Experimental Confirmation of Whispering Gallery Modes with Different Parities in Elliptical Microdisks

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A phase shift of $\pi$ between two whispering gallery modes with the same angular momentum number in elliptically deformed microdisks has been demonstrated experimentally using far-field measurements. The near-field pattern of one mode has a phase shift of $\pi$ relative to that of the other mode. With the experimental techniques used in this study, we were able to excite the two modes separately. The parity of the individual mode was identified by analyzing the far-field pattern of the identical parity. The distinct far-field pattern was observed according to the parity of the mode. Finite-difference time-domain (FDTD) calculations were found to be in good agreement with the experimental results.

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I. INTRODUCTION

Various types of small optical resonators have been studied for their potential use in compact practical components, such as lasers and filters, and as experimental tools in cavity quantum electrodynamics [1,2]. In particular, microdisks of a few microns in size have attracted much interest due to the advantages of their integration with planar light circuits and their high coupling efficiency with waveguides [3]. Whispering gallery modes (WGMs) are traces of light propagated by successive total internal reflections in the ray optics region and are, in general, confined to the vicinity of the boundary of dielectric microdisks and microspheres [4,5].

In general, two mode numbers are needed to characterize two-dimensional WGMs, a radial mode number $q$ and an angular momentum number $l$ [6]. The mode numbers $q$ and $l$ are related to the numbers of field-intensity maxima in the radial and the azimuthal directions, respectively. In the system we investigated, WGMs with the same angular momentum number $l$ were inherently doubly degenerate due to azimuthal symmetry. These degenerate modes could be described by the superposition of a clockwise propagating wave and a counter-clockwise propagating wave. However, for real structures, the inevitable imperfections around their boundaries broke azimuthal symmetry; hence, the degeneracy was broken, leading to frequency splitting of the two modes. This phenomenon has been observed experimentally in both passive and active components based on WGMs [7,8]. However, it can be a hindrance to the use of wavelength-division multiplexing filters with high resolution or of microlasers with low thresholds and high spontaneous emission factors. Fujita and Baba have recently reported the production of microgear lasers by enhancing one of the two degenerate modes through the introduction of gratings near the surfaces of microdisks [9].

In this paper, we unambiguously confirm the origin of the split mode patterns of an elliptically deformed microdisk laser by using far-field measurements. To date, the elliptical microdisk has attracted much interest due to its high directionality and selection of modes with low radial numbers [1,10]. Thus, this study will also be helpful to analyzing the features of an elliptical microdisk regarding its advantages.

II. EXPERIMENTS

In this study, we fabricated an elliptical microdisk structure in order to observe the splitting phenomenon. It is well known that WGMs are conserved in elliptical structures, despite the broken azimuthal symmetry [11]. Because emission from elliptical microdisks predominantly occurs close to the region of highest curvature, the far-field pattern for each of two modes with the same angular momentum will be clearly discerned. Note that two modes are doubly degenerate if the elliptical microdisks are circular. The major axis of our microdisk has a length of 5.2 $\mu$m and an aspect ratio...
of 0.74. The microdisk laser has an InGaAsP/InP slab structure. The refractive index of the structure is 3.4. Seven pairs of InGaAsP quantum wells were employed as an active material, and emitted near 1.55 \(\mu\)m. We used typical electron-beam lithography to precisely define the shape of the structure; then, a dry etching technique using Ar/Cl\(_2\) chemically assisted ion-beam etching was carried out with poly(methylmethacrylate) as a mask layer [2]. To reduce the vertical losses coupled to InP substrate, we reduced the width of the pedestal supporting the microdisk through a wet etching process with a dilute HCl. The inset in Fig. 2 shows a scanning electron microscope (SEM) image of our elliptical microdisk after all fabrication procedures had been completed.

The experimental setup for the far-field measurements (Fig. 1) was identical to that of Ref. 12. We measured the far-field emissions from the microdisk laser directly by scanning the escaping radiation over the whole hemisphere. The fabricated microdisks were pulse-pumped using an external 980-nm diode laser at the backside of the wafer so that the femto-watt detector was able to move freely. Careful alignment of the pump beam with respect to the samples was needed to excite the desired mode. The pulse width was 40 ns, and the duty cycle was 4 %. The angular resolutions of the far-field measurements were 3.6° in the azimuthal direction and 2° in the polar direction. Standard lock-in techniques were employed in order to eliminate unwanted signals. The modulation frequency was set at 740 Hz because of the response time of our femto-watt photodetector. The photodetector was positioned 30 cm from the sample. The raw data obtained from the far-field measurements over the curved surface of the hemisphere were projected onto a two-dimensional surface and are shown in Fig. 1 [12].

