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Whispering-gallery modes in a triple-layer-coated microsphere resonator for refractive index sensors

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ABSTRACT

In this study, a highly sensitive refractive index (RI) sensor is designed by functionally coating three layers of high, low, and high RI from inside to outside on the external surface of an optical microsphere resonator. The properties of whispering-gallery modes, confined in normal microspheres, as well as triple-layer-coated microspheres are presented theoretically and numerically through electromagnetic analyses. The whispering-gallery modes in such a triple-layer-coated microsphere resonator are found to be efficiently excited when optimizing the gap between the microsphere and waveguide. Two cladding modes, referred to as the inner mode (IM) and outer mode (OM), are exhibited in two high-RI layers. Potential RI-sensing applications stemming from the coupling for the IM and OM are investigated thereafter using the perturbation theory and the finite difference time domain method. It is found that the sensing properties of the OM can exceed single-layer-coated microspheres in terms of sensitivity. Specifically, an increased sensitivity of 49.5 nm/RIU (Refractive Index Unit) can be achieved by tailoring the film thickness of the middle low-RI layer. When applying a thick coating in the middle layer, there is a mode bonding in the sensitivity for the IM and OM. The detection limit, or quality factor, is also investigated by using an approximate theory. Results demonstrate that it is possible to reach a detection limit with a variation of $\sim 10^{-6}$. The study's theoretical and numerical predictions provide guidelines for the improved design and fabrication of microsphere RI sensors.

1. Introduction

In the past decade, a considerable amount of research has been focused on the excitation of optical dielectric microresonator structures [1] for observing resonant light trapping based on whispering-gallery mode (WGM) generation in numerous fields, such as narrow linewidth filters [2], nonlinear optics [3], and especially high-sensitivity sensors [4,5]. These microresonators have a very variety of geometrical shapes, including spheres, disks, toroids, and even bubbles [6]. The WGMs in them guide strongly light waves circulates about the equator of the cavity geometry by continuous total internal reflection (TIR), especially the microsphere ones, leading to quality (Q) factors in excess of 10^9 being achieved [7]. Due to the advantages of high Q factors and low mode volumes, microspheres are widely used as optical refractive index (RI) sensors for a wide variety of applications, such as measuring chemical composition, probing concentration changes, and detecting biological materials [8,9]. For example, Krioukov et al. came up with a RI sensor based on integrated WGM microresonators, which can measure a RI change of 10^{-4} RIU (refractive index unit) of the surrounding medium [10].

Coating of microresonators is a very promising technique for optimizing their properties and preserving the high Q factor. Dong et al. experimentally showed the ultra-high Q factor of WGM in a silica microsphere coated with poly-(methyl methacrylate) (PMMA) and helped to reduce scattering on the microsphere surface [11]. Most research focused on the high RI layer to study the optical field of the WGMs, exposing a stronger evanescent field compared with a plain microsphere without the coating. Moreover, Teraoka and Arnold et al. confirmed that coating a microsphere resonator with a high RI layer could expose a stronger evanescent field [12]. In sensing applications, they investigated the micro-resonators with coatings had been calculated theoretically by several research groups and the results shows that an appropriate coating can greatly enhance the sensitivity of WGM wavelength shift sensors [12,13]. Lin et al. then proposed WGM in a microsphere coated with zeolite and PMMA as ultra-high sensitive chemical sensors and RI sensors [14,15]. Thus the coating microresonators are extremely promising in sensing fields.

Previously, the multilayer-coated microsphere was calculated using the generalized Lorenz–Mie scattering theory and discovered each of

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two high-RI layers could sustain its own WGM if the RI of the intervening layer was low [16]. More recently, we proposed an approach to simultaneously detect the RI and temperature changes with the multilayer-coated microsphere by using finite element method (FEM) [17]. We demonstrated dispersion engineering of the multilayer-coated microsphere structures further [18]. In addition, to analyze the microsphere resonator system, the most commonly acknowledged numerical model is to use the finite difference time domain (FDTD) method. The method can precisely predict the electromagnetic (EM) field and the energy distribution [19]. It is extremely effective to analyze these optical systems associated WGM microresonators.

