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Discussion

Systematic analysis of whispering-gallery modes in planar silicon nitride microdisks

Tae-Kyeong Lee [a], Hong-Seung Kim [a], Geum-Yoon Oh [a], Byeong-Hyeon Lee [a], Doo Gun Kim [b], Tae-Kyung Chung [a], David McCloskey [c], John F. Donegan [c], Young-Wan Choi [a,*]

[a] School of Electrical and Electronics Engineering, Chung-Ang University, 221 Heuksuk-Dong, Dongjak-ku, Seoul, 156-756, Republic of Korea
[b] Photonics Bio Research Center, Korea Photonics Technology Institute, Gwangju 500-460, Republic of Korea
[c] Centre for Research on Adaptive Nanostructures and Nanodevices (CRANN), School of Physics, Trinity College Dublin, Dublin 2, Ireland

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ABSTRACT

We have investigated the electric-field intensity distributions and characteristics of the whispering-gallery mode (WGM) from a planar microdisk using a three-dimensional finite-difference time-domain method. Silicon nitride (Si_3N_4) planar microdisks on silica (SiO_2) substrates have been systematically analyzed considering the effects of the sidewall angle, etching depth, and height. Superpositioning of the TE and TM modes which is caused by the skew effect according to the sidewall angle has been demonstrated. Furthermore, the mode splitting caused by the change from single mode to multi-mode regimes due to an increase in the height has been analyzed. Several planar microdisks of Si_3N_4 on SiO_2 were fabricated, and their resonance characteristics were probed by using micro-photoluminescence spectroscopy. A quality factor of 5×10^3 for microdisks with a diameter of 3.5 μm and sidewall angle of 35° was observed in the visible range. The WGMs of fabricated microdisk were analyzed according to the details of the model and found to be in good agreement

1. Introduction

Microdisks have attracted considerable attention owing to their high quality-factor (*Q*-factor), small volume, and a simple fabrication process [1–3]. Furthermore, the structure is an important element in integrated optics for various applications such as laser, modulator, filter, and biosensor [3]. Inside a microdisk, the light-wave circulating around the circumference can be considered as a propagating optical mode called the whispering-gallery mode (WGM) due to the total internal reflection at the interface of the microdisk with air [4]. Because these modes are very sensitive to the surrounding environment, these structures can be utilized for very efficient sensors for detecting the change in the refractive index surrounding the disk.

Micro-resonator structures such as a ring [5], toroid [6], and disk [1–3,7] exhibit the characteristics of the WGM. Although a ring resonator with easy fabrication has been studied for many applications, the *Q*-factor is relatively low as compared to that of other resonator structures. The toroid type, which consists of a floating donut-shaped waveguide in air, has a very high *Q*-factor owing to low loss inside the resonator. However, it is difficult to fabricate and measure a toroid resonator, because the resonance characteristic is observed by coupling a tapered optical fiber. The coupling coefficient has an effect on the *Q*-factor of the resonator, and it is not easy to integrate it with other devices. Floating microdisk resonators also have disadvantages similar to those of the toroid resonator [7]. However, the fabrication and integration of planar microdisk resonators on a substrate are relatively easy as compared to that of other resonator structures. A planar microdisk resonator is typically characterized by waveguide coupling or photoluminescence (PL) measurements. In addition to these advantages, arranging several electromagnetically coupled microdisks into so-called "photonic molecules" offers new functionalities for the devices, without compromising the *Q*-factors of the individual cavities [8]. The properties of these photonic molecule states are very similar to those of confined electron states in atoms. Owing to this similarity, optical microcavities are sometimes termed "photonic atoms" [8]. In order to design photonic molecules, the resonance characteristics of a single microdisk should be analyzed first with several parameters, because strong coupling in each photonic atom is caused by the resonance condition.

* Corresponding author. Tel.: +82 2 820 5326; fax: +82 2 822 5326.
E-mail address: ychoi@cau.ac.kr (Y.-. Choi).

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Recently, studies have been conducted on vacuum Rabi splitting for strong coupling of a single two-level solid-state system with a photon, as realized by a single quantum dot in a semiconductor microcavity [9–12], and mode splitting of the emitted light in multiple microdisks via a coupling mode (bonding and anti-bonding) [8,13,14]. In another study, mode splitting for WGMs according to the nonlinearity due to the surface roughness of a single microdisk was also researched [15]. The nonlinearity can be obtained through processes such as two-photon absorption, Raman scattering, and free-carrier absorption. Furthermore, the WGMs are determined by several other structural conditions. Above all, the microdisk structural parameters such as the diameter, effective index, and layer height have a great effect on the WGMs. Although a vertically etched microdisk shape is commonly used for simple analysis, a sidewall angle is inevitably generated during the dry etch process for anisotropic materials [16]. The resulting etched sidewall angle depends on controlling the ratio of the material removed in the horizontal direction to that removed in the vertical direction and the ratio of etching rates between the substrate and the etch mask [16]. For these reasons, it is difficult to accurately etch in the vertical direction. Therefore, mode splitting or a superposition phenomenon can occur because the sidewall angle has a serious effect on the WGMs. There have been recent experimental works on microdisks with sidewall angle [26–28]. Although a vertically etched microdisk is intended to be generated, the sidewall angle is inevitably generated during the dry etch process for anisotropic materials. In general, the values of sidewall angle are in the range from 10° to 40° depending on the etching conditions. Nonetheless, most of WGM analysis has been performed assuming vertical sidewall.

