], electro-optic/acousto-optic modulators [8-11], and mode converters [12], have been fabricated on LNOI and achieved excellent performance. Very recently, lasers [13-19] and amplifiers [20-23] based on erbium-doped LNOI have been reported, which greatly promote the study of active devices based on LN. However, their integration and performance need further improvement.

As a typical microlaser, whispering gallery mode (WGM) microcavity lasers based on microsphere, microbottle, microdisk, micro-toroid, and microring have been widely investigated. Compared with the distributed feedback (DFB) lasers, quantum well lasers, and vertical-cavity surface-

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emitting lasers (VCSEL), WGM microcavity lasers exhibit higher modal confinement and higher quality \((Q)\) factor through total internal reflection, and thus have a lower laser threshold. In virtue of integration, ring cavities integrated with bus waveguides have better performance. Recently, we reported an LNOI microring cavity laser [15]. Compared with the disk cavities, mode confinement in space has achieved significant improvement, and its pump threshold decreased significantly to 20 μW. However, it presents a multi-mode operation, which is undesirable for applications, such as optical communications and nonlinear optical investigations.

There are several methods for achieving single-mode lasers. One is to shape the spatial profile of the optical pump into a laser cavity [24]. Another is to make the high-order laser modes suppressed by pairing them with the losing mode to achieve a single-mode laser [25]. Using parity-time symmetry to implement mode selection [26-28] is also available. Furthermore, increasing the free spectral range (FSR) of the WGM microcavities is a feasible solution. It is well known that the FSR of WGM is inversely proportional to the size of the resonator. To achieve a large FSR, a cavity with a radius of several microns is often required, which inevitably increases the optical loss, deteriorates the laser \(Q\) factor, and ultimately increases the pump threshold. An effective alternative method is to use multiple resonators coupled with each other with different radii to improve the FSR of the system through the Vernier effect [16,17,29-31].

In this study, we designed and fabricated an LNOI photonic molecule with two coupled ring resonators, whose FSR is about 11 nm. In this device, we obtained a 1531.1-nm single-mode laser with a stable output and a high side-mode suppression ratio (SMSR) of 26.3 dB under the pump of a 980-nm continuous laser. The laser can be flexibly integrated with various functional LNOI devices on a chip.

2 Design and characterization of LNOI photonic molecules

Figure 1(a) shows the basic configuration of the LNOI photonic molecule. It consists of two single-ring resonators with radii of \(R_1\) and \(R_2\), and two bus waveguides used to couple the pump light and extract optical signals. The light with wavelengths of \(\lambda_i\) resonates in a single ring resonator when the resonant condition \((2\pi n_i R_i/m_1 \lambda_i, i = 1, 2)\) is satisfied, in which \(m_i\) is an integer, and \(n_i\) is the effective refractive index of the mode. The interval between adjacent resonant wavelengths of the mode is \(\Delta\lambda_i = \lambda_i^2/(2\pi n_{g_i} R_i)\), where \(n_{g_i}\) is the mode group index. For photonic molecules with two coupled microcavities, the proper choice of \(R_1\) and \(R_2\) can make the two ring resonators have the same resonant wavelength \(\lambda_0 = \lambda_1 = \lambda_2\). In this case, supermodes with \(\Delta\lambda \approx \lambda_0^2/(2\pi n_{g} |R_1 - R_2|)\) are supported in the photonic molecule. If \(R_1 \approx R_2\), then \(\Delta\lambda\) approaches infinity. Therefore, a relatively large FSR can be achieved in a photonic molecule with a relatively large radius supporting high \(Q\) factors. To achieve simultaneous resonance in two ring resonators near 1532 nm, at which erbium ions (Er\(^3\+\)) demonstrate the strongest radiation, we fixed the radius of the larger resonator at 100 μm and fine-tuned that of the smaller resonator near 85 μm.

We numerically calculated the resonant wavelengths of the
fundamental transverse electric modes in these two resonators using a two-dimensional axisymmetric model for photoluminescence efficiency. The simulation results showed that when the radius of the small cavity was 84.96 μm, dual resonance could be achieved at 1531.8 nm (Figure 1(b)). Considering the fabrication error, we adjust the radius of the small ring from 84.90 to 85.02 μm with a step size of 0.02 μm in the fabrication. Here, Δλ was estimated to be about 11 nm.

