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Research Article

Comparison of Resonance Modes in Two-Dimensional and Three-Dimensional Microsphere Structures

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In this article, we have investigated the performance of a resonator in 2D, in an asymmetric form using the physical method and using the Matlab software, we have analyzed it in 3D. According to the simulation results, in asymmetric 2D and 3D structures, whispering gallery modes, or resonances appeared at similar wavelengths for the same radial and polar mode number. Also, the results obtained from the simulations indicated that the resonances of the asymmetric 2D structure would occur at wavelengths close to the wavelengths of 3D structure and the resonance wavelengths for transverse electric (TE) and while transverse magnetic (TM) modes would not change by altering the lateral mode number. Accordingly, 2D structures can be used to obtain resonance wavelengths in microsphere resonators. Achieving results with high accuracy, as well as faster speed offered by smaller meshing volume is one of the advantages of 2D structures in the physical method.

1. Introduction

In recent years, researcher attention to optical whispering gallery mode (WGM) microsphere resonators has increasingly grown, due to the high-quality factor and the small mode volume [1]. WGM optical microresonators are used as biosensors in various microcavity geometries such as disks [2], rings [3], toroids [4], and microspheres [5]. WGM resonances occur close to the surface of the cavity and have a high sensitivity to perturbations in the surrounding medium via its evanescent tail. Therefore, the WGM resonances are widely used in the applications such as miniature biosensors for the monitoring of viruses, peptides, proteins etc. [6]. The quality factor and the sensitivity are two key parameters that determine the sensing performance of the microresonators by using a figure of merit (FOM) defined as the product of Q and S [7].

Optical biosensors based on WGM resonators are one of the most important and basic tools for detecting viruses and bacteria [8, 9]. Fast and accurate diagnosis of the types of viruses and bacteria is very important. Thus, these sensors have very wide applications in the diagnosis and treatment of diseases. One of the most important features of biosensors is very high speed in detecting the type of virus and bacteria, their usability in small and portable devices, the simplicity of the biosensor structure, label-free detection [10], as well as the very high accuracy of the sensor. Among the resonators of WGM with different geometries such as ring and disk, microspheres have been studied more due to their easy manufacturing from various organic and inorganic materials in the laboratory as well as in an industrial environment [11–15]. These resonators have very high-coupling efficiency due to a controlled coupling method through tapered fiber, which leads to very low transmission and optical losses. As a result, a very high quality factor between 10^8 and 10^9 can be achieved in these resonators.

2. Materials and Methods

As displayed in Figure 1, the WGMs are coupled into the microsphere through the tapered fiber, and these modes propagate along the hemispherical plane of the sphere.

The WGMs in the microsphere structure, by two polarized modes, TE (transverse electric mode) and TM (transverse magnetic mode), and three mode numbers l (field component in polar direction), m (field component in lateral

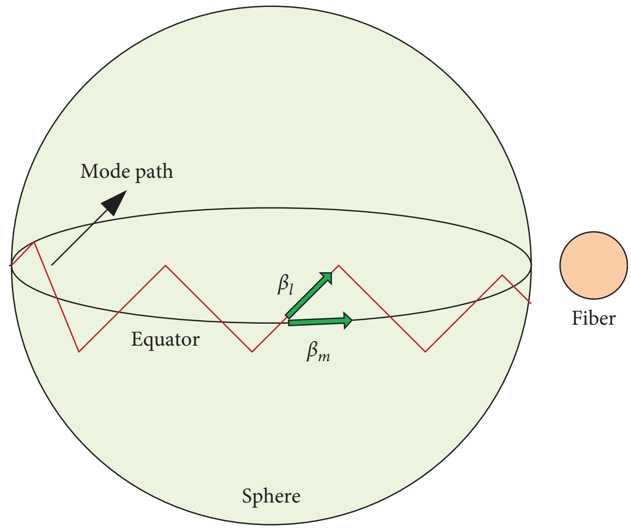

FIGURE 1: Schematic of a microsphere resonator coupled to a tapered optical fiber.

