The erbium-doped lithium niobate on insulator (LNOI) laser plays an important role in the complete photonic integrated circuits (PICs). Here, we demonstrate an integrated tunable whispering gallery single-mode laser (WGSML) by making use of a coupled microdisk and microring on LNOI. A 974 nm single-mode pump light can have an excellent resonance in the designed microdisk, which is beneficial to the whispering gallery mode (WGM) laser generation. The WGSML at 1560.40 nm with a maximum 31.4 dB side mode suppression ratio (SMSR) has been achieved. By regulating the temperature, the output power of the WGSML increases, and the central wavelength can be changed from 1560.30 to 1560.40 nm. Furthermore, 1560.60 and 1565.00 nm WGSMLs have been achieved by changing the coupling gap width between the microdisk and microring. We can also use the electro-optic effect of LNOI to obtain more accurate adjustable WGSMLs in further research. © 2021 Optical Society of America

https://doi.org/10.1364/OL.441167

In recent years, lithium niobate on insulator (LNOI) has become a research focus of photonic integrated circuits (PICs). Due to its excellent material features, such as high electro-optical ($r_{33} = 30.8 \times 10^{-12}$ m/V) and second-order nonlinear ($d_{33} = -33$ pm/V) coefficients, extraordinary acousto-optic effects, piezoelectric effects, photoelastic effect, and wide transparency window from visible to mid-infrared, LNOI is a promising platform for compact photonic circuits [1,2]. Plenty of on-chip optical devices have been achieved successfully on LNOI, for instance, electro- and acousto-optical modulators [3–5], frequency combs [6,7], nonlinear frequency converter [8–15], and optomechanical applications [16]. However, to achieve complete PICs on LNOI, integrated C-band light sources are essential, and the pure lithium niobate (LN) does not have gain characteristics. Inspired by erbium-doped fiber amplifiers, doping rare-Earth ions into the LNOI is easily considered a way to overcome this shortcoming.

Recently, erbium-doped LN has been developed, and a series of research has been reported including waveguide amplifiers [17,18] and microcavity lasers [19–21] on Er$^{3+}$-doped LNOI, which exhibit great potential applications in LN PICs. Nevertheless, most of the reported lasers based on Er$^{3+}$-doped microdisk are multi-modes. The on-chip integrated C-band single-mode laser is critical and needs to be developed to improve monochromaticity, stability, and beam quality [22]. To achieve the on-chip single-mode laser, one can use a microring resonator with a properly designed width to filter out high-order transverse modes. Simultaneously, a single-longitudinal mode laser can be achieved by decreasing the radius of the microring to increase the free spectral range (FSR) [23]. However, the quality (Q) factor of microring reduces with the decrease of the size, which leads to higher loss and lower laser power. There are other approaches to realize single-longitudinal mode output, for example, using gratings to select a particular mode or producing a single-mode laser by breaking parity–time symmetry [24–27]. Another more feasible and suitable method for on-chip integration is to fabricate a photonic molecule consisting of two coupled microresonators with different FSRs to achieve mode selection [28,29]. It is worth noting that research [30–33] on the LNOI single-mode laser by using a single microdisk, two coupled microdisks, or microrings has been published very recently. But two coupled microrings need to use a tunable pump light to achieve an effective laser emission, which limits the practical application. Furthermore, suspended microdisks and coupling light with a tapered fiber are not conducive to integration, which limits its practical application in PICs on LNOI.

Here, we design and fabricate a whispering gallery single-mode laser (WGSML) on erbium-doped LNOI based on a photonic molecule, which consists of a designed microdisk coupled with a microring resonator. The WGSML with a wavelength of 1560.40 nm is achieved with the 974 nm single-mode pump. The threshold pump power of WGSML is about 1.31 mW, and the corresponding slope efficiency is $4.41 \times 10^{-5}$. By regulating the temperature, the output power...
designing a relatively large radius ($R$). We chose the microdisk to generate laser signals. By mask is removed by wet etching. plasma-reactive ion etching (ICP-RIE); finally the remaining photonic silicon on the Er$^{3+}$-doped LNOI. The LNOI consists of a 600 nm Er$^{3+}$-doped thin film LN, a 2-µm-silica buffer layer, and a 400 µm silicon substrate. The Er:LNOI is developed as same as [19]. Figure 1(b) is the SEM image of the coupled waveguide, the microdisk, and microring, and disk being the microring with a radius of $R_3 = 165$ µm. The pentagram points to the same wavelength resonant at 1560.20 nm.

