Effects of edge inclination angles on whispering-gallery modes in printable wedge microdisk lasers

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Abstract: The ink-jet technique was developed to print the wedge polymer microdisk lasers. The characterization of these lasers was implemented using a free-space optics measurement setup. It was found that disks of larger edge inclination angles have a larger free spectral range (FSR) and a lower resonance wavelength difference between the fundamental transverse electric (TE) and transverse magnetic (TM) whispering-gallery modes (WGMs). This behavior was also confirmed with simulations based on the modified Oxborrow’s model with perfectly matched layers (PMLs), which was adopted to accurately calculate the eigenfrequencies, electric field distributions, and quality parameters of modes in the axisymmetric microdisk resonators. Combined with the nearly equivalent quality factor (Q-factor) and finesse factor (F-factor) variations, the correlations between the TE and left adjacent TM modes were theoretically demonstrated. When the edge inclination angle is varied, the distinguishable mode distribution facilitates the precise estimation of a resonance wavelength shift. Therefore, the flexible and efficient nature of wedge polymer microdisk lasers extends their potential applications in precision sensing technology.

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1. Introduction

Since single molecule detection with WGMs microcavities was demonstrated [1], more and more researchers have started to apply these microcavities with different geometries to fabricate different sensing devices [2–5]. The sensitivity of a sensor is strongly dependent on the linewidth of the resonance spectrum, which is represented by the Q-factor of a WGM resonator. So far, a variety of methods have been used to improve Q-factors of cavities, such as using a doped gain medium to compensate round-trip propagation loss [6], a thermal reflow technique to smoothen lithographic and etch-related blemishes [7], a chemical etching process [8], and an optimized design of the microdisk resonator to tradeoff the optical field confinement and interaction with interface material [9]. Among these methods, the investigations of active WGMs microcavities are more interesting because of their excellent optical properties [10, 11], and potentially higher sensitivities [12, 13]. The combination
between the gain medium and the high-Q wedge WGM resonator features multimode emission including the TE and TM polarization modes in a microdisk laser. The multimode emission would lead to overlap of modes. When the geometry of wedge microdisk resonator is changed during the fabrication, the phenomenon of mode overlap may broaden the linewidth and directly disturb the precise estimations of the FSR and sensitivity. Based on the above challenges, however, there is little work to systematically investigate the distribution between the TE and TM modes in a lasing spectrum. In order to understand the characteristics behind the multimode emission, it is appropriate to start with the exploration of mode distribution because the stability and clearness of the multimode emission spectrum is not only related to the gain medium, but also related to the geometries of a wedge microdisk resonator, e.g., radius, edge inclination angle, etc.

For the microdisk configuration, the main material systems are silica and polymer. According to the properties of materials, the most common fabrication method is lithographic technology [14], because the disk shape is easy to be achieved with optical mask and exposure. In addition, the high precision and good reproducibility could also be considered as the merits of this method. However, the lithographic processes may affect the feasibility of pre-doping the gain mediums because the high energy photons/electrons or high reflow temperatures will deteriorate their functions. For simple fabrications of the high-performance active WGMs microdisk resonators at room temperature, the ink-jet technique was developed to print dye-doped polymer microdisk lasers with low thresholds [15]. Meanwhile, the ink-jet technique is suitable for different substrates with pre-defined shapes, which enables the flexibility of this fabrication method. Due to the effect of the surface tension, a small wedge angle was naturally formed near the rim of a printed microdisk resonator. When an object is placed in the evanescent field of a high-Q microdisk resonator, the wedge microdisk resonator in combination with a nanomechanical device provides an attractive platform for both precision sensing technology and basic quantum optics research, such as Heisenberg-limited displacement sensing [16], ultrasensitive force measurement [17]. However, the optomechanical coupling strength is sensitive to relative position between a nanomechanical object and a wedge microdisk resonator because the evanescent field distribution is related to the edge inclination angle of a wedge microdisk resonator. Therefore, based on the requirements of the sensing applications mentioned above, the demonstration of correlations between the mode distributions and edge inclination angles is worthwhile.

