Signal analysis of micro-bottle NOA61 polymer optical resonators using tapered optical fibers

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This work analyzes the whispering gallery modes (WGM) in the reflected spectrum from micro-bottle resonators (MBRs) excited using an optical fiber taper tip. The tapers are fabricated using a plasma technique and have a waist diameter of 8 μm. Micro bottle resonators have a maximum diameter of 38μm and are fabricated by curing NOA61 polymer droplets on a fiber taper. Empirical mode decomposition and Fourier transform are used to analyze the modes.

Introduction

Interest in Whispering Gallery Mode resonators (WGMR) arise due to their high-quality factor (Q-factor), small mode volume, and compact size; these allow for a wide range of applications, including sensors, lasers, and nonlinear optics [1-3]. Lord Rayleigh discovered whispering gallery resonance in St. Paul's Cathedral in London for acoustic waves, observing that a whisper could be heard clearly even at long distances. The concept has been extended to Optics, where light is confined through the principle of total internal reflection and circulates the surfaces of a cavity. Different structures have been studied, such as micro-spheres, micro-bottles, micro-disks, and micro-toroids [4-7]. Micro-bottle resonators (MBR) receive special attention due to the efficient excitation of WGM modes in the cavity, which stems from their geometry, which has a curved shape that is narrower at the ends and wider in the center. They are widely used in temperature, humidity, and magnetic field sensors [8-10]. The main methods for fabricating micro bottle resonators are polymer deposition, heat-and-pull, and soften-and-compress; the polymer deposition technique is given special attention here because it does not require a mechanical process and can fabricate multiple resonators simultaneously. This work shows an analysis of the WGM modes of a micro-bottle resonator. A plasma technique was used to fabricate the optical fiber taper, which was employed as the light coupling mechanism to the MBRs. Thinned fibers are fabricated on which the MBRs are fabricated using NOA61 polymer. The resultant reflection spectrum is analyzed using a fast Fourier transform and empirical mode decomposition.

Methodology

The experimental setup is shown in Figure 1. It consists of a super luminescent diode with broad emission centered at 1050 nm, a 50/50 optical fiber coupler, the optical fiber taper, which is in contact perpendicular to the micro bottle resonator (see Figure 1 inset); finally, the reflection spectrum is monitored by a high-resolution spectrometer (HR2), from OceanOptics. The process for the fabrication of the optical fiber taper was conducted using an in-house plasma technique, described extensively in [11]. The optical fiber taper was made using a segment of 60 cm of 980HP fiber, which has an operating wavelength in the range of 980 to 1600 nm with a core diameter of 3.6 μm; the diameter of the waist

of the optical fiber taper was approximately 8 μm and a length of 3 mm. To work in reflective mode a perpendicular cleave was made on the taper. To manufacture the micro bottle resonator, an optical fiber taper was first manufactured using the same plasma technique with a diameter of approximately 6 μm. The taper was fixed vertically and a drop of Norland Optical Adhesive 61 (NOA61) polymer with a refractive index of 1.5448 (1050 nm) was applied; by the effect of gravity and viscosity, the polymer adheres to the fiber. The polymer is then separated into different sections that form multiple micro bottles, and finally, the polymer is cured with UV light for one minute. This method allowed us to obtain micro-bottle resonators, as shown in Figure 2, with a maximum diameter of D_c=38 μm and length of L=62 μm; only the MBR0 shown in the inset of Figure 2 was used for the tests performed. WGM modes are excited when the optical path of the cavity surface is an integer multiple of the excitation wavelength. The free spectral range or wavelength interval between consecutive resonant modes can be expressed as $FSR=\lambda^2/(2\pi nR)$, where λ is the wavelength, n is the refractive index, and R is the cavity radius. The resulting *FSR* for MBR0 corresponding to the central diameter is 5.97 nm.

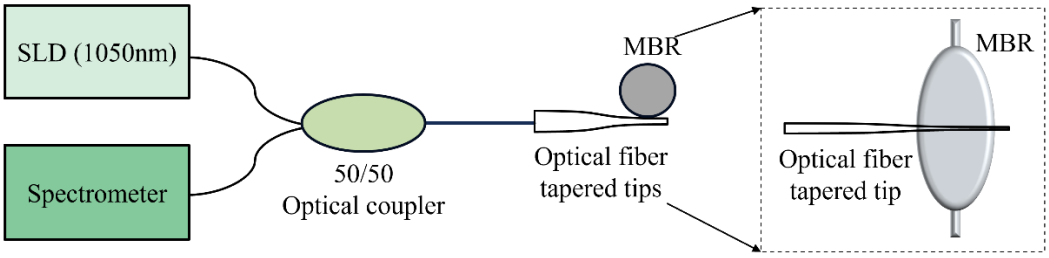

Figure 1: Experimental setup for reflection analysis of MBR.