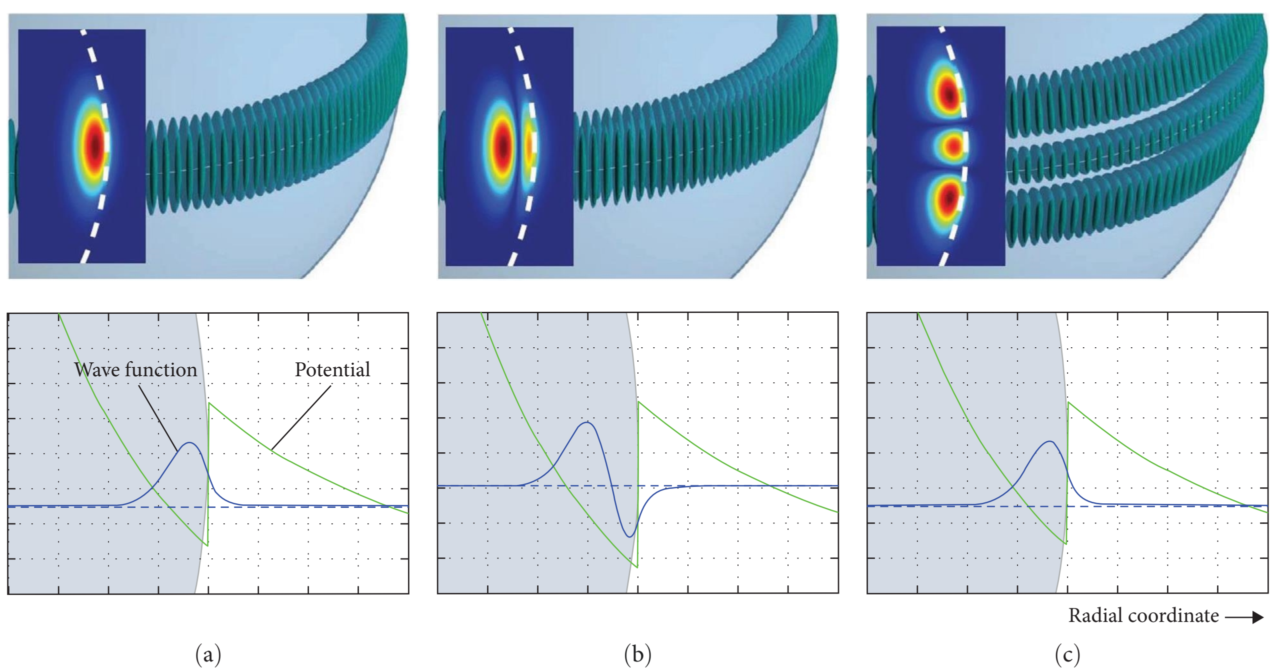

FIGURE 2: (a) Top: intensity on the surface and intensity cross-section (inner figure) basic TE mode ($l = m$); (b) second-order radial mode ($n = 2$); (c) lateral mode in a spherical resonator ($m = l-2$).

direction), and n (field component in radial direction) are specified.

As depicted in Figure 2, the fields of the WGM change with the alternation of the mode numbers n, m, and l.

The resonance wavelength is determined by the values of l and n. For any fixed value of mode number l, mode number m has a range between $-l$ and l. Different values of m indicate that the modes move in zigzag paths with different deviations from the hemispherical plane [16]. In fact, for each fixed value of l, there are $2l + 1$ modes that rotate with different deviations from the hemispherical plane with respect to the lateral mode number m and have the same resonant wavelength [17].

The 2D structure of the microsphere is in two forms in the physical method. In the first case (Figure 3), the viewing angle is from the front and the angle changes in the zx plane. The y-axis is perpendicular to the zx plane and toward the inside of the plane. In this case, the changes in the WGM field will be observed in the polar and radial directions (asymmetrical structure).

In the second case (Figure 4), the viewing angle will be from above and the angle changes in the xy plane. The z-axis is perpendicular to the xy plane and to the outside of the plane. In this case, the changes to the WGM field will be seen in the lateral and radial directions (symmetrical structure).