In this paper, we demonstrated the fabrication of the polymer wedge microdisk laser using the ink-jet technique. In the experiments, the lasing spectra of the polymer wedge microdisk lasers with the edge inclination angles of 8.4° (DiskA) and 13.1° (DiskB) were measured based on a free-space optics measurement setup. By observing the lasing spectra of the two microdisk lasers, the variations of the FSR and resonance wavelength difference between the fundamental TE and adjacent TM modes were compared and analyzed using a numerical simulation method. In the simulation, the modified Oxborrow’s model with the PMLs was adopted to accurately calculate optical parameters of modes, including the eigenfrequencies, the electric field distributions, and the quality parameters, in the axisymmetric wedge microdisk resonators. As a result, combining the study of the effects of the edge inclination angles on the optical parameters of modes, the correlations between the fundamental TE and left adjacent TM modes in the lasing spectra were theoretically demonstrated.

2. Experiment

2.1 Fabrication of microdisk laser

Microdisk lasers were fabricated by the ink-jet technique. The ink-jet printing system can only use low-concentration polymer inks because high-concentration polymer inks are too viscous to eject [18]. However, in order to create an ideal microdisk geometry under the coffee-ring effect, the high-concentration polymer ink is helpful to guarantee the smoothness and completeness of a printed microdisk resonator. Thus, considering the tradeoff between
them, the hyperbranched polymers including the FZ-001 and TZ-001 were used in our experiments.

The printing processes of a polymer microdisk laser were shown in Fig. 1(a). Here the fluorine-based hyperbranched polymer FZ-001 (n = 1.45, Nissan Chemical Industries, Ltd.) was used as the cladding pedestal layer. The triazine-based hyperbranched polymer TZ-001 (n = 1.78, Nissan Chemical Industries, Ltd.) with a high refractive index was used as the core disk layer. A pedestal layer with the diameter of about 300 µm was fabricated with five shots from an ink-jet nozzle with the diameter of 70 µm (MD-K-130, Microdrop Technologies GmbH.) on the polyethylene terephthalate (PET) substrate. As an ink for the pedestal layer, the concentration of the polymer FZ-001 dissolved in 1,4-dioxane was 10 wt.%. A disk layer with the diameter of about 120 µm was fabricated with one shot from an ink-jet nozzle with the diameter of 50 µm (MD-K-130) on a pedestal layer. As an ink for the disk layer, the Rhodamine 590 as the gain medium was doped into the polymer TZ-001 dissolved in cyclohexanone. To print two kinds of microdisk resonators with the different edge inclination angles, the inks of TZ-001 with concentrations of 10 wt.% (DiskA) and 5 wt.% (DiskB) were used, respectively. The concentrations of 5 mM and 2.5 mM for the gain medium were doped into DiskA and DiskB inks, respectively, to guarantee the same concentration of the gain medium after inks dried. The scanning electron microscope (SEM) image of a printed microdisk laser was shown in Fig. 1(b) & (c). The thicknesses of both microdisk lasers were estimated to be 1 µm. The edge profiles of the DiskA and DiskB were measured by an atomic force microscope (VN-8000, Keyence Corp.). As shown in Fig. 1(d), the edge inclination angles of the DiskA and DiskB were 8.4° and 13.1°, respectively. We have fabricated microdisk lasers and group them according to their polymer concentrations. The atomic force microscopy (AFM) measurement results show that the tolerance of the edge inclination angle was estimated to be ± 0.3°, which demonstrates that the fabrication process has a good reliability and repeatability.

