Measurement of hydrostatic pressure using a hollow bottle microresonator

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July 1, 2018

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Abstract. In this paper, we report the experimental results of the design and manufacture of a device in the form of a hollow bottle manufactured from a polymer for the measurement of hydrostatic pressure in microfluidics. The fabricated device bases its operation on the optical resonances of a capillary optical microresonator that has the ability to couple the evanescent light from an optical fiber tapers with a central diameter in the range of 3-5 μm which excites the resonant modes WGMs inside the cavity. The microcavity was manufactured using a heating-pressurization technique by a system built to measure which allowed reaching a minimum wall thickness in the central region of the order of 19.78 μm with a sensitivity of the order of 0.5567 nm/bar.

1. Introduction

Optical sensors based on optical fibers have been extensively studied due to their diverse applications in different areas of science. At present, different optical sensors have been reported for the measurement of different variables, such as physical, chemical and biological, that use different configurations and that can base their operation principle through different physical phenomena. Within the different optical devices used for measurement that have been manufactured from optical fibers, the optical micro-resonators are remarkable, which present different morphologies in the shape of rings [1], spheres [2], capillaries [3-5], hollow bottles [6], solid bottles [7] from different types of materials such as silicon, silica and some types of polymers with applications for the measurement of different physical variables, such as temperature [8], relative humidity [5,7], refractive index [9] and some other physical variables of interest [2,10]. This type of device is studied for its facility for the confinement of light within a small region of the microcavity and whose confinement capacity is determined from the Q factor, which for materials such as silica and some polymers have values of the order of 10^4-10^8 depending on the geometry of the cavity. In this type of devices, only certain components of the light that satisfy the resonance condition will be confined to the interior of the structure by internal total reflection between the interfaces with different refractive indexes whose resonant modes are called Whispering Gallery WGMs modes. These types of modes are supported by resonant structures that present symmetry and their confinement in the microresonator obey the refractive index differences in three different dielectric media. In this type of experiment, the WGMs modes that are supported by the microcavity can be excited through an external light source coupled through an optical fiber, an integrated waveguide or microprism whose light can interfere constructively reaching levels of recirculation of photons with extremely high lifetimes.

In this paper, the measurement characteristics of a microcavity manufactured from the polymer Polymethyl-Methacrylate PMMA in the form of a hollow bottle are described as a function of the hydrostatic pressure changes in a fluid. The sensitivity in the device, can be determined from the displacement of the resonance peaks of the light that is evanescently coupled from an optical fiber taper. For this, in section 2, the experimental technique used to manufacture the microcavities in the form of a hollow bottle and the experimental setups used for the characterization of the sensitivity of each of the manufactured samples are described, while in section 3, the experimental results obtained in the characterization of the samples analyzed are described. In section 4, the conclusions of the investigation will be described.

2. Manufacture of hollow microbottles and experimental setup

In the manufacture of hollow microbottles for use as resonant optical cavities, different manufacturing techniques have been reported, such as the technique of heating through a CO_2 laser, which can produce a radiative heat with good stability that allow to achieve a control of the geometric parameters in the microcavity [6], being the most common material the silica. On the other hand, another technique used for the manufacture of this type of structures is the technique of heating by an electric arc, where the swelling in a pressurized capillary is induced using a modified fusion splicer ensuring a good reproducibility in the manufacture of the samples [11].

In this research, we report the manufacture of a PMMA microbottle, manufactured from local heating and pressurization of a PMMA polymer capillary, which was manufactured from a PMMA preform tube from a polymer microstructure fiber design tower. In the process, one end of a capillary fiber was sealed whereas the other was connected to a homemade pressurization system, that allowed a variation of the pressure inside the capillary in the range of 1.0-3.0 Bar. To reach the smooth swelling on the surface of the capillary, a small section of the microcapillary is heated to a temperature that varies between 150-220 °C, through an induction heating coil of helical form of five turns, which is controlled by a high voltage electrical system. A sketch of the experimental setup for the manufacture of the hollow microbottle is shown in figure 1. The sealed and pressurized PMMA capillary tube is introduced into the coil in the hot zone, forming a bulge as a consequence of surface tension and the internal pressure in the capillary tube. During the heating process of the capillary, it is softened and its wall expands until it reaches the paraboloidal shape. With this technique, it was possible to manufacture micro-bottles with a maximum diameter of the order of 2987.65 μm and a thin wall thickness of the order of 19.78 μm. In figure 2, a general outline of the desired structure is observed, which must have a high symmetry and a region of maximum diameter where it is possible to obtain the thinnest wall thickness along the protuberance. In the figure, the dotted lines indicate a circumferential increase of the internal and external radii of the cavity as a consequence of the internal pressure, which can be studied from the theory of elasticity in polymers.