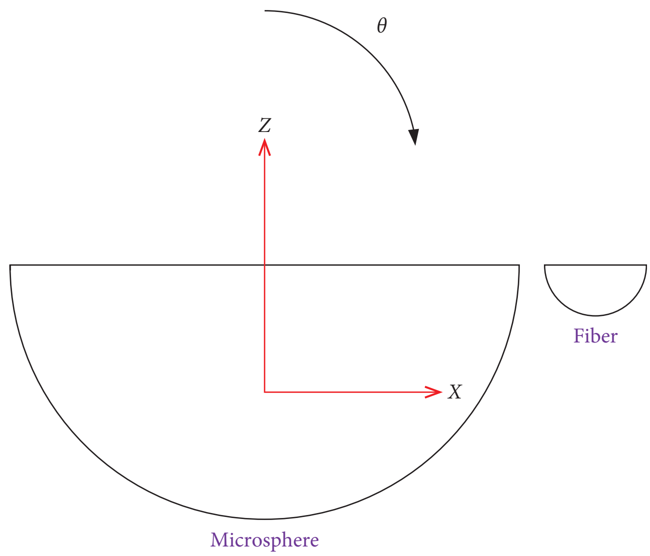

FIGURE 3: View from the front: angle changes in the zx plane.

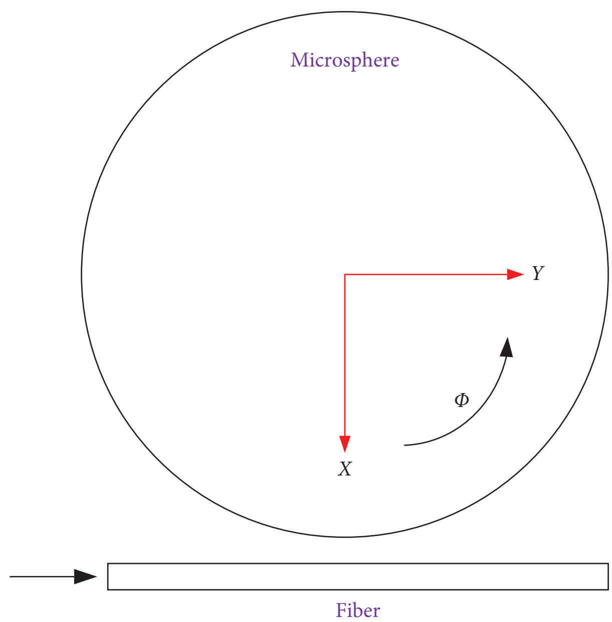

FIGURE 4: View from above: angle changes in the xy plane.

In the asymmetric 2D system, the angular or polar dependence of the electric field is defined by the following relationship:

$$\exp[\pm jm\varphi]. \quad (1)$$

In the above relationship, m is an integer. Angular dependence is related to the above relation and this relation specifies the fields that move around the z axis [18].

3. Whispering Gallery Modes in a Microsphere Resonator

In this section, first, the effect of lateral mode number m is investigated on the resonance wavelength of microsphere modes. In the first asymmetric structure, a chalcogenide glass microsphere resonator with a refractive index of 2.8 and a radius of 25 μm is used.

Air with a refractive index of 1 is considered as the surrounding environment. Figure 5 presents the results of an asymmetric 2D simulation for a polar mode number with a value of 272, a radial mode number with a value of 1, a lateral mode number with a value between 269 and 279, as well as TE and TM polarization.

The results of Table 1 show that upon changing the lateral mode number (m) and fixed values of l and n, the resonance wavelength for TE and TM modes will not change. Indeed, the changes in the field of the WGMs in the direction of the angle θ have no effect on the resonance wavelength.

In the second asymmetric structure, a silica microsphere with a radius of 15 μm and a refractive index of 1.51 is employed. Air with a refractive index of 1 is considered as