![Fig. 1.](image_url)

**2.2 Measurement**

Different from passive microcavities, active microcavities do not need a waveguide or a tapered fiber for coupling. Active microcavities could be simply pumped and collected based on a free-space optics measurement setup. In our experiments, the lasing spectra were measured by collecting scattering signals from the printed microdisk laser, as shown in Fig. 2. Here a passively Q-switched and frequency-doubled Nd:YAG pulsed laser (λ = 532 nm, PNG-002025-040, Nanolase Corp.) was used as the pumping source. The pulse width and repetition rate were ~5 ns and 50 Hz, respectively. The pumping source with a 350-µm-diameter beam spot was focused on a microdisk laser using a plano-concave lens with a focal
length of 20 mm. With the help of the optical microscope system (Eclipse TE2000-U, Nikon), an oscillating lasing signal was collected from the bottom-side edge of a printed microdisk laser using a multimode fiber (Thorlabs, FP600ERT, core diameter: 600 µm). Prior to the measurement, the alignment of the multimode fiber was performed to reduce the effect of the photoluminescence background intensity on a lasing signal. Finally, the collected WGMs lasing signals were recorded by the grating spectrometer (MS7504, Solar TII). The exposure time of the spectrometer was 10 s.

Fig. 2. Experimental measurement setup of a printed WGMs microdisk laser, which is consist of the pump and aligned probe systems.

3. Analysis and calculation

3.1 Spectra analysis

By using our microscope based free-space optics measurement setup, the lasing spectra of the DiskA and DiskB could be obtained under the 600 l/mm grating at the pump energy density of 27.03 µJ/mm², as shown in Fig. 3. In the experiments, the average lasing thresholds of the printed microdisk lasers was measured to be 5.5 µJ/mm² [19]. The TE mode tends to scatter into outer direction of a disk due to the dominated transverse electric field component. The TM mode tends to scatter into inner direction of a disk due to the dominated longitudinal electric field component. Considering that the multimode fiber collecting scattering lasing signals was placed slightly away from the outer rim of a disk, the TE polarization mode was preferentially captured, especially for the long wavelength regions with low photoluminescence intensities, which was demonstrated in the right regions of the lasing spectra. In the short wavelength regions with high photoluminescence intensities, the enhanced signal intensities led to the remarkable co-existence of the fundamental TE and TM modes. It implied that much more TM modes were collected by the multimode fiber. This was demonstrated by enhanced peak intensities distributed among the FSRs, as shown in the left regions of the lasing spectra. Here the FSRs were determined by the TE modes from the long wavelength regions. Compared with lasing spectrum of the DiskA with the edge inclination angle of 8.4°, the DiskB with the edge inclination angle of 13.1° has a slightly larger FSR. The insets of the Fig. 3 show the resonance wavelength differences between the TE and left adjacent TM modes. The average resonance wavelength differences between them for the DiskA and DiskB were estimated to be 0.25 nm and 0.35 nm, respectively. In order to understand the characteristics behind these variations, starting with the study of the effects of the edge inclination angles on the optical parameters of modes is a feasible solution because the lasing spectrum distribution is related to the edge profile formation of a wedge microdisk resonator. In the following, the optical parameters of WGMs in the wedge microdisk resonators, including the eigenfrequencies, the electric field distributions, and the quality parameters, were calculated separately using a numerical simulation method to demonstrate these measurement results.
3.2 WGMs simulation in microdisk