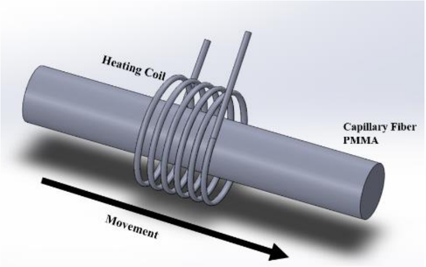

Figure 1. Fiber capillary inserted in an induction heating coil

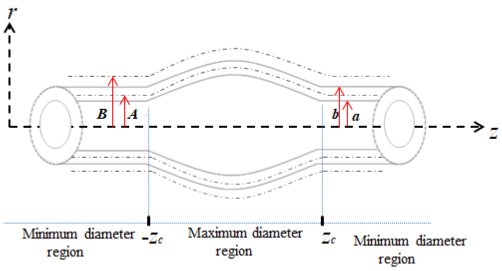

Figure 2. A general outline of the desired structure

During the manufacturing process, it is required to guarantee a constant local temperature in the capillary close to 190 °C inside the coil, which was possible thanks to the monitoring by a thermocouple. The bottle-shaped bulge formed in the capillary tube was produced by the pressure of nitrogen inside the capillary causing an expansion of the capillary in the region exposed to the heat source. If the capillary is hot enough at a constant temperature, the expansion of the capillary increases until it reaches a very thin wall and from there, the expansion is accelerated until the force of the air pressure exceeds the force of the surface tension. In the experiment, it must be taken into account that during the rapid expansion of the protuberance can present deformations if the heat experienced by the capillary is not homogeneous producing microbottles with an asymmetric shape. In addition to this, the gravitational force and the force of the surface tension can cause an asymmetry in the geometry of the bottle when the capillary experiences movements. During the experimental procedure it was necessary to develop different tests until reaching the desired shape in the microbottles. In the experimental setup developed for the determination of the sensitivity of the device for the measurement of hydrostatic pressure, the figure 3 show a microscope image of a hollow bottle obtained in the laboratory with a maximum diameter of 1354.71 µm and a wall thickness of 94.16 µm, which is traversed by an optical fiber tapers with a central diameter of the order of 3-5 µm, while the figure 4 show a sketch of the experimental setup developed to obtain the displacement of the resonance peaks that are confined to the interior of the structure as a function of the internal hydrostatic pressure in the cavity. In the figure a micro-bottle is sealed and pressurized at the other end with nitrogen through a custom-made pressurization system. The optical fiber tapers it is approached to the surface of the cavity on the equatorial zone allowing the coupling of the light inside the structure and exciting the WGMs modes in the confinement region. The excitation of the WGMs modes on the surface, it is achieved through an optical fiber taper that has been manufactured using the technique of stretching by heating that couples light to the interior of the cavity through the evanescent field that arises from the thinned region of the fiber. This fiber is connected at the end to a TLS tunable laser system with wavelengths of operation in the range of 1500 -1600 nm and at the other end it was connected to an OSA BraggMeter FS 2100 of FiberSensing with a resolution of 10 pm. At the fiber output, the transmission spectrum is detected and the existence of resonance peaks is verified, which guarantees that the device couples part of the light inside it according to the resonance condition $m\lambda_{res} = n_{eff}(2\pi r)$, where m represents the modal order of the mode, λ_{res} is the resonance wavelength of the mode, n_{eff} represents the effective refractive index and r represents the maximum radius of the cavity.