In this work, we report the study of the coupling properties of microsphere resonators coated with three layers of high, low, and high RIs from inside to outside and their application for RI sensors. Two kinds of RI sensors due to the two cladding modes can be achieved by changing the thickness of the middle low-RI layer. In Section 2, we will give an overview of WGMs of microsphere resonator using the Lorenz–Mie scattering theory. The triple-layer-coated microsphere structure model will be introduced in detail based on the perturbation theory. We present and analyze numerical results for several representative cases. In Section 3, this structure of a triple-layer-coated microsphere coupled by a fiber waveguide will be analyzed and the phase matching condition of coupling structure will be explored. The WGMs in such a microsphere resonator with three layers coupled the waveguide is investigated by using FDTD method. Relative intensity spectra, transmission spectra and EM field distributions, will be observed. Q factors will be obtained to analyze resonant characteristics of the WGMs. The results and discussion are also shown. The detection limit for the sensibility of RI sensors is discussed in Section 4. Lastly, some meaningful results are summarized in Section 5.

2. Theoretical and numerical model

2.1. Whispering gallery modes

To explain the modes and fields in a triple-layer-coated microsphere, first it is necessary to have a view of normal microspheres. The normal microsphere ($n_1 = 1.452$) resonators, which support specific class of high-Q optical modes, the so-called WGMs, were generally produced by melting the tip of standard optical telecommunications fibers [20,21]. In fact, as shown in Fig. 1(a), a WGM can be represented by an optical ray, trapped near the surface of the microsphere and tracing a zig-zag path around the equator plane (the main plane of propagation). The WGMs are EM resonances that belong to the wider family of Mie resonances and they guide strongly light waves circulates in the equation of microsphere by continuous total internal reflection (TIR) when $\theta > \theta_c = \arcsin(n_0/n_1)$. The applied electrical field inside and outside the microsphere can be obtained by taking the gradient of the electrical potential. To solve the steady state for static electrical field of the microsphere, we can solve the Navier's equation, which is starting from Laplace's equation for linear elasticity at steady state [22]. Moreover, Helmholtz's equation is applied to solve this steady state [23,24]. These equations are all inferred from the Maxwell's equations. Starting from Helmholtz's equations and applying appropriate boundary conditions, one can derive the field inside a dielectric microsphere analytically. Here, we focus on Helmholtz's equation, in the spherical polar coordinates (r, θ, φ), the equation is deformed as:

$$\frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2\frac{\partial W}{\partial r}\right) + \frac{1}{r^2 \sin\theta}\frac{\partial}{\partial \theta}\left(\sin\theta\frac{\partial W}{\partial \theta}\right) + \frac{1}{r^2 \sin 2\theta}\frac{\partial}{\partial \theta}\left(\sin\theta\frac{\partial^2 W}{\partial \varphi}\right) + k^2 W = 0 \quad (1)$$

where W is the electrical field. The EM field of intra-microsphere, when phase match, can be approximated as two polarization modes (transverse electric (TE) and transverse magnetic (TM) mode). In our work, we only focus on TE mode. It is worthing mentioning that a modified Lorenz–Mie scattering theory makes us have a strict analytical solution to the problem of scattering of electromagnetic wave by a homogeneous sphere of arbitrary radius and with arbitrary dielectric constant [12–16]. This theory can be applied to calculate parameters of scattered radiation. More importantly, it is more suitable to study WGM shifts due to changes in the RI of the surrounding medium outside the microsphere when we combine with the perturbation approach.