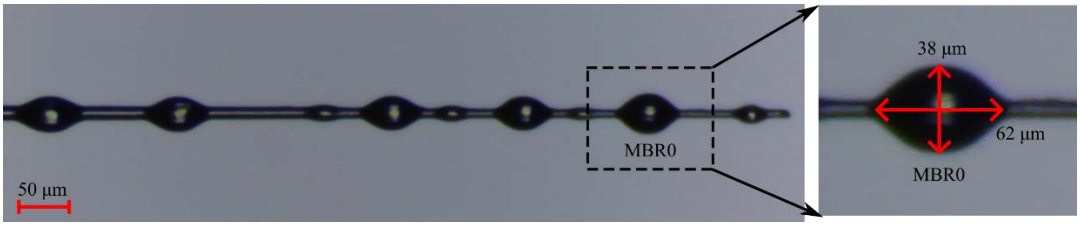

Figure 2: Microscope image of micro-bottle resonators.

Results

Figure 3 shows the reflection spectrum when the optical fiber taper comes into contact with the cavity, the reflection spectrum is calculated by comparing the signal intensity of the micro-bottle resonator when excited with the spectrum of the optical fiber taper; an image of the light coupling is shown in the inset. This signal is transformed by the Fast Fourier Transform (Figure 4); by using appropriate scaling on the horizontal axis, we can obtain the appropriate value of the spatial frequency. The peak centered at 0.1772 nm^{-1} corresponds to an *FSR*=5.64 nm, close to the theoretical value. It can be seen that other frequencies corresponding to different modes generated by the variation of the radius of the micro bottle arise; as the radius of the cavity decreases, the *FSR* increases, and therefore, its spatial frequency decreases. Figure 4 shows the FFT of different reflection spectra, all of which display a spatial frequency centered at fp=0.1772 nm^{-1}.

The reflection signal was also analyzed using empirical mode decomposition (EMD), see Figure 5. This technique represents the signal as a sum of intrinsic mode functions (IMF); that highlight all of the signal's oscillations, whereas the FFT shows only harmonic

oscillations. EMD is first used to clean the data. Furthermore, decomposing the signal into simpler components, without leaving the original domain, allows us to identify features that were not previously visible, such as improving the visibility of resonances. In future work, this can also be implemented to measure various parameters, such as temperature and deformation. Thus, multiple IMFs may contain information about the MBR resonance; IMF2 (Figure 5) reveals an FSR of 5.46 nm that is again similar to that calculated theoretically from the resonant mode of the micro-bottle cavity. In addition, calculating the fast Fourier transform of IMF2 gives us a spatial frequency centered at 0.1772 nm^{-1}, the same value obtained above.

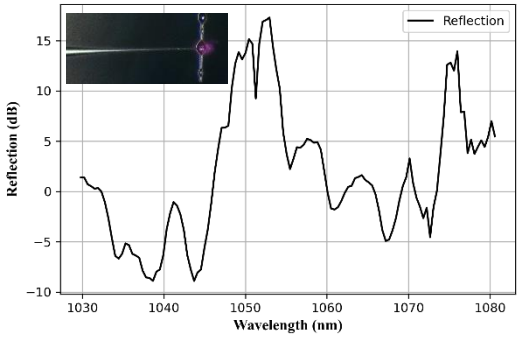

Figure 3: Reflection spectrum of MBR0

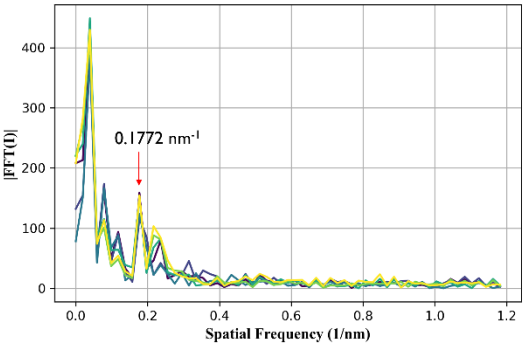

Figure 4: Fast Fourier Transform of reflection spectrum.

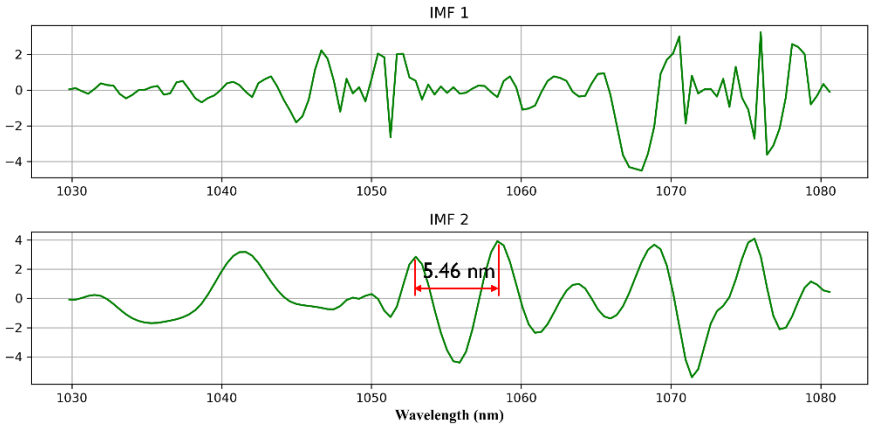

Figure 5: Empirical mode decomposition of reflection spectrum.