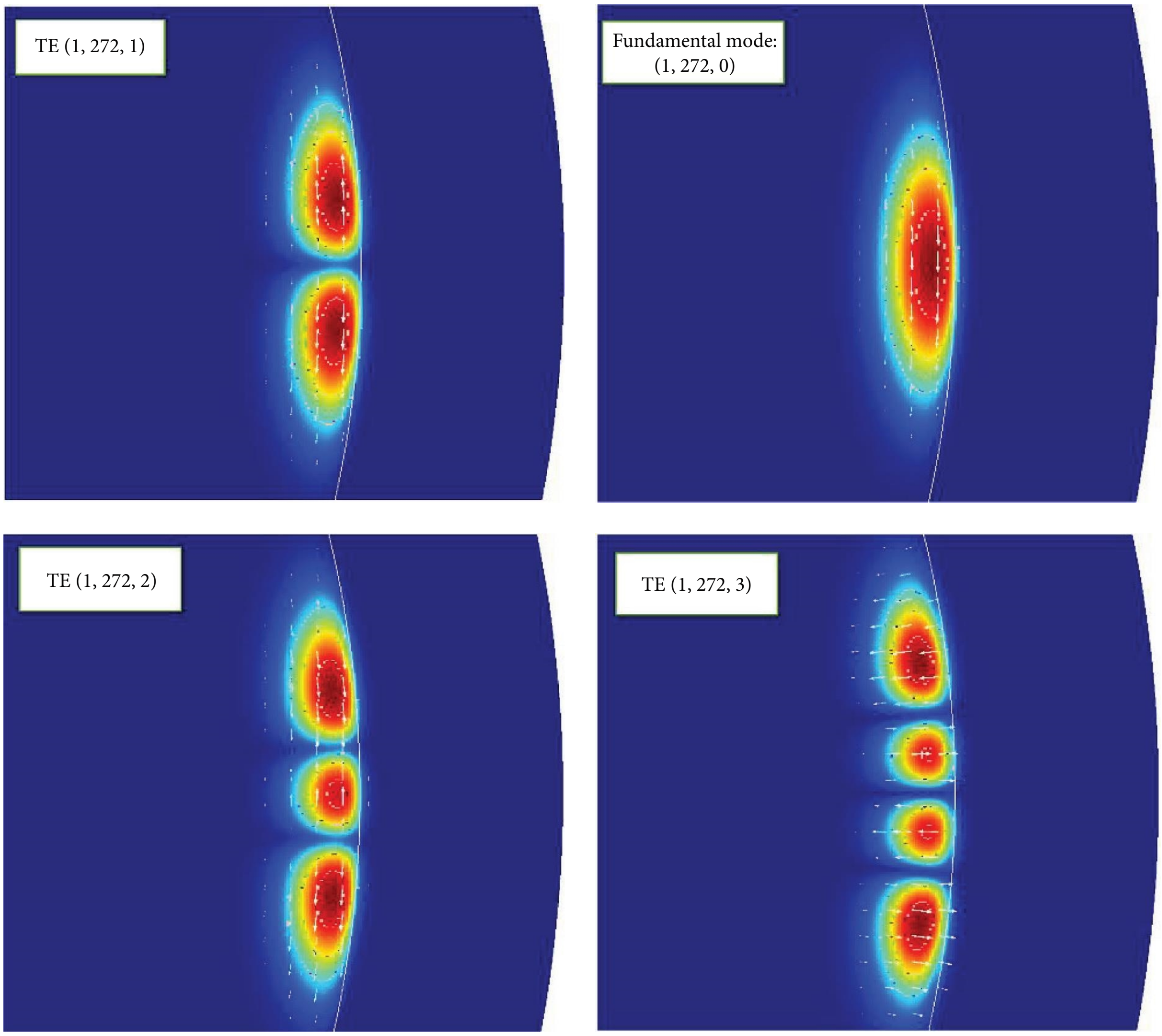

Figure 5: Distribution of the whispering gallery modes field for different values of m and fixed values of l and n.

Table 1: Investigating the effect of the lateral mode number (m) on the resonance wavelength.

Resonance wavelength (nm)	$L-M$	M	L	N	Polarization
1,550.835	0	272	272	1	TE
1,545.717	0	272	272	1	TM
1,550.835	1	271	272	1	TE
1,545.717	1	271	272	1	TM
1,550.835	2	270	272	1	TE
1,545.717	2	270	272	1	TM
1,550.835	3	269	272	1	TE
1,545.717	3	269	272	1	TM

the surrounding environment. The results of an asymmetric 2D simulation for the polar mode number with a value of 25, radial mode number with a value of 1, lateral mode number with a value between 21 and 25 as well as TE and TM polarization are demonstrated in Figure 6.

Table 2 reports resonance wavelengths by altering the lateral mode number (m) and fixed values of l and n, for TE and TM modes, as a simulation with physical method (asymmetrical 2D) and analysis with Matlab software (3D).

