Active mode selection by defects in lithium niobate on insulator microdisks

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Abstract: Whispering gallery mode (WGM) optical microcavities are important building blocks in photonic integrated circuits. Operation of such cavities on specific lower- or higher-order transverse modes has much interest in application perspectives. Here, we demonstrate active mode selection by introducing defects in lithium niobate on insulator microdisks. A focused ion beam is applied to precisely inscribe nano slits into the perimeter of the microdisk. The transmission spectra can be significantly thinned out without severe quality factor degradation. Either fundamental or high-order transverse WGMs can be retained by properly designing the size and location of the defects. The approach may have promising applications in single-mode lasing and nonlinear optics.

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1. Introduction

Whispering gallery mode (WGM) microresonators with small mode volumes and high quality (Q) factor can greatly enhance the light-matter interaction [1]. They are ideal platforms for studying various optical phenomena. Up to now, WGM microresonators have been applied in a wide variety of research fields, including cavity optomechanics [2,3], cavity quantum electrodynamics [4,5], nonlinear optics [6–9] and optical sensing [10–13]. Due to multiple degrees of spatial freedom, WGMs supported in large microcavities generally show complex mode profiles and large mode density [14]. Rich resonant modes in microcavities are useful in some cases. For example, in the study of nonlinear optics, large mode density increases the probability that light of different frequencies matches to cavity resonance [15–18], thereby reaching multiple resonance enhanced nonlinear effects. However, in other cases, rich mode distribution may limit the application of WGM microresonators. For instance, the WGM microresonator is widely used as sensitive sensors where the sensing process mainly relies on the drifting, splitting or broadening mechanisms of the microcavity resonance [10,11]. But dense modes may interfere with each other, affecting the recognition and tracking of the desired mode. Another example is the WGM microresonator based narrow optical filters [19]. Sparse WGMs are required to suppress unwanted light at different frequencies and let only one in a wide wavelength range to be resonant in the microresonator. In addition, when the WGM microresonator is applied for low-threshold lasers, its closely spaced modes would easily cause multimode lasering, leading to mode competition and subsequent adverse effects like gain saturation, mode hopping and others in practical applications. Therefore, effective control of microcavity resonant modes is necessary.
A lot of research on mode suppression and spectral simplification in optical microcavities have been studied. There are already several methods to achieve this goal. First, by controlling the size or shape of WGM resonators properly, like ultrasmall microcavities and microring resonators [20,21]. Second, selective excitation by optimizing the coupling condition between the waveguide and microcavity [22,23]. Third, by inserting appropriate defects in resonators, such as micro/nano grooves, slits, holes and gratings to selectively suppress undesired modes [24–29]. Fourth, by breaking the parity-time (PT) symmetry in the resonator to achieve single mode control [30,31]. Fifth, by changing the spatial distribution of pump light field to selectively excite the resonant lasing modes [32,33]. Although there are plenty of approaches to achieve fundamental order mode excitation or lasing, there are much fewer ways to suppress low-order modes and only allow for higher-order ones. The excitation of high-order WGMs may have potential applications in dispersion engineering [34] and nonlinear optics [35].

The abovementioned researches on mode selection of WGM microresonators have mostly been carried out in materials such as SiO$_2$, GaAs and InGaAsP, but is less active in lithium niobate on insulator (LNOI) WGM microresonators. LNOI microresonators are an important platform for photonic integrated circuits [36–42]. It is also an indispensable part of integrated active photonic chips. With the maturity of the on-chip lithium niobate laser technology [43,44], which favors the microdisk structure to incorporate more gain medium, mode selection in the microcavity will greatly promote the realization of single-mode output of on-chip light sources. Therefore, it is necessary to study mode management in the LNOI microresonator.

In this article, we achieve flexible mode selection in LNOI microdisks by introducing extra defects. The defects with specific sizes and positions in the LNOI microdisk surface are finely etched by taking advantage of the focused ion beam (FIB) direct writing method. Experimentally, the selective excitation of fundamental and higher radial order modes in the microdisk is successfully realized, and the influence of the defect size and location on the Q factor of the microdisk is also analyzed.

2. Experiment and results

The experimental setup is schematically depicted in Fig. 1. The laser source is an external cavity tunable continuous laser in the telecommunication C band (New Focus, 1520–1570 nm). A variable optical attenuator (VOA) is used to adjust the input power. A mechanical polarization controller (PC) is applied to control the polarization of input light. Light is coupled into the LNOI microdisk in the form of evanescent wave through a segment of tapered fiber. The tapered fiber is prepared by the heating-and-pulling method with a waist diameter of approximately 1 µm. The LNOI microdisk is mounted on a 3D nanostage to precisely adjust the coupling position. The output end of the tapered fiber is connected to a photodetector, and monitored by an oscilloscope to observe the transmission spectrum.