In order to accurately calculate the eigenfrequencies and electric field distributions of WGMs in the axisymmetric wedge microdisk resonator using finite element method (FEM), the Oxborrow’s model with PMLs modified by Cheema et al was adopted in the COMSOL Multiphysics software [20, 21]. In the model, Oxborrow used a simple penalty term in his master equation to avoid the spurious modes and remove the size limitation for a resonator. With this model, 3D rotationally symmetric problems are reduced to 2D. However, the WGM quality factor could not be determined accurately because of the absence of PMLs in the Oxborrow model. In 2013, Cheema et al improved the Oxborrow’s model by modifying the master equation and implemented the PMLs along the boundaries of the computation domain. The PMLs were treated as anisotropic absorbers and implemented in the cylindrical coordinate system. Figure 4(a) shows the geometry of a wedge microdisk resonator. Here the curved edge profile of the microdisk was negligible because all of the samples show very small curves which can be approximated to linear ramps. According to the measured device sizes, the diameter and thickness were set to be 120 µm and 1 µm, respectively. The edge inclination angle was denoted as $\theta$, which was varied from 2°-89° to investigate the WGMs distributions near the rims of the wedge microdisk resonators. Figure 4(b) shows the electric field distributions of the fundamental TE and TM modes at the different edge inclination angles. Here the azimuth angle number was denoted as $M$, which was maintained at 950. Obviously, the radial positions of the TE and TM modes are increasingly close to the outer rims of the wedge microdisk resonators with the increase of edge inclination angles, which directly affects the resonance wavelength shifts. Meanwhile the TE mode has a slightly larger radial position than the TM mode, which implied that the TE mode has a longer resonance wavelength.

Figure 5(a) shows the radial position shifts of the TE and TM modes at the different edge inclination angles. This data was obtained by estimating radial distances relative to the center positions with maximum electric field intensities using the MATLAB scripts. With the increase of edge inclination angles, the radial position shifts increase. It is the reason that the edge inclination angle causes the mode far away from the outer rim of a disk. The smaller for the edge inclination angle, the more significant for the mode offset relative to the outer rim of a disk, as shown in Fig. 4(b). Compared with the TE mode, the TM mode has a larger radial position shift with the increase of edge inclination angles due to its larger mode offset, which is consistent with variations of the resonance wavelength shifts represented by Fig. 5(b). The maximum radial position shifts and resonance wavelength shifts were estimated to be 5.53 µm and 111.17 nm for TE and 7.07 µm and 127.87 nm for TM, respectively. The radial position differences between the TE and TM modes decrease with the increase of edge inclination angles, which is consistent with variations of the FSR differences between them.
represented by Fig. 5(c). The maximum radial position difference and FSR difference between them were estimated to be 1.49 µm and 0.03 nm at 2°. When the M was set to be 949, the other group of eigenfrequencies of modes could be obtained. The FSRs were calculated by contrasting the resonance wavelength differences between M = 950 and M = 949 at the different edge inclination angles. Figure 5(c) shows that the FSRs increase with the increase of edge inclination angles. It is the reason that the variation of the FSR was dominated by the remarkably increased resonance wavelength shift compared with the increased radial position. A slightly larger FSR of the DiskB than the DiskA in the experiment was demonstrated. Combined with the calculations of the radial position differences between the TE and TM modes, the resonance wavelength differences between them were simulated at the different edge inclination angles, as shown in Fig. 5(d). The maximum resonance wavelength difference was estimated to be 17.6 nm at 2°. For the edge inclination angle of 8.4°, the simulated average FSR and resonance wavelength difference were estimated to be 0.617 nm and 5.8 nm, respectively. Thus it can be calculated that the resonance wavelength difference between the TE and TM modes was nearly 9.4 times of the FSR. It means that the azimuth angle number and resonance wavelength differences between the TE mode and left adjacent TM mode were 9 and 0.247 nm, respectively. Similarly, for the edge inclination angle of 13.1°, the simulated average FSR and resonance wavelength difference were estimated to be 0.635 nm and 4.1 nm, respectively. It can be calculated that the resonance wavelength difference between the TE and TM modes was nearly 6.457 times of the FSR. It means that the azimuth angle number and resonance wavelength differences between them were 6 and 0.3 nm, respectively. As observed in the experiments, the resonance wavelength differences between the TE and left adjacent TM modes obtained by simulation were very close to the measurement results.

Fig. 4. (a) The model of a wedge microdisk resonator. (b) The electric field distributions of the fundamental TE and TM modes at the edge inclination angles of 4, 9, 14, 19, 29, 49, 69 and 89 degrees.
Figure 5. (a) The correlations between the edge inclination angles and (a) radial positions, (b) resonance wavelength shift, (c) FSR for the TE and TM modes. (d) The correlations between the edge inclination angles and resonance wavelength differences between the TE and TM modes. The inserts show the error bars of the both microdisk lasers.