Fig. 1. (a) Schematic diagram of the photonic molecule on Er$^{3+}$-doped LN. (b) The scanning electron microscope (SEM) image of the fabricated sample (top) and the coupling regions among straight waveguide, microdisk, microring, and pulley-coupling waveguide (bottom). Colored regions: waveguide, microring, and disk. (c) Principle of the WGSML emission in the microring and microdisk. (d) The resonant wavelength of two coupled microresonators with different radii. Red solid lines and green dashed lines are numerically calculated resonant wavelengths of the microdisk with a radius of $R_1 = 150$ µm and the microring with a radius of $R_2 = 165$ µm. The pentagram points to the same wavelength resonant at 1560.20 nm.

of the WGSML increases, and the central wavelength can be changed from 1560.30 to 1560.40 nm. A coupled microdisk and microring with different gap widths is fabricated, and 1560.60 and 1565.00 nm WGSMLs have been achieved.

Figure 1(a) shows the structure of the WGSML with a designed microdisk and a microring on a 1 mol.% $Z$-cut Er$^{3+}$-doped LNOI. The LNOI consists of a 600 nm Er$^{3+}$-doped thin film LN, a 2-µm-silica buffer layer, and a 400 µm silicon substrate. The Er:LNOI is developed as same as [19]. Figure 1(b) is the SEM image of the coupled waveguide, the microdisk, and microring with the radii $R_1 = 150$ µm and $R_3 = 165$ µm, respectively. The microring has a narrow width of 1.2 µm. The top widths of the straight bus waveguide and pulley-coupling waveguide are 0.6 µm and 0.95 µm, respectively, in order to satisfy the coupling phase-matching condition. The insets in Fig. 1(b) show the gap width of the coupling regions, with the gap width between the straight coupled waveguide and the microdisk being $g_1 = 500$ nm, $g_{20} = 360$ nm between the microdisk and microring, and $g_3 = 770$ nm in the pulley-coupling region. The main fabrication process of our designed WGSMLs is as follows: first we deposit a 600-nm-thick amorphous silicon on the Er$^{3+}$-doped LNOI as a hard etching mask and spin-coat a layer of resist; then the configuration of the coupled microcavities is patterned by electron-beam lithography (EBL), and the mask layer patterns are transferred on the Er$^{3+}$-doped LNOI layer surface via inductively coupled plasma-reactive ion etching (ICP-RIE); finally the remaining mask is removed by wet etching.

Figure 1(c) shows the principle of the WGSML emission in the device. We chose the microdisk to generate laser signals. By designing a relatively large radius ($R_1 = 150$ µm), we ensure that the pump light can resonate easily in the microdisk without extra adjustment and more pump power can be stored in the microdisk. As shown in Fig. 1(c), the pump light is coupled into the microdisk through the straight bus waveguide and resonates to produce laser signals. Then the signal light generated by the microdisk is coupled into the microring through the evanescent wave with a certain whispering gallery mode (WGM), which finally couples out of the microring through the pulley-coupling waveguide.

Figure 1(d) is the schematic diagram of the resonant wavelengths of a coupled microdisk and microring with different radii. The red solid line and green dashed line are numerically calculated resonant wavelengths of the microdisk and microring. As we know, the mode supported by resonators should satisfy the resonant conditions: $2\pi R n_{\text{eff}} = m\lambda$, where $R$ is the radius of resonators, $n_{\text{eff}}$ is the effective refractive index, $m$ is the model index, and $\lambda_{\text{m}}$ is the resonant wavelength. The FSRs of $R_1$ and $R_2$ are 1.1 nm and 0.95 nm, respectively. The resonant super-mode of the coupled system exists when the resonances of the microdisk and microring coincide [34], as Fig. 1(d) displays that only the super-mode with $\lambda = 1560.20$ nm is supported by the photonic molecule in the range of 1550–1565 nm. Therefore, the FSR of the photonic molecule around 1560.20 nm is $\text{FSR} = \lambda_{\text{m}}^2/2\pi n_{\text{eff}}(R_2 - R_1) = 13.7$ nm, which is much larger than microdisk and ring, thus leading to a reduction in the number of longitudinal modes. Facilitated by gain competition and the resonant condition, we can achieve single-mode laser emission by this device.