Before carrying out the far-field measurements, we measured the spectrum of the elliptical microdisk laser by placing the fiber tip of an optical spectrum analyzer (OSA) as close as possible to the sample. The graph in Fig. 2(a) shows the spectrum of the elliptical microdisk laser. Two adjacent lasing peaks were visible when the pumping configuration was almost uniform over the sample. These two modes correspond to the doubly degenerate modes with the same angular momentum number \(l\) because the spectral range between two neighboring modes with a different \(l\) is up to 60 mm in this structure. Additionally, these two modes should have the same fundamental radial mode number \(q = 1\) because higher radial modes do not show high directionality, which is different from our far-field results. This splitting is caused by the coupling of two degenerate modes, \(\exp(\imath l\phi)\) and \(\exp(-\imath l\phi)\), as previously described [13]. Since the mode patterns are separated by a phase of \(\pi\), which prevents gain competition, both modes can sometimes lase simultaneously even though they are positioned close together in the spectrum. Fig. 2(b) shows the far-field results when the intensities of the two lasing peaks in the spectrum are nearly identical. The far-field pattern is positioned orthogonally to the major axis of the ellipse, which reflects the universal law of directionality of a deformed microdisk [14]. The high directionality of the far-field pattern is attributed to the enhanced tunneling near the region of highest curvature [10]. However, the emission pattern is blurred, and definite lobes are not observed.

It is worth emphasizing that we were able to separate each split mode experimentally by adjusting the pumping configuration. In the far-field measurement setup, we used a \(\times 40\) objective lens to focus the pump beam. The illuminating beam size at the cavity is around 3 mm. Although the beam size is large enough to cover most of the area of the cavity, a fine adjustment of the pump beam position enabled us to excite only one mode. It is hard to tell the exact pump beam position in the cavity, but we infer that the pump beam shone close to the edge of the microdisk. We confirmed that the far-field pattern arose from a pure single mode by checking simultaneously the spectrum obtained with the OSA. Figs 3(a) and 3(b) show the far-field emission patterns of the two split modes. The dashed lines in the far-field pattern
data indicate the direction of the minor axis of the elliptical microdisk. As shown in Fig. 3, one of the far-field patterns has an antinode on the dashed line while the other mode has a central node. This phenomenon can be explained by considering the WGMs (for transverse electric (TE) polarization modes) to be a sum of almost equally distributed electric dipoles in the vicinity of the boundary of the structure (Figs. 4(b), (e)). When electric dipoles are located with even (odd) symmetry with respect to one axis, constructive (destructive) interference occurs on the other axis in the far-field region. In other words, the parity of the near-field pattern with respect to one axis determines whether the intensity of the far-field pattern on the other axis is maximum or zero. This implies that the beam always propagates tangentially to the boundary of a microdisk when it escapes. Thus, we deduce that the two split modes correspond to two degenerate modes with a phase difference of \( \pi \). Note that because the electric dipoles near the major-axis in the elliptical microdisk mainly contribute to its far-field pattern, it is sufficient to inquire into only their symmetry.

To confirm our experimental results, we carried out far-field simulations for elliptical microdisks with two WGMs (for TE) with angular momentum numbers 8 (Fig. 4). The major axis of the ellipse we used in these calculations had a length of 1 \( \mu \text{m} \) and an aspect ratio is 0.87. We used a refractive index 3.4 for this slab structure. Since the far-field characteristics of the mode-pattern are due to the WGMs’ symmetry rather than its size, the above analysis also applies to this structure. Thus, we chose a smaller structure than was used in the experiment in order to clearly observe the features of the far-field pattern that are due to symmetry. We can select even or odd modes individually in the finite-difference time-domain (FDTD) calculations by applying symmetry conditions. As Figs. 4(a) and (d) show, the features of WGMs in an elliptical structure are preserved, for dipoles with opposite phases occur alternately along the structure’s boundary. When the electric field direction has even (odd) symmetry with respect to the \( x \)-axis (Figs. 4(b) and (e)), the far-field emission has an antinode (a node) on the orthogonal axis (Figs. 4(c) and (f)), which is in good agreement with our experimental results. Because modes with different symmetries have different far-field patterns, from the viewpoint of directionality, the symmetry of each mode must be recognized, especially for smaller structures for which few lobes appear in the far-field pattern [14].

III. CONCLUSIONS

In summary, we have demonstrated the origin of doubly degenerate WGMs in elliptical microdisks through far-field measurements. We conclude that the intensity of the far-field pattern on one axis is determined by the parity of the mode pattern with respect to the other axis. The two degenerate WGMs within the microdisk were confirmed to have a phase difference of \( \pi \). Our far-field simulations also support these experimental observations.

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REFERENCES