According to the results obtained in Table 2, changes in the lateral mode number m has no effect on the value of the resonance wavelength. As a result, the changes in the direction of the angle θ can be completely ignored and the 2D structure can be used instead of the 3D structure.

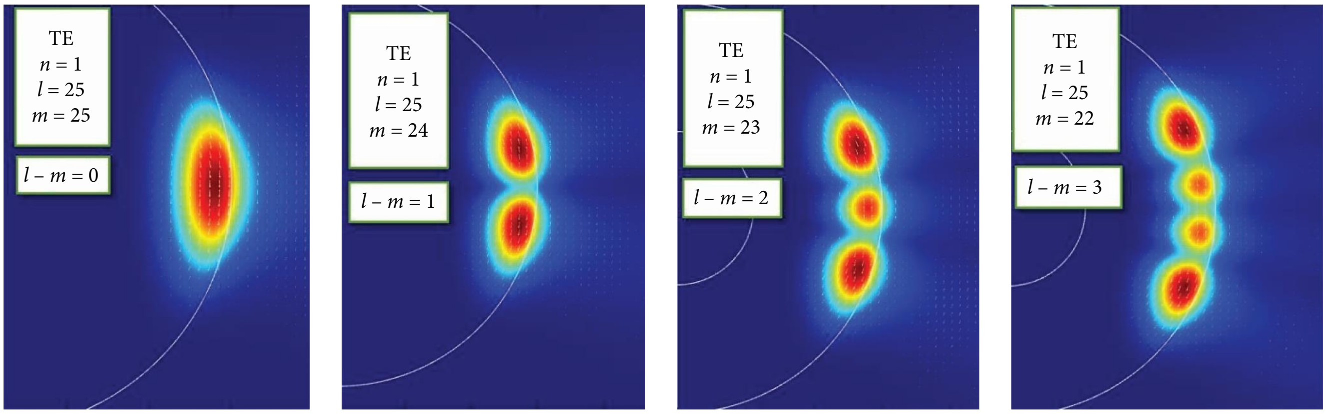

Figure 6: Distribution of the whispering gallery modes field for different values of m and fixed values of l and n.

Table 2: Comparison of the effect of the lateral mode number (m) on the resonance wavelength using two simulation and analysis methods.

Simulation (nm)	Analysis (nm)	$L - M$	M	L	N	Polarization
4,780.38	4,780.47	0	25	25	1	TE
4,675.84	4,675.89	0	25	25	1	TM
4,780.38	4,780.47	1	24	25	1	TE
4,675.84	4,675.89	1	24	25	1	TM
4,780.38	4,780.47	2	23	25	1	TE
4,675.84	4,675.89	2	23	25	1	TM
4,780.38	4,780.47	3	22	25	1	TE
4,675.84	4,675.89	3	22	25	1	TM

4. Conclusion

The n value represents the maximum number of fields in the radial direction and $n = 1$ indicates the fundamental mode. The fundamental is desirable in most applications and is characterized by an intensity maximum only in the radial and polar directions and a field maximum close to the hemispherical plane.

The fundamental mode that appears on the surface of the sphere and hemispherical plane is one of the most important resonance modes for sensing nanoparticles on the surface of the microsphere. The WGMs in the microsphere structure are characterized, by two polarized modes, TE and TM, as well as three mode numbers l (field component in polar direction), m (field component in lateral direction), and n (field component in radial direction). The obtained results reveal that the resonance wavelength of each WGM is determined only by the values of l and n. For any fixed value of mode number l, mode number m has a range between $-l$ and l. All modes with the same value of l and n, regardless of m, have the same resonant wavelength. As a result, for the microsphere structure, TE and TM whispering gallery modes can be described by only two mode numbers without lateral dependence (m); also, the 3D problem can be solved by radial (n) and angular (l) dependences using the finite-element method in 2D. The use of 2D analysis of microsphere structure can enhance the speed of calculations.

Data Availability

We believe that ensuring that the data underlying the findings of a paper are publicly available wherever possible—as open as possible and as closed as necessary—will help ensure that the work you describe in an article can potentially be replicated. We therefore firmly support and endorse the FAIR Guiding Principles for scientific data management and stewardship—that of findability, accessibility, interoperability, and reusability. There are many benefits to sharing data—it increases not only both the utility and reliability of your work, but also its impact and visibility and your profile and credibility as a researcher.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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