For an integrated biosensor based on a photonic microdisk, when the concentration of the target material covering on the surface changes, the effective refractive index of the microdisk waveguide will change and consequently the resonant peak of the microdisk will shift. By measuring the shift in the resonance wavelength or the intensity variation for a fixed wavelength, one obtains the change of the refractive index. These characteristics can be employed to measure biochemical events, such as the presence of a biomolecule or the amount of biochemical pathogen. Therefore, characterization of the resonance peak would be very important for the application of sensitive biochemical sensors. Recently, a plasmonic biosensor, in which a thin metal layer is deposited on the sidewall of a floating microdisk, has been studied [25]. Here, in the floating microdisk, metal deposition on the sidewall and measurement using tapered fiber near the disk are not easy tasks. However, if it makes use of a planar microdisk with a defined sidewall angle, the sensor device with the characteristics of both plasmonics and microdisk can be more easily fabricated. It appears that a systematic and comprehensive WGM analysis has not been studied considering the refined structure of a microdisk. Accordingly, this work provides a critical analysis of the resonance structure of the microcavity for its future application as a sensor.

In this paper, we describe the systematic analysis for WGMs of a silicon nitride (Si_3N_4) planar microdisk on a silica (SiO_2) substrate. Si_3N_4 is a suitable material for integrated photonics owing to its low cost, compatibility with standard CMOS fabrication processes, and low optical loss throughout the visible and IR regions [3,17]. In addition, Si_3N_4 is a well-characterized material as a dielectric spacer in the microelectronics industry. It has been recently reported that a resonator with a high *Q*-factor is possible in this material system [3]. Here, we simulate the expected electric-field (*E*-field) intensity distributions and characteristics of visible WGMs by using a three-dimensional finite-difference time-domain (3D FDTD) method. The effects of the sidewall angle, etching depth, diameter, and height of a microdisk have been studied. In addition, several planar microdisks with Si_3N_4 on a SiO_2 substrate were fabricated and measured for comparison.

The outline of the rest of the paper is as follows. In Section 2, we briefly discuss the operation principle of a microdisk through theoretical analysis. Then, the changes of resonance peaks in a microdisk, such as shift, superposition, and splitting, are analyzed according to the sidewall angle, etch depth, and height by the 3D FDTD method and theoretical analysis in Section 3. Finally, we compare the simulation results with experiments and identify mode splitting in microdisks with an inclined sidewall in Section 4.

2. Operation principle of a microdisk with WGMs for the theoretical analysis

Dielectric resonators make use of total internal reflection at the boundary between two low-loss dielectric materials. The confined rays skim around the inside rim of the resonator with an angle of incidence that is always greater than the critical angle, preventing them from transmitting out of the resonator. When the core width of a bent waveguide increases, the mode profile changes, and the bent waveguide eventually becomes multimodal, as in the case of straight waveguides when they become wider. However, another interesting phenomenon occurs at the same time, which cannot happen for straight waveguides. When the core width of a bent waveguide increases beyond a certain limit, a regime is reached where the bend modes are guided by only the outer dielectric interface, and the precise location of the inner dielectric interface becomes irrelevant. These modes are known as WGMs [18]. Although the WGM has been reported by many researchers [4,18], we carry out a theoretical analysis for the resonance characteristics because the mode number of the planar microdisk with a WGM should be accurately defined based on material, size and shape for the case of Si_3N_4. A microdisk with a WGM can be characterized using a simple analytical model [4,18]. If the disk is treated as an infinite cylinder with an effective index given by the mode of a planar waveguide, this effective index depends on both the wavelength and height of the disk and is different from each mode of the planar waveguide. In the microdisk, it may be possible to support multiple modes in the center direction of the cylinder because it means that the waveguide width increases in a bent waveguide. These modes are defined according to the polarization and the number of modes in the direction from the edge to the center.

Fig. 1(a) shows the layer structure of the planar waveguide. Here, the sidewall angle and height of the core are assumed to be 0° and 400 nm, respectively. The refractive indices for Si_3N_4, SiO_2, and Si are 2.1, 1.45, and 3.5, respectively. For mode number definition, the effective indices of the Si_3N_4 and SiO_2 layers on a Si substrate should be obtained. There are number of ways to calculate the effective index [4,19,20]. We obtain the effective indices by the plane wave propagation equation and Maxwell's equations. The equation for the effective index for the TE mode is given by [4,19,20]

$$2v\sqrt{1-b} = m\pi + \tan^{-1}\sqrt{\frac{b}{1-b}} + \tan^{-1}\sqrt{\frac{b+\gamma}{1-b}}, \tag{1}$$

where the normalized frequency is $v=\sqrt{k^2a^2(n_1^2-n_s^2)}$, the cut-off condition is $b=n_{eff}^2-n_s^2/n_1^2-n_s^2$ (for guided modes, $0 \le b \le 1$), the asymmetry parameter is $\gamma = n_s^2-n_0^2/n_1^2-n_s^2$, the height of the waveguide is $2a$, and m is an integer. Then, the effective index for the mode is defined as $n_{eff}=\beta/k$, where $k=2\pi/\lambda_0$ is the vacuum wavenumber, and β is the propagation constant. A similar