PMMA Solid bottle optical microresonator for measure relative humidity.

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Abstract. In this work we studied experimentally the performance of an solid bottle optical resonator made of PMMA (polymethylmethacrylate) for measure the relative humidity of the medium. In the developed device, the WGMs modes within the microcavity are excited by the proximity of an optical fiber taper with an outer diameter of the order of 3-5 microns made from stretching a standard optical fiber of Silica by the flame brushing technique. In the resonant device, the field produced by a laser system tunable TLS is guided through the fiber taper and is coupled into the microcavity by the approach of the fiber taper to the equatorial zone of the microbottle, causing the excitation of the WGMs resonant modes inside the same. When the device is subjected to changes in relative humidity of the medium, the wavelengths of resonance of WGMs modes that have been coupled in the microresonator are shifted spectrally depending on the external humidity, showing an experimental sensitivity in the resonator due to changes in the relative humidity of the medium.

In the experiment, it was possible to produce different samples of optical resonators with a profile shaped bottle with different maximum diameters achieving a maximum sensitivity of 0.032 nm /% RH for a resonator with equatorial diameter of 1250 µm.

1. Introduction
The optical resonators play an important role in modern optics, being not only important in the design and manufacture of Laser, but also are essential devices for performing high-accuracy measurements in interferometry, experiments nonlinear optics, etc.

One of the most significant advances in the manufacture of these devices is the miniaturization of optical resonators made from different materials, the most important material reported in the literature, silica, silica and some types of polymers that have allowed an interconnection with systems integrated optics used in the area optical telecommunication. These devices have great attention due to its ability to light confinement within them, which has led to breakthroughs in the area of sensors applied to biology, physics, chemistry and the study of nonlinear optical effects.

Actually, these structures are designed with dimensions on the order of microns to allow coupling easily dielectric structures of waveguides with high symmetry and thus exploit the advantages of the morphological characteristics, its properties and its relative ease for treatment mathematical.

The propagation of Whispering Gallery Modes WGMs in a resonator bottle have been experimentally obtained in 3D structures shaped bottles using materials such as silica [1]-[4]. This type of bottle-shaped microresonators double neck support WGMs modes that are different modes of the resonators of microspheres and WGMs modes microtoroides called equatorial modes.

Currently, the manufacture and its corresponding theoretical study the transmission spectrum of such resonators, made from fibers of silica is reported, however not been reported jobs that relate the application of this type of resonators in some area using a specific polymer. Actually, the manufacture and its corresponding theoretical study the transmission spectrum of such microresonators, made from...
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During this investigation, were exploited the resonant properties of the optical microresonators in a solid bottle and was studied its application as relative humidity sensor using the physical principle of the displacement of the wavelengths of resonance modes WGMs which are confined to their inside, the same physical principle used in some previous work [5],[6]. Samples of optical microcavities in the form of solid bottles were manufactured from the polymer PMMA, with the intention to increase the sensitivity for measurement of relative humidity, for it was necessary to characterize the spectral response of the samples according to the changes relative humidity.

2. Excitation WGMs modes within a dielectric cavity in a solid bottle.

In the dielectric structures have a circular symmetry, the field can be confined by total internal reflection inside and whose modes of propagation are commonly referred Whispering Gallery Modes WGMs. In the literature the excitation of WGMs modes is reported within cavities with rotational symmetry in the form of spheres, cylindrical, toroids, rings, discs, and in some cases shaped structures bottle and bubbles, which have been fabricated from different materials such as silice and silica. These structures show behavior of resonant cavities when an external field is coupled to the cavity. For this reason, in such cavities is important to study the wavelengths/frequencies of resonance, the Q factor of the oscillations within the cavity, the free spectral range FSR and Full width at half maximum FWHM.