Figure 3. Microscope image of a hollow micro bottle with a maximum diameter of 1354.71 µm and a wall thickness of 94.16 µm traversed by a fiber taper.

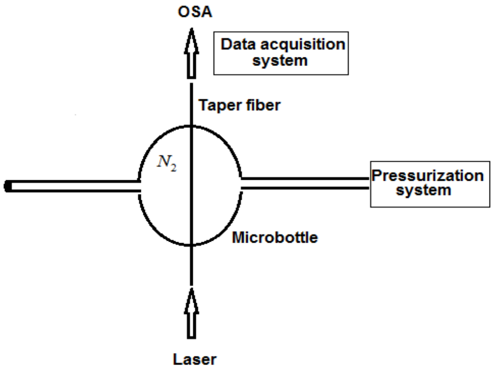

Figure 4. General sketch of the experimental setup of the fiber-resonator coupled system used to determine the sensitivity of each of the manufactured samples.

3. Experimental results

In the experimental results obtained, different samples of microcavities in the form of a hollow bottle with different geometrical parameters were manufactured, as seen in table 1. In the table, it is possible to observe that the sample N ° 1 presents a greater maximum diameter and a smaller wall thickness in comparison with the other samples, which indicates that during the manufacturing process, when the internal pressure in the capillary is increased, the wall thickness in the equatorial zone is reduced and at the same time, the size of the micro bottle is increased.

Table 1. Geometrical parameters of manufactured hollow micro-bottles

Samples			Experimental sensitivity
N°	Maximum diameter (µm)	Estimated wall thickness (µm)	(nm/bar)
1	2987.65	19.78	0.5567
2	2507.21	62.46	0.1694
3	1354.71	94.16	0.0687
4	2216.87	69.89	0.1015
5	2639.13	51.51	0.1941

In the development of the experimental setup of the system, it was necessary to control the mechanical and climatic variables that could affect the measurements through external disturbances or cross sensitivities that the device may experience. For this reason, it was necessary to perform a mechanical stability analysis to ensure that the response of the device is not affected by any other type of external disturbance. In Figure 5, an analysis of the spectral stability of sample No. 3 with zero pressure inside the cavity in the frequency range between 1569-1570 nm is observed, where it was possible to make an analysis of the transmission spectrum of the sample over time in conditions of temperature, humidity and vibrations controlled. In the range of the studied wavelengths, four resonance peaks appear whose wavelengths of resonances do not register important displacements during a period of ten minutes. These results show us that this type of resonant devices exhibit a good stability during relatively long measuring times, allowing its use as optical sensors of spectral modulation. On the other hand, the resonance peaks present a symmetrical shape with a constant free spectral range of the order of 0.88 nm and $Q \approx 4.3x10^4$. In Figure 6, we observe the behavior of two peaks of nearby resonances with wavelengths of 1580.0167 nm and 1580.8967 nm from left to right respectively and their FSR for sample No. 3 at an internal capillary pressure of 3 Bar. For the experimental determination of the Q factor the expression $Q = \lambda_0/\delta\lambda$ is used, where λ_0 represents the resonance wavelength and $\delta\lambda$ represents the full width at half Maximum FWHM measured at an intensity drop of 3 dB of the maximum value of the resonance peak.

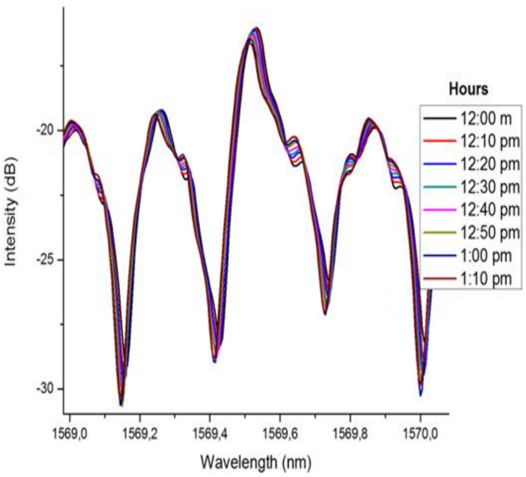

Figure 5. Spectral stability analysis of the hollow microbottle sample No. 3.