The experimental setup is shown in Fig. 2(a). A 974 nm LD light source (Golight Co., Ltd) is used as the pump source to produce laser emission in the microdisk on the Er$^{3+}$-doped LNOI. The pump light propagates through the polarization controller (PC) and couples into the straight waveguide. The device was placed on a thermoelectric cooler (TEC) to adjust the temperature. Then laser signals are collected and analyzed by the spectrometer to obtain emission spectra. A powermeter is connected to the PC to measure the pump power, and a tunable continuous-wave laser in C-band (1520–1570 nm) and oscilloscope are used to analyze the transmission spectrum of the device. During the experiment, green upconversion fluorescence is observed in the device from the photograph of the 974 nm pumped microdisk, shown in the inset (green dashed frame) of Fig. 2(a). On the one hand, this phenomenon illustrates that the pump light is coupled and localized well in the device. On the other hand, 974 nm pump light mainly resonates in the microdisk, which avoids the pump light resonating in the microring to produce laser signals of other longitudinal modes. Figure 2(b) shows the transmission spectrum of the coupled microring and microdisk from 1550 to 1565 nm. A Q factor of $1.7 \times 10^5$ is evaluated from the Lorentz fitting in Fig. 2(c) for the mode around 1561.11 nm in the green dashed box in Fig. 2(b), which shows the device has a low loss of laser signal and, thus, a relatively low single-mode threshold pump power.

Figure 3(a) illustrates WGSML emission spectra in the range of 1520–1570 nm under different pump powers of 1.63 mW, 1.74 mW, 1.88 mW, 1.97 mW, and 2.13 mW. A WGSML with a wavelength of 1560.40 nm can be obtained stably from the photonic molecule. With the increase of the pump power, the peak power of the laser signal increases, and the center wavelength keeps stable. The peak laser power with 2.13 mW pump light is $-44.02$ dBm, and the relevant side mode suppression
Figure 3(c) shows the output power of WGSMLs with a fixed pump power of 1.88 mW under different temperatures. We find that the output power of WGSML increases with the temperature, which may be caused by more pump light resonating to produce signal light under the refractive index changing with the temperature. Furthermore, we also found that the WGSML central wavelength changes with the temperature, shown in Fig. 3(d), which should be caused by the resonant condition changing due to the thermal effect of the LNOI. The WGSML central wavelength shows the increasing tendency with the temperature from 1560.30 to 1560.40 nm. It is worth stating that more accurate laser wavelength regulation can be achieved by using the electro-optic effect of LNOI [35].

The effect of the gap width between microdisk and microring on WGSMLs is also analyzed in our experiment. A coupled microring and microdisk with a different gap width of $g_{21} = 410$ nm ($Q \approx 3.74 \times 10^5$) and $g_{22} = 460$ nm ($Q \approx 5.10 \times 10^3$) is fabricated and measured. Figures 4(a) and 4(b) show the WGSML emission spectra and output power versus different pump power with $g_{21} = 410$ nm. The emitted WGSML is at 1565.00 nm and has a SMSR of 22.60 dB, shown in Fig. 4(a). The corresponding threshold pump power is 2.72 mW, and the slope efficiency is $2.92 \times 10^{-5}$. Figures 4(c) and 4(d) illustrate the laser spectra and the relation between the pump power and the output power with $g_{22} = 460$ nm. Its threshold pump power and slope efficiency are 3.18 mW and $3.38 \times 10^{-5}$. Compared with the laser at 1560.40 nm of $g_{20} = 360$ nm, the laser wavelength of $g_{22} = 460$ nm changes larger to 1560.60 nm. Furthermore, the SMSR of the single-mode laser with a 460 nm gap is 22.38 dB, which still maintains a relatively satisfactory single-mode property.