![Fig. 1. The experimental setup to observe WGMs of LNOI microdisks. VOA, variable optical attenuator; PC, polarization controller; Det., photodetector.](image)

In the experiment, the z-cut LNOI wafer with a thickness of 300 nm from NANOLN Co. is selected to fabricate the microdisk. Four LNOI microdisks with the same size are fabricated by using FIB direct writing, denoted as S1, S2, S3 and S4 hereafter, respectively. The diameter of the LNOI microdisks is 50 µm. The fabrication procedure details are the same as described in
Ref. [45]. Among them, sample S1 without any defect is used as the reference. A radial nano slit, with a length of 2 µm, width of 300 nm and depth of 100 nm, is etched on the surface of sample S2. The slit defect is 2 µm away from the edge of the microdisk. The slit in the microdisk S3 is 3 µm long, 300 nm wide and 300 nm deep, and is 1 µm away from the perimeter. The parameters of the slit in sample S4 are the same as those in S3, except that the slit is engraved at the edge of the microdisk. The ion beam current to etch such small-sized slits is kept low. The used accelerating voltage and ion beam current during the fabrication is 30 kV and 20 pA, respectively. All the LNOI microdisk microfabrication is finished at the Center for Advanced Electronic Materials and Devices (AEMD), Shanghai Jiao Tong University.

Each order WGM in the microdisk can be represented by the radial mode number $q$ and azimuthal mode number $m$. Previous research results indicate that quasi-TM modes are forbidden when the thickness of the microdisk is less than $\lambda/2n$, so only TE modes exist in the 300-nm thick LNOI microdisk at the telecommunication bands. Thus, from reasonable selection of the disk thickness, TM modes in the microdisk can be “cleared.” Fig. 2 shows the simulated electric field intensity distribution of different radial order TE($q$, $m$) modes in a LNOI microdisk with a radius of 25 µm and a thickness of 300 nm. The area enclosed by the white rectangle is the microdisk, and the surrounding area is the air. As the radial mode number $q$ increases from 1 to 6, the maximum of the electric field profile moves toward the center of the microdisk. The main idea of the proposed method is to introduce defects on the surface of the microdisk to disturb WGMs by increased scattering loss while leaving the designated one least impacted. The nano slit acts as a strong scattering center, so as to suppress the excitation of the specific transverse mode and finally to achieve the mode selection.

![Calculated mode profiles for different radial order TE($q$, $m$) modes.](image)

To characterize the optical modes, transmission spectra of the four microdisk samples are measured, as shown in Figs. 3(a)–3(d). The corresponding optical microscope images of the microdisks are shown in Figs. 3(e)–3(h), respectively. For the microdisk S1 without slit defect, there are abundant resonance modes in the wavelength range of 1525–1555 nm. The radial ($q$) and azimuthal ($m$) mode numbers corresponding to each resonant wavelength within the transmission spectrum are identified by comparing the numerical simulation with the experimental data, which shows good agreement with each other. As shown in Fig. 3(a), 1st, 5th and 6th-order TE modes are marked. It can be seen from Figs. 3(a)–3(d) that with the changes of position and size of the nano slit, the density of WGMs in the transmission spectrum clearly presents a decreasing trend.

In order to perform a more detailed analysis, the spectra in the orange region in Fig. 3 are enlarged, as shown in Fig. 3(i). TE modes of continuous radial orders $q$=1, 2, 3, 4, 5, and 6 are observed from the spectrum of S1 (the microdisk without slit defect). For sample S2, the etched slit is located at the position $R= 21, 23$ µm of the microdisk, where $R$ is measured from the center of the microdisk. According to the simulation results in Fig. 2, the slit defect overlaps with
Fig. 3. (a)-(d) Transmission spectra corresponding to the S1, S2, S3 and S4 LNOI microdisks in the communication C-band. (e)-(h) Optical microscope images of the respective samples. (i) The enlarged view of the orange region of the transmission spectrum.