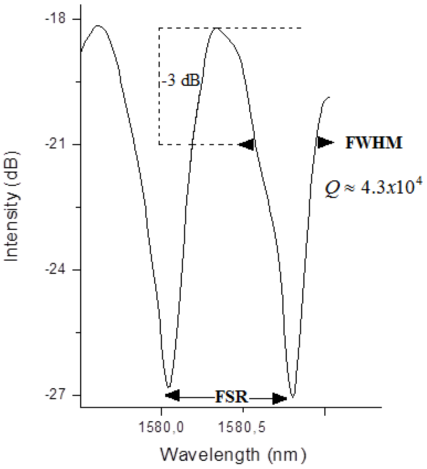

Figure 6. Resonance curve of sample No. 3 at a pressure of 3 Bar.

On the other hand, in order to find the experimental sensitivity of the manufactured device, it is necessary to determine the displacement of the resonance peaks as a function of the pressure in the capillary. Figure 7 shows a general outline of the experimental setup used to determine the sensitivity of the device. In the figure, it is observed that the internal pressure of the nitrogen inside the hollow bottle is controlled through the valve S_3 and measured on the manometer. In the experiment, the resonance peaks are detected in the OSA, obtaining resonance peaks for different pressure values. Figure 8 shows the wavelengths of resonances for different pressure values in the range of 4.8-6.2 bar for sample No. 3. These results reveal that when the pressure inside the cavity increases, displacements of the resonance wavelength are detected towards larger wavelengths, which clearly shows that there is a sensitivity of the device to changes in pressure. In Table No. 1, the experimental sensitivities of each of the samples manufactured are recorded.

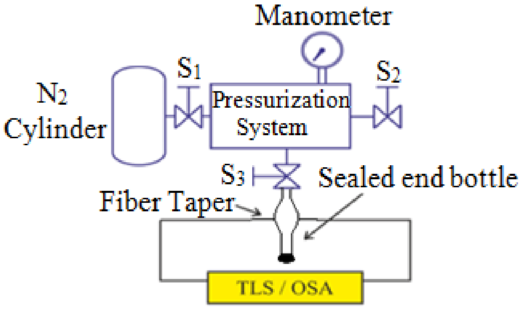

Figure 7. General sketch of experimental setup for the measurement of sensitivity.

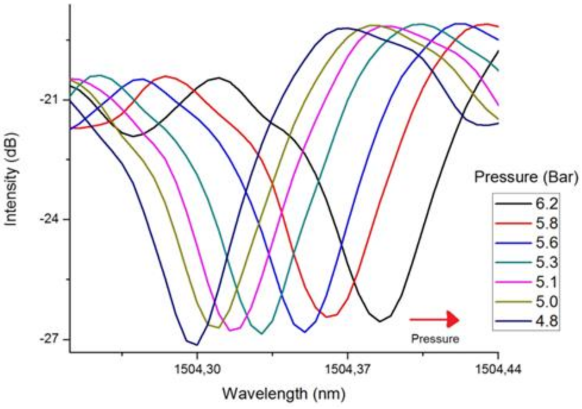

Figure 8. Displacement of resonance peaks with different pressures for sample No. 3.

4. Conclusions

During the development of the experiment, we have developed an experimental technique that allows the manufacture of cavities in the form of hollow bottles using a heating and pressurization technique. During the results we have obtained samples with diameters in the range of 1354.71-2987.65 µm and with a wall thickness in the range of 19.78-94.16 µm with sensitivities between 0.0687-0.5567 nm/bar. These results show that this type of devices has a good sensitivity to internal hydrostatic pressure changes that depend on the geometry of the structure and in such circumstances it was shown that the sensitivity is improved when the microcavity has a large external diameter and a thin wall thickness. The results obtained in the experiment show that these devices experience better sensitivities than some other resonant structures that have been reported by some authors [3,4].

5. Acknowledgments.

This research has been financed through scientific research projects with agreement 241/2016 y 182/2017 of the University Popular of Cesar. On the other hand, the author thanks the Laboratório de Fibras Especiais of the University of Campinas UNICAMP and especially the professor Cristiano M. B. Cordeiro for the experimental support offered for experimental development.

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