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Cylindrical optical microcavities: Basic properties and sensor applications

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Abstract

A detailed theoretical analysis of the basic properties of whispering-gallery modes (WGM) of thin capillaries is presented. The sensitivity of the resonances, as well as the Q factor is analyzed as a function of the structural parameters of the capillary and the refractive index inside the capillary. A practical application where thin capillaries are used for the measurement of glucose concentration in water is presented as a chemical sensor demonstrator. A best sensitivity of 1.24 nm/% of glucose concentration in water is reported, which corresponds to more than 850 nm/RIU. Additionally, different experimental approaches are discussed to improve the sensitivity and the detection limit that can be achieved using thin capillaries. Using thin and large diameter microcapillaries, and using a tapered fiber with the proper diameter for the excitation of the WGM, we estimate that refractive index changes smaller than 10^{-6} can be detected, maintaining an optimum compatibility with microfluidic systems.

Keywords: Optical microcavities; Microcapillaries; Chemical sensors; Refractometer; Whispering-gallery modes

1. Introduction

Whispering-gallery-mode (WGM) resonances of dielectric microcavities have received an important attention due to the high Q factor and their potential applications. Silica microspheres [1–4] have been studied for years, while recent developments of micro- and nano-fabrication technologies drive and reinforce the study of other cavities as microdisks [5,6] and microrings [7–11]. The basic characteristics of optical microresonators are very attractive for sensing. Several applications as chemical and biological sensors have been proposed [3,7,9]. The response of these sensors is based on the wavelength shift of the WGM resonances as the refractive index at the surface (or in the surrounding medium) is changed. Typically, the WGM resonances are excited by evanescent wave coupling. In this sense, thin tapered fibers have demonstrated a high efficiency in the evanescent wave excitation of WGMs [12].

Recently, a series of studies on microcapillaries have been reported [13–17]. Microcapillary resonators are readily compatible with microfluidic systems since a liquid can flow easily inside the capillary. Regarding practical applications, this is an important difference with respect other microcavities, such as microspheres or microrings, which always require the implementation of a liquid cell containing the optical device. Moreover, microcapillaries exhibit some unique properties: first the spatial separation between the outer surface where total internal reflection takes place – preserving the guidance of

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WGM – and the inner surface where the evanescent fields of WGM interact with the fluids and, second, the possibility of using fluids with refractive index higher than the refractive index of the capillary material. In fact, the Q factor of the WGM resonances increases when the refractive index of the fluid is higher, in contrast with what it happens in other microresonators [17]. These properties are not present in common microcavities which combine in a single surface both functions and make straightforward the use of microcapillaries as tunable microcavities and high sensitivity refractometers. In particular, the tunability is an outstanding feature of which most microcavities lack.

The sensitivity of capillaries to refractive index changes depends on the structural parameters of the capillary, i.e. radius and wall thickness. As an example, a sensitivity of about 10 nm/RIU [13–16] was reported using silica capillaries with 3 μm wall thickness. Reducing the wall thickness enhances the overlapping of the WGMs fields with the analyte, so improving the sensitivity. In this sense, we developed a technique to fabricate microcapillaries with submicrometric wall [17]. The radius of the capillary also affects the sensitivity, as well as the Q factor of the resonances. A sensitivity larger than 100 nm/RIU for water solutions was reported using a capillary of 0.8 μm wall thickness and 11 μm diameter [17]. Here we report the experimental characterization of a series of capillaries with rather different geometrical parameters, covering the wall thickness range 0.60–2 μm and the diameter range 9.0–60 μm, and including the characterization of second radial order resonances. A sensitivity as high as 850 nm/RIU is achieved for water solutions, using a capillary of 1.64 μm wall thickness and 55.6 μm diameter. This sensitivity is about one order on magnitude higher than the values previously reported for WGM-based microcavities.

A potential disadvantage of cylindrical microcavities (including microcapillaries) against other microresonators, is the lack of light confinement along the longitudinal axis. Typically, the WGM resonances are excited and interrogated using a thin fiber taper. The excitation of a WGM causes a dip in the spectrum of the light transmitted through the fiber taper. When the resonator is a microsphere the dips are symmetric and narrow. However, the dips observed when the microresonator is cylindrical are asymmetric and broader than expected, but narrow linewidths are required to achieve low detection limits in chemical and biological sensor applications. Our investigations reveal that this effect is strongly dependent on the WGM excitation and interrogation conditions. A proper understanding of the dispersion properties of WGM surface modes in cylindrical microcavities is the key to overtake this limitation. In the present work, we demonstrate that adjusting the excitation it is possible to control the linewidth of the resonances, reporting experimental values lower than 2 pm.

This paper has been organized as follows. Section 2 provides a brief theoretical review of the most relevant characteristics of thin microcapillary WGMs. Resonance wavelength and Q factor of the WGMs are investigated as a function of the structural parameters of the capillary and the refractive index that fills the inside of the capillary. Section 3 presents our experimental results on the use of thin microcapillaries for the measurement of glucose concentration in water solutions. The use of higher order radial resonances, which show larger sensitivity, is discussed. In Section 4, the effect of the excitation and interrogation conditions on the resonances' linewidth is investigated. Section 5 concludes the paper.

2. Theoretical analysis

A theoretical analysis of the WGMs of thin capillaries was carried out by solving Maxwell equations with the corresponding boundary conditions. Fig. 1 shows a diagram of the capillary, where the coordinates system, as well as the different parameters of the capillary, are indicated.

WGMs are waves that propagate in the azimuthal direction with an axial propagation factor equal to zero. The spectrum of these modes splits into the two well known TM^z and TE^z series [18]. The longitudinal component of the magnetic field for a TE^z WGM is given by,

$$H_z = e^{-jm\phi}\, e^{j\omega t} \begin{cases} b_1 J_m(k_1\rho) & \rho < b \\ b_2 J_m(k_2\rho) + b_3 Y_m(k_2\rho) & b < \rho < a \\ b_4 H_m^{(2)}(k_3\rho) & \rho > a \end{cases} \tag{1}$$

where

$$k_i = \frac{2\pi}{\lambda} n_i; \quad i = 1, 2, 3 \tag{2}$$

where J_m and Y_m are the Beseel functions of 1st and 2nd kind, respectively, $H_m^{(2)}$ are the Hankel functions, m is the angular order, $b_1, \ldots, b_4$ are the amplitude coefficients, n_i is the refractive index of each medium, and λ is the wavelength. Similarly, it can be expressed the longitudinal component of the electric field for a TM^z WGM. The application of Maxwell equations