WGMs are characterized by three quantum indices (l, m, n), l, m, and n represent the EM field component along the radial direction, the angular direction, and the azimuthal direction, respectively [25]. In the spherical polar coordinates (r, θ, φ), for a steady-state WGM at resonance, microsphere resonances are found as roots of a transcendental equation of TE mode and the electric field $Q(r)$ for different m on radical distribution is written as:

$$H(r) = \begin{cases} \psi_l(n_1 kr) & r < R \\ T_l \cdot \chi_l(n_0 kr) & r > R \end{cases} \quad (2)$$

where R is the radius of the microsphere, n_1, n_0 stand for the RI of the microsphere and the surrounding medium. Here, $\psi_l(z) \equiv z j_l(z)$ and $\chi_l(z) \equiv z n_l(z)$ are spherical Ricatti–Bessel and Ricatti–Neumann functions, where $j_l(z)$ and $n_l(z)$ stand for the spherical Bessel and Neumann functions of first kind. The coefficient $T_l = \psi_l(n_1 kR)/\chi_l(n_0 kR)$ is determined from the continuity in the boundary at $r = R$. Moreover, $k = 2\pi/\lambda_R$ is the resonant wave factor and λ_R is the resonant wavelength. The characteristic equation to specify λ_R in the resonance spectrum is expressed by:

$$\frac{n_0}{n_1} \cdot \frac{\acute{\chi}_l(n_0 kR)}{\chi_l(n_0 kR)} = \frac{\acute{\psi}_l(n_1 kR)}{\psi_l(n_1 kR)} \quad (3)$$

The electrical field $X(r)$ on the equator plane is given as:

$$X(r) = N_s H_m\left(\sqrt{m}\theta\right) \cdot \exp\left(-\frac{m\theta^2}{2}\right) \cdot H(r) \quad (4)$$

where $H_m(z)$ is the Hermitian function, N_s is normalization constant, and θ is the angular angle. The electrical field $W(r)$ in the microsphere is written as: $W(r) = X(r) \cdot \exp(\pm jn\varphi)$, where φ is the azimuthal angle. For given (l, m, n), the WGMs (TE) of a silica microsphere resonator can be calculated by using MATLAB. Normalized modal distributions of microsphere resonators of 15 μm in radius with (l, m, n) = (1, 50, 50), (2, 50, 49), and (3, 50, 48) are shown as Fig. 2. We conclude three mode numbers l, m and n determines the distribution homogeneity of WGMs. The index m determines the maximum of WGMs on the equator plane and it satisfies the resonant condition ($m = 2\pi R n_1/\lambda_R$). The index $m - n$ stands for the number of the peaks on the azimuthal distribution and $0 < n \leq m$ from Fig. 2(a)–(c). The smaller the value of $m - n$ is, the closer to the equator plane the mode is. The index l stands for the number of ψ_l or j_l on the radial distribution, and also represents the peaks on the radial distribution from Fig. 2(d)–(f). The smaller the value of l is, the closer to the boundary of sphere the mode is from Fig. 2(g)–(i). The most confined mode ($l = 1$, $m - n = 0$) is usually more conscious and is called the fundamental mode of WGMs because it can realize higher photon degeneracy of WGM and smaller mode volume. However, the fundamental mode is difficult to be excited by near-field coupling. Therefore, much research use the coated technique to ameliorate the challenge of energy dispersion in other WGMs. For a perfect microsphere, the resonant wavelength λ_R is just related to the index l and m. Thus, the resonance frequency of WGM modes for different l is degenerate. The WGM resonance inside the microsphere is typically a brilliant equatorial ring. It is suitable to utilize a two-dimensional (2D) numerical model to describe the course to excite the WGMs in our study. Moreover, a majority of energy is confined inside of the microsphere. However, there is less energy outside the microsphere, called as "evanescent field". Due to the evanescent field, λ_R will have a shift have when the surrounding medium, such as RI, temperature or pressure, changes. The resonance wavelength shift be easily detected in the spectra in some sensing applications.