We used an erbium-doped X-cut LNOI wafer with a doping concentration of 0.1 mol% to fabricate the photonic molecule. The thickness of LN film, silicon dioxide (SiO2) buffer layer, and silicon (Si) substrate are 0.6, 2, and 500 μm, respectively. The fabrication process of the LNOI photonic molecule is similar to that in our previous study [15]. The etching depth of the LN film is 300 nm, the ring resonators and waveguides have a ridged shape with a sidewall angle of about 60°. The shape of the fabricated LNOI photonic molecule was first characterized using a scanning electron microscope (SEM). Figure 1(c)-(e) show the SEM images of a typical LNOI photonic molecule. As designed, the ring radii of the small and large rings are about 85 and 100 μm, respectively. The top width of the rib of the rings is 1.2 μm, and the gap between the two rings is 0.65 μm. The width of the bus waveguide with port 1 and port 2 (port 3 and port 4) is 1 μm (0.6 μm), and the gap between the waveguide and the small (large) ring is 0.65 μm (0.4 μm).

3 Experimental setup, results, and discussions

To characterize the linear optical properties of the LNOI photonic molecule near 1532 nm, we used a tunable laser in the band of 1550 nm as the light source. Figure 2 shows the specific experimental setup. First, we connected the optical fiber at S1 to port 1 and S2 to port 2 on the chip. The laser performed a frequency sweep in the range of 1518-1545 nm. The transmission spectrum was collected through photodetector (PD) and oscilloscope (OSC). Then, the optical fiber at S1 was switched to port 3, and its transmission spectrum was still observed at port 2 in the same wavelength range.

We tested the designed photonic molecule structures one by one. Finally, in the photonic molecule structure with \( R_1 = 85.02 \) μm, double resonance was achieved at 1531.6 nm. Figure 3(a) shows the transmission spectra from port 1 to port 2 (blue lines) and from port 3 to port 2 (red lines). From the transmission spectrum in red, we can see three distinct peaks with about 11-nm Δλ corresponding to the supermodes of the photonic molecule, which agrees with the theoretical results. The same information can be obtained from the blue transmission spectrum from port 1 to port 2, i.e., when the resonant wavelengths of the two cavities are the same, the mode coupling between the waveguide and photonic molecule is deeper. Figure 3(b) shows the enlarged view of the mode highlighted by the dashed black box in Figure 3(a), from which two supermodes with a splitting δ=0.85 GHz were observed. The frequency interval between the two supermodes is determined by the coupling strength between the rings [32]. Additionally, the fineness of the 85 and 100-μm radius resonators of the photonic molecule were measured to be 156 and 116, respectively.

We also investigated the laser emission from the erbium-doped LNOI photonic molecule using the experimental setup shown in Figure 2. Here, we introduced a 980 nm-band tunable laser as the pump and used the variable optical attenuator (VOA) to change the pump power entering the photonic molecule. The optical coupler 1 (OC 1) was re-
quired to divide the pump into two parts. Most (90%) of the pump passed through the polarization controller and entered the chip. The remaining part (10%) was sent to the power meter (PM) to monitor the pump power. The coupling efficiency between the lensed fiber and waveguide tuned to about 20% per facet by three-axis piezo stages. The lensed fibers at S1 and S2 are connected to port 1 and port 2 on the chip, respectively. The signal and transmitted pumps were divided into two parts through the optical coupler 2 (OC 2) after the extracted lensed fiber. The most collected light (90%) went into an optical spectrum analyzer (OSA) to observe the 1550-nm band signal. Additionally, a small part of the collected light (10%) was sent to a PD, which is connected to OSC to monitor the transmission spectrum of the pump mode around 980 nm. Considering the coupling losses, the pump and signal powers mentioned in the following are on-chip power.