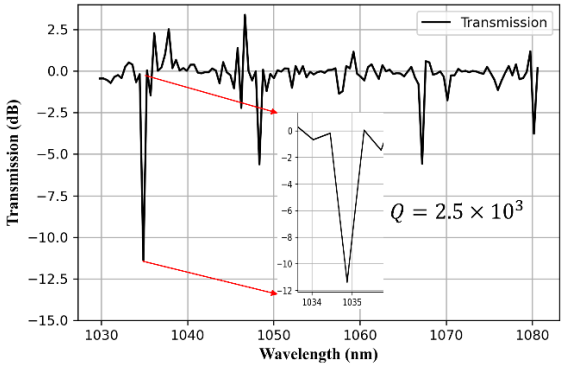

Figure 6: Transmission spectrum of MBR.

Finally, the transmission spectrum of the micro-bottle resonator is shown (Figure 6), where sharp resonance peaks are observed. The *FSR* is not uniform because different WGM modes corresponding to the different radii of the cavity are excited; however, a resonance centered at 1034.876 nm with a *Q-factor* of 2.5×10^3 can be observed. Thus, the analysis of the reflection spectrum using the fast Fourier transform and the empirical mode decomposition provides relevant information about the performance of the cavity as a WGMR through the *FSR*.

Conclusions

A micro-bottle resonator was fabricated by deposition of. NOA 61 on an optical fiber taper, creating a cavity with a diameter of about 38 μm and a length of 62 μm. Light was coupled to the micro-bottle resonator using an optical fiber taper fabricated using the plasma technique, with a waist diameter of 8 μm. Using a 50/50 fiber coupler, the reflection spectrum of the MBR could be observed, and its signal was analyzed via fast Fourier transformation and empirical mode decomposition, *FSR* values of 5.64 and 5.46 nm respectively were obtained, in good agreement with the calculated theoretical value of 5.97 nm. The fabrication techniques of the MBR and the optical fiber taper are simple to implement.

Acknowledgements

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References

[1] N. A. Baharuddin, N. Mokhtar, H. A. Zain, M. A. M. Johari, R. Apsari, and S. W. Harun, "Micro-bottle resonator for sodium hypochlorite sensor," Optik (Stuttg.), vol. 242, no. 167328, p. 167328, 2021.

[2] Q. Lu, X. Chen, S. Xie, and X. Wu, "Controllable and selective single-mode lasing in polymer microbottle resonator," Opt. Express, vol. 26, no. 16, pp. 20183–20191, 2018.

[3] Y. Yang, Y. Ooka, R. M. Thompson, J. M. Ward, and S. N. Chormaic, "Degenerate four-wave mixing in a silica hollow bottle-like microresonator," Opt. Lett., vol. 41, no. 3, pp. 575–578, 2016.

[4] X. Liu and D. N. Wang, "Optical dual-microsphere whispering-gallery-mode resonator coupled by a pair of tapered fibers," Optik (Stuttg.), vol. 242, no. 167187, p. 167187, 2021.

[5] N. Zhu, B. Shi, Y. Guo, B. Han, and Y.-N. Zhang, "Polydimethylsiloxane self-assembled whispering gallery mode microbottle resonator for ethanol sensing," Opt. Mater. (Amst.), vol. 107, no. 110024, p. 110024, 2020.

[6] T. Ma et al., "Simultaneous measurement of the refractive index and temperature based on microdisk resonator with two whispering-gallery modes," IEEE Photonics J., vol. 9, no. 1, pp. 1–13, 2017.

[7] B.-Q. Shen et al., "Detection of single nanoparticles using the dissipative interaction in a high-QMicrocavity," Phys. Rev. Appl., vol. 5, no. 2, 2016.

[8] G. Nemova and R. Kashyap, "Silica bottle resonator sensor for refractive index and temperature measurements," Sensors (Basel), vol. 16, no. 1, p. 87, 2016.

[9] M. A. Md Johari, M. I. M. Abdul Khudus, M. H. Bin Jali, A. Al Noman, and S. W. Harun, "Whispering gallery modes on optical micro-bottle resonator for humidity sensor application," Optik (Stuttg.), vol. 185, pp. 558–565, 2019.

[10] F. Hou et al., "Magnetic fluid infiltrated microbottle resonator sensor with axial confined mode," IEEE Photonics J., vol. 12, no. 5, pp. 1–9, 2020.

[11] L. F. Granados-Zambrano et al., "Plasma-based optical fiber tapering rig," HardwareX, vol. 19, no. e00578, p. e00578, 2024.