In addition, comparing the WGSML threshold pump power with $g_{20} = 360$ nm, $g_{21} = 410$ nm, and $g_{22} = 460$ nm, the increased gap width leads to a decrease in the coupling efficiency of the microdisk and microring. This behavior causes more energy to lay in those WGMs that merely exist in microdisk and do not resonate in microring. Thus, WGSML threshold power increases with the gap width. Similarly, the WGSML ratio (SMSR) is 31.40 dB, which demonstrates prominent single-mode characteristics. Figure 3(b) demonstrates the output laser power as a function of pump power, which indicates that the threshold pump power is 1.31 mW, and the slope efficiency is $4.41 \times 10^{-5}$. Compared with other research [30,33], the $Q$ factor of our microcavity is lower, leading to a relatively low slope efficiency. A more efficient single-mode laser can be achieved by optimizing the fabrication process to improve the $Q$ factor of device. Although the FSR (13.7 nm) of the photonic molecule is smaller than the gain spectral range of Er$^{3+}$, the coupled system can still achieve a single-mode laser output due to gain competition.

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**Fig. 2.** (a) Schematic diagram of the experimental setup. Inset, the optical microscope image. (b) Transmission spectrum of the photonic molecule from 1550 to 1565 nm with $g_{20} = 360$ nm, $g_1 = 500$ nm, and $g_3 = 770$ nm. (c) Lorentzian fitting of a measured mode at 1561.11 nm wavelength in the green dashed frame in (b), exhibiting a $Q$ factor of $1.7 \times 10^5$.

**Fig. 3.** (a) Spectra of the WGSML under different wavelengths and pump powers, with $g_{20} = 360$ nm and $T = 25^\circ$C. The side mode suppression ratio (SMSR) is 31.4 dB. (b) The relationship between the WGSML 1560.40 nm power and the 974 nm pump power. (c) and (d) are the relationship between the temperature and the output power of the WGSML and central wavelength with a fixed pump power of 1.88 mW, respectively.

**Fig. 4.** (a) and (c) are the spectra of the WGSML under different wavelengths and pump powers, with $T = 25^\circ$C, $g_{21} = 410$ nm, and $g_{22} = 460$ nm, respectively. (b) and (d) are the relationship between the 1565.00 nm and 1560.60 nm WGSML power and the 974 nm pump power, respectively. $g_1$ and $g_3$ are the same as before.
slope efficiency with $g_{22} = 460$ nm ($3.38 \times 10^{-5}$) is reduced compared to the laser with $g_{20} = 360$ nm ($4.41 \times 10^{-5}$), which should be caused by the decrease of the coupling coefficient. However, we find an abnormal mode change of the WGSML with $g_{21} = 410$ nm, which leads to the slope efficiency ($2.92 \times 10^{-5}$) less than that of the other two single-mode lasers with $g_{20} = 360$ nm and $g_{22} = 460$ nm. The mode change may be caused by the gain competition, and the FSR of the microdisk and microring are fairly small due to their large radii and dense mode distribution resulting in the modes near the resonant super-mode remaining in the device [36]. Our numerical simulation results also explain the mode change from the same perspective. Calculated resonant wavelengths in Fig. 1(d) display that the microdisk support mode at 1564.80 nm while the microring supports 1565.00 nm. This tiny deviation may enable signal light at 1565.00 nm to resonate in the coupling system. Furthermore, with the increase of pump power, more pump light may also couple into the microring. Thus, the WGSML at 1565.00 nm in the microring is emitted after the gain competition, which is consistent with our calculation that the mode at 1565.00 nm is supported by microring. More details still need to be further studied.

In conclusion, an integrated WGSML has been fabricated on Er$^{3+}$-doped LNOI. Facilitated by a coupled microdisk and microring with different radii, WGSML at the wavelength of 1560.40 nm can be stably emitted with a threshold pump power of 1.31 mW and slope efficiency of $4.41 \times 10^{-5}$. A maximum 31.4 dB SMSR is achieved. The central wavelength and output power of WGSML changed by adjusting the temperature are observed. The effect of the gap width between microdisk and microring on WGSML is also analyzed. 1560.60 and 1565.00 nm WGSMLs have been achieved by changing the coupling gap width between the microdisk and microring. With the integrated C-band single-mode laser on erbium-doped LNOI, a series of on-chip optical devices and applications can be developed and shows great potential in LNOI PICs.

**Funding.** National Key Research and Development Program of China (2017YFA0303701, 2019YFB2203501); National Natural Science Foundation of China (11734011, 12134009, 91950107); Shanghai Municipal Science and Technology Major Project (2019SHZDZX01-ZX06); Shanghai Jiao Tong University (21X010200828).

**Disclosures.** The authors declare no conflicts of interest.

**Data Availability.** Data underlying the results presented in this Letter are not publicly available at this time but may be obtained from the authors upon reasonable request.

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