According to the theoretical analysis reported in the literature by some authors, when a cavity has the shape of a bottle it is possible to associate a profile that depends on the geometric shape of the cavity, which can be adjusted through various functions such as a function parabolic, cosine or a truncated harmonic oscillator [1]

\[
D(z) = \begin{cases} 
D_b \left[1 + (\Delta k z)^2\right]^{1/2} & |z| \leq L_b / 2 \\
D_s & |z| > L_b / 2
\end{cases}
\]  

(1)

Where \(D_s\) is the diameter of the solid polymer fiber chosen before the heating process, whereas \(D_b\) is the maximum diameter reached at the center of the cavity through the heating technique, \(L_b\) is the length of the protuberance and \(\Delta k\) is the radius of curvature of the profile. The latter term is considered in many situations a very small amount, for bottles having a minimum variation of fiber diameter or a protuberance in the center of the solid fiber, so that it is necessary that the relation \(dD/dz \ll 1\) is satisfied for a smooth protuberance. This type of microcavities of solid bottle, can be used as optical cavities 3D dimensional asymmetrical, topologically equivalent to a sphere-shaped resonator, which have been extensively studied in the literature.

In the literature it has been reported manufacturing optical microcavities silica in the form of bottles with a high Q factor, where the light confinement is caused by total internal reflection on the walls of the cavity. In this regard, it may be noted that the confinement of modes WGMS into the cavity is performed along a thin ring along the Ecuador on the surface of the bottle by total internal reflection experienced by rays. The WGMs excitation of modes within the cavity is performed through coupling of the field by the phase-matching of WGMs modes with external waveguide to achieve important values for the factor Q.
3. Experimental setup.

In order that the resonant structure can be used as an optical sensor for detecting changes in relative humidity it is necessary to couple the field inside the microcavity. To this end, it was used an optical fiber taper, which enables the excitation of resonant modes WGMs within the cavity.

In the fabrication process of the optical fiber taper, it was used the flame brushing technique, which is suitable due to its high flexibility for controlling the movement of the flame, the length of the taper zone and speed control stretching the fiber. In the experiment was used an optical fiber commercial step index SMF 20 type Corning, where a small portion of the fiber of the order of millimeters is selected to remove the coating and then is subjected to a heat source produced by a flame to heat the fiber to a temperature close to 1500 ° C, while simultaneously the fiber is fixed at the ends to achieve the stretch and thus to obtain the desired profile. During the fabrication process of the tapered fibers, it was possible to obtain neck diameter fibers 2-5 microns, sufficient to ensure optimum field coupling cavity.

In the test transmission fiber, a tunable laser system TLS with operating wavelengths in the range of 1500-1600 nm and optical spectrum analyzer OSA available in BraggMeter FS 2100 FiberSensing with a resolution 10 pm was used for measurements.

The diagram of experimental setup for obtaining transmission spectrum of fabricate fibers is shown in Figure 1a, while in Fig 1b the transmission spectrum obtained for a taper 4 µm diameter observed in the range of 1500 -1600 nm wavelength. In the same figure, the spectral response of the fiber in the range of 1562-1572 nm wavelengths is observed.

![Figure 1. a) Diagram of the experimental setup for obtaining transmission spectrum of the fiber taper fabricated.](image1)

![Figure 1. b) Transmission spectrum 4 µm taper diameter. Within the circle an image with increased range of 1562-1572 nm.](image2)

BMRs bottles microresonators are solid structures having shape of ellipsoid that can support WGMs nondegenerate modes. These optical cavities are fabricated in the form of hollow and solid bottles from Silica and have been used primarily as sensors optofluidics applications.

In this paper was fabricated a type of solid shaped microresonator bottle made from PMMA for use in optical measurement of the relative humidity and thus, it was possible for the first time report for the first time the fabrication of this type of resonators fabricated from a solid PMMA fiber.

The fabrication process of the cavity began with the use of a PMMA solid optical fiber with diameters in the range of 300-2000 µm. To acquire the desired shape, the solid fiber must be heated to a temperature near 200 ° C. To this it was possible to use a heating technique through an induction heating coil. When the tip of the solid fiber is inserted inside the solenoid during a given time, it is produced a protuberance at the tip of the fiber, which is molded by the gravitational force and the force of surface tension. The exposure time of the fiber to the heat source is of great importance for achieve the symmetrical shape.
The figure 2a shows a solid PMMA fiber within the induction coil, which is heated and softened in the process, while in Figure 2b is observed microscope image of the fabricated samples with the technique. During the experiment, the selective excitation of WGMs modes within the cavity is performed through a Tapers fiber coupled to the resonator along its equatorial zone, which allowed the excitation of WGMs modes and thus was possible analyzing resonance curves obtained by confining the field within the cavity.