In experiments, considering the absorption of Er\(^{3+}\) and the maximum tuning wavelength of the laser, WGM for the pump we selected was at about 979.6 nm. The pump mode has a loaded Q factor of \(2.97\times10^5\) and operates in the under-coupling regime. Figure 4(a) shows a series of lasing spectra with various pump powers. It shows that stable single-mode operation can be achieved in the wavelength range of 1500 to 1600 nm over a wide range of pump power. Due to the photorefractive effect of LN, the signal wavelength changes from 1531.4 nm at low power to 1531.1 nm at high power [33].

We performed power integration and Lorentz fitting for a range of 0.2 nm near the signal peak in the emission spectrum and obtained the signal power and linewidth. Figure 4(b) shows the experimental results. The blue hollow box shows signal power as a function of the pump power, showing two increasing regions under the log-log coordinate. The first is the linearly increasing region, whereas the second is the superlinearly growing region [34,35]. In theory, there should be another linear region, and these three regions form an S-shaped curve. Due to the limitation of the maximum power of the pump laser, we did not collect the S-shaped relationship between the pump and the signal powers. As the pump power increases, the signal linewidth gradually decreases, and eventually fluctuates around a certain value, as shown in the red hollow circle in Figure 4(b) with log-linear coordinate. Due to the limited resolution of OSA (about 10 pm), the linewidth information in the figure at high power is not an accurate representation of the actual linewidth of the laser signal in this case. It might be much smaller [16,17]. As shown in Figure 4(b), the kinks of the signal power and linewidth with the pump power tend to be the same, and the laser threshold is estimated to be 200 μW. This is an order of magnitude higher than our previous study in microring lasers [15] because of lower Q factors and weak coupling of the pump. In the future, we will introduce chemo-mechanical polishing [36] to the fabrication process to improve the Q factor of the ring cavities. We will use the pulley-coupling scheme [37] to enhance the coupling depth of the pump to reduce the lasing threshold.

Figure 4(c) shows the single-mode lasing signal in logarithmic coordinates collected at the 979.9-nm pump wavelength and 900-μW pump power. The power of the main

![Figure 4](image-url) (Color online) (a) Single-mode lasing signals in the range of 1500-1600 nm from an erbium-doped LNOI photonic molecule under different pump power. (b) Power (blue hollow box) and linewidth (red hollow circle) of the signal light at different pump power. (c) A high side-mode suppression ratio (SMSR) lasing signal was observed at a pump power of about 900 μW. The inset is a micro-image showing the strong green up-conversion fluorescence in the photonic molecule.
mode and the highest side mode of the laser are −44.0 and −70.3 dBm, respectively, and the corresponding SMSR is 26.3 dB. Here, the strong green up-conversion fluorescence of the LNOI photonic molecule is shown in the inset in Figure 4(c). At this pump wavelength, only the ring resonator with a small radius meets the resonance condition. The pump energy is mainly concentrated in the small ring resonator; however, the signal mode exists in both ring resonators. In addition to the photonic molecule mode at 1531.6 nm, the photonic molecule mode exists at 1520.6 and 1540.9 nm (Figure 3(a)). Due to the low emission coefficient of Er\(^{3+}\), the other two wavelengths, the laser conversion efficiency is low, and the corresponding laser signal is weak. Thus, we can obtain the single-mode laser signal with high SMSR.

### 4 Conclusion

In summary, we fabricated the photonic molecule on erbium-doped LNOI and demonstrated a 980-nm-laser-pumped stable C-band single-mode laser by the Vernier effect. The lasing threshold is about 200 μW. When the pump power is 900 μW, the SMSR of the single-mode laser reaches about 26.3 dB. In the future study, we will integrate electrodes into the photonic molecule. Thus, a tunable single-mode laser can be realized by electro-optic or thermo-optic modulations, which is more convenient for practical application. A high-performance single-mode laser may promote the development of LNOI integrated photonics.

This work was supported by the National Key Research and Development Program of China (Grant No. 2019YFA0705008), the National Natural Science Foundation of China (Grant Nos. 12034010, 11734009, 92050111, 62641127, 62651114, 62627810, and 62622061), and the 111 Project (Grant No. B07013).

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