The spatial distribution of electric field of TE($q=2$), TE($q=3$) and TE($q=4$) modes. Therefore, the modes of these three groups will experience high scattering loss at the slit defect and the excitation is thus suppressed. The TE($q=1$) mode is nearest to the perimeter of the microdisk, while TE($q=5$) and TE($q=6$) modes are closer to the center of the disk. The main lobe of these modes is basically unaffected by the slit. Thus, the modes of TE($q=2$), TE($q=3$) and TE($q=4$) are cleared, while the TE($q=1$), TE($q=5$) and TE($q=6$) modes are retained, whose resonant wavelength are indicated by the three arrows in Fig. 3(i). It can be seen that the spectrum has been thinned out to a certain extent. For sample S3, the slit length and depth is further increased, so its influence on the WGMs is stronger. By comparison with Fig. 2, the nano slit coincides with the spatial modes of TE($q=1$), TE($q=2$), TE($q=3$) and TE($q=4$), resulting in the suppression of these modes by strong scattering loss. Meanwhile, the overlap between TE($q=5$) and TE($q=6$) modes and the slit defect is relatively small, only they remain as shown in the transmission spectrum of the microdisk S3. For sample S4, the resonance corresponding to the TE modes of radial orders $q=1$, 2, 3 and 4 disappear from the perspective of transmission spectrum. The spectrum of the microdisk S4 is sparser than that of S3, with the 5th- and 6th-order radial modes retained in the spectrum.

Further, the Q factor of the microdisk is measured to analyze the effect of the slit on the loss of WGMs. In the experiment, accurate measurements of the Q factors of TE(5,145) mode and TE(6,139) mode in samples S1, S3 and S4 are performed by finely scanning the laser frequency at low power to avoid thermal broadening. As illustrated in Fig. 4(a), the Q factor of TE(5,145) mode of the microdisk S1 at 1535.7 nm is calculated to be $1.47 \times 10^4$ by Lorentz fitting (red solid line). Compared with sample S1 without any defect, the Q factors of the same mode in samples S3 and S4 are $1.21 \times 10^4$ and $0.89 \times 10^4$, reduced by about 18% and 39%, respectively, as shown in Figs. 4(b) and 5(c). Then, we study the effect of the defect on the Q value of the 6th-order mode. For the TE(6, 139) mode of the microdisk S1, the Q factor measured at 1544.8 nm is $1.15 \times 10^4$, as shown in Fig. 4(d). The Q factor of this mode in sample S3 is $1.16 \times 10^4$, consistent with that in sample S1. The Q factor of the microdisk S4 dropped by about 16% as compared with S1. The decrease in the Q factor can be explained by an enhancement of scattering loss. The introduced slit defect etched by FIB plays the role of a scattering center. A part of the light will be scattered into the surrounding environment when WGMs encounter the slit. As shown in Fig. 4, the Q
factor of the microdisk S4 has a larger drop than that in S3, which is caused by the etching of the edge of the microdisk in S4. Compared with sample S3, the slit in sample S4 damages the symmetry structure of the microdisk more severely. The light field in sample S4 experiences not only surface scattering but also lateral scattering, thus its scattering loss is greater. At the same time, we find that the decline of the Q factor of the 6th-order mode in samples S3 and S4 is significantly smaller than that of the 5th-order mode. According to the simulation results in Fig. 2, the higher the mode radial order is, the closer the energy distribution is to the center of the microdisk. For the 6th-order mode, the slit defect overlaps very little with the main lobe of the 6th-order mode, so the scattering induced loss to the 6th-order mode is smaller, resulting in a relatively low drop in its Q factor. Furthermore, for sample S2 with a smaller slit depth of 100 nm less than those of samples S3 and S4, we can readily conclude that a deeper slit causes stronger light scattering loss by the result that the Q factor of sample S2 is higher than those of samples S3 and S4, as shown in Fig. 3.

Fig. 4. Experimentally measured Q factors of the microdisks with and without nano slits.

Fig. 5. (a) Optical microscope image of the sample. (b) The corresponding transmission spectrum. (c) Experimentally measured Q factors of the microdisk.

Besides, to prove that the proposed method is also applicable in selection of fundamental WGMs, that is, to retain only the first radial order mode ($q=1$), we fabricate a 5.6 µm long, 300 nm wide and 300 nm deep slit locating at 2.0 µm away from the rim of another LNOI microdisk, as shown in Fig. 5(a). Combined with the simulation of distribution of electric field intensity for
different order radial TE modes in Fig. 2, the slit is long enough to overlap the main lob of second and higher-order radial modes. As shown in Fig. 5(b), there is only 5 dips in the whole scanned wavelength region, from 1525 to 1560 nm, respectively corresponding to different azimuthal order TE modes. The Q factor is $2.3 \times 10^4$ at 1552.0 nm, as shown in Fig. 5(c). It indicates that the etched slit defect clears all high-order radial modes and caused scattering loss to the first radial order WGMs.

3. Conclusion

In conclusion, we have achieved active mode selection in LNOI microcavities by introducing defect into the microdisks. Due to high resolution of the FIB etching method, the selective excitation of higher order modes is realized through precise control of the nano slit, thereby achieving high-precision mode selection and spectral simplification. This mode selection mechanism can also be applied in lithium niobate microcolumn, microring and microtoroid. This research has a great potential on the development of LNOI in integrated photonics.

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