In order to determine the sensitivity of the device to changes in relative humidity environment, it was necessary to a humidity chamber that was constructed from the controlled ingress of wet and dry air into a chamber, which presented an operating range between 53-78% RH. For measuring the relative humidity it was used a hygrometer PCE-555 of PCE Instruments with an accuracy of 0.1% RH. In Figure 3a, the coupling of the field in the equatorial region is observed through the Taper fiber. The excitation of the modes into the cavity, is performed using a tunable laser (TLS) in the range of 1500 to 1600 nm and optical spectrum analyzer (OSA) with a maximum resolution of 10 pm (Fiber Sensing FS22).

In the measurement of the spectral response, the field was collected at the exit of the field transmitted along the fiber taper, showing a very dense spectrum with a Q factor of the order of $3.5 \times 10^4$ when the taper was approached the equatorial zone of the bottle. During the experiment it was necessary to ensure stability of the spectrum in each of the fabricated samples, for it was important to control external variables to avoid possible cross-sensitivity that may experience the sensor. Within these external variables that can cause changes in the spectral response, it was possible to consider external vibrations, which may occur involuntarily during measurements. To do this, once the system is adjusted, a test spectral stability consisted of measuring the spectrum at ten minute intervals under constant temperature and humidity was performed. The result of measurement of the spectral response for the sample No. 1 is shown in Figure 4. The test results show a spectrum with good stability for the selected sample.
Figure 4. The spectral stability of the sample No. 1 under conditions of humidity and temperature constant. The spectrals measurements were taken every ten minutes.

During the experiment, they were fabricate different samples of bottle-shaped resonators and were selected five different samples for the experiment. The geometric parameters of the samples are summarized in Table 1.

Table 1. Geometrical parameters and relative humidity sensitivity of microcavities fabricated bottle-shaped. In all cases fiber preform PMMA polymer used it had a diameter of $D = 850 \mu m$.

| Sample No | Maximum diameter $D_b$ (µm) | Sensitivity nm/% |
|-----------|-----------------------------|------------------|
| 1         | 1522                        | 0.0117           |
| 2         | 1425                        | 0.0219           |
| 3         | 1250                        | 0.0325           |
| 4         | 1491                        | 0.0161           |
| 5         | 1917                        | 0.0088           |

In Table 1, the results of experimental measurements of the sensitivity of the samples were manufactured are recorded. In Figure 5a, an analysis of the hysteresis is observed the sample No. 1. The experimental data plotted in red show the displacement of a resonance peak with fixed wavelength in response to changes in relative humidity of the environment when the humidity increases. Likewise, the line plotted in black shows the response of the same cavity when the humidity is decreasing. In this case, the sensitivity measured by increasing or decreasing humidity acquire not significantly important differences, therefore have a better response than the capillaries resonators reported in some papers for humidity measurement [6].
In Figure 5b, the response sensitivity of the samples is observed. Of the analyzed results it is clear that the device with smaller maximum core diameter $D_b$ corresponding to sample No. 3 has better sensitivity $0.033$ nm/% RH, while the sample with the highest maximum diameter (sample No. 5) has lower sensitivity $0.009$ nm/% RH [6].

4. Analysis and conclusions

In this paper we have demonstrated an efficient, simple and practical method for the design and manufacture of microcavities of solid bottle using a solid fiber standard PMMA polymer, which is used as an optical microresonator whose field has been effectively confined by a fiber optical adiabatic taper profile. The experimental Q factor of the oscillations confined within the microcavity is about $3.5 \times 10^4$, which is slightly lower than those reported for microcavities shaped capillary for the same type of material [5,6]. The fabricated device can measure with good accuracy the relative humidity of the medium when the radius of curvature of the profile is small enough.

During the developed experiments, it was found that the solid shaped microresonators bottle exhibit an improvement in spectral stability for measuring the relative humidity under changing relative humidity ensuring a good hysteresis in the measuring device. However, the experimentally obtained sensitivity are not comparable with those obtained in the capillary fiber microresonators reported in some previous studies, since this type of resonators have a sensitivity ten times higher. The fabrication of these devices allow measurement of relative humidity with good accuracy and at the same time can be incorporated into integrated photonic devices for detecting substances, viruses or bacteria.

5. References

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