Figure 6 shows the variations of Q-factors and F-factors of WGMs at the different edge inclination angles. With the increase of edge inclination angle, the Q-factor and F-factor all slightly decrease. It is the reason that the radiation losses of modes decrease when the resonance modes are shifted away from the outer rims of the disks. This result is different from the work of Gandolfi et al because there is no coupling loss considered in our model [22]. In our simulation, we only took into account the absorption loss and radiation loss [15]. Since the root-mean-square surface roughness of the outer rim of a printed polymer wedge microdisk resonator was measured to be less than 1 nm due to the surface tension, the scattering loss is experimentally negligible. The extinction coefficient of the core layer polymer (TZ-001) of a printed microdisk resonator was set to be 9.74 × 10^{-8} at 600 nm as the intrinsic material absorption. For the device configurations fabricated in our experiments, the optical loss was calculated to be about 0.018 cm^{-1} due to radiation loss. Compared with the TM modes, the TE modes have slightly lower Q-factors due to the increased radiation losses. The F-factors were calculated via equation

\[ F = Q \times \frac{FSR}{f_0} \]  

(1)

to consider the effect of the geometry of a microdisk on the quality parameter of a wedge resonator [23], where \( f_0 \) denotes the eigenfrequency of mode. Figure 6(b) shows that the F-factor of the TM mode is comparative with the F-factor of the TE mode when the edge inclination angle is larger than 4°, which demonstrates that the TM modes have competitive lasing intensities comparing with the TE modes in the measured lasing spectra. The variations in F-factor as a function of inclination angle are influenced by the Q-factor, FSR, and eigenfrequency. The physical geometry of the wedge microdisk resonator has caused the effective optical loss to kick-in at a faster rate for the TE mode around inclination angle of
10°. The quicker rate of change in the effective optical losses around inclination angle of 10° was manifested by the quicker rate of decrease in Q-factors of the TE mode as shown in Fig. 6 (a). The rate of decrease in Q-factors around inclination angle of 10° is faster than the rate of change in FSRs, as well as eigenfrequencies. Therefore, minima in the vicinity of 10° inclination angle were observed in the TE mode in Fig. 6 (b).

Fig. 6. (a) The correlations between the edge inclination angles and Q-factors. (b) The correlations between the edge inclination angles and F-factors.

4. Conclusions

In this work, the wedge polymer microdisk lasers with the edge inclination angles of 8.4° (DiskA) and 13.1° (DiskB) were printed using the ink-jet technique and characterized using a free-space optics measurement setup. By observing the lasing spectra of the two microdisk lasers, it was found that the DiskB has a larger FSR and resonance wavelength difference between the TE and adjacent TM modes than the DiskA. In order to confirm these variations, the modified Oxborrow’s model with PMLs was adopted to accurately calculate the eigenfrequencies, electric field distributions, and quality parameters of modes in the axisymmetric wedge microdisk resonators using FEM. The results show that the radial position shifts, resonance wavelength shifts, and FSRs increase with the increase of edge inclination angles with respect to the two polarization modes. Compared with the TM mode, the location of TE mode closing to the outer rim of the wedge microdisk resonator illustrates that it has a longer resonance wavelength, especially for the small edge inclination angle. Combined with the nearly equivalent Q-factors or F-factors, the correlations between the TE and adjacent TM modes were theoretically demonstrated, which facilitates the precise estimation of a resonance wavelength shift when a printed wedge polymer microdisk laser is used as a sensor. Therefore, the flexible and efficient nature of these wedge polymer microdisk lasers will further expand their adaptability and repeatability in precision sensing applications, especially for a large array device. Meanwhile, the primary investigations under water environments provide the evidence for the good stability of micro-scale laser [24].

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