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Introduction of Microbottle Resonator for Honey Concentration Sensing

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ABSTRACT

This paper investigates the behaviour of whispering gallery modes (WGMs) in a silica-based micro bottle resonator (MBR) for honey concentration sensing. The MBR was fabricated using the soften-and-compress technique on standard SMF-28 silica fibre, creating a bottle-shaped structure with controlled bottle diameter, stem diameter, and bottle length. A tapered microfiber with a 2 µm waist diameter was used for coupling, enabling the resonator to achieve a high quality factor ($Q > 1.5\times10^5$), confirming its low-loss performance and strong field confinement. Honey samples with concentrations ranging from 10% to 60% were analysed. The MBR sensor demonstrated a sensitivity of 0.0824 dB/% with excellent linearity of 97%, while wavelength-shift analysis showed an additional sensitivity of 4.0 pm/%. The sensor exhibited stable and repeatable responses across multiple experimental cycles and short-term stability tests. Compared with conventional techniques such as refractometry, FTIR, and electrochemical methods, the MBR offers significant advantages in compactness, non-destructive measurement, and sensitivity. These findings establish the MBR as a reliable platform for honey quality monitoring and authenticity testing, with potential for broader food and industrial sensing applications.

INTRODUCTION

Optical micro resonators (OMRs) that operate through whispering gallery modes (WGMs) have gained wide attention in recent years due to their ability to confine light within small dielectric structures with exceptionally high quality factors (Q-factors) and long photon lifetimes. By circulating light around a curved boundary, WGMs achieve strong confinement and large optical intensities, making them ideal for optical sensing, plasmonic devices, and micro lasers [1–3]. Various OMR geometries have been demonstrated, such as micro disks, micro rings, micropillars, and photonic crystal cavities [4,5]. Among these, WGMs are notable for combining low intrinsic losses, high Q-factors, and relatively simple fabrication processes [6,7].

One particularly promising structure is the micro bottle resonator (MBR), which is fabricated by reshaping a segment of standard silica fibre into a bottle-like shape through the soften-and-compress technique [8,9]. This unique geometry allows WGMs to circulate along its curved surface, producing a strong evanescent field that directly interacts with surrounding materials [10–13]. Compared with other OMR geometries, MBRs provide several advantages: large free spectral ranges (FSR), stable mechanical properties, versatile fabrication control, and the ability to achieve strong coupling with tapered microfibers [14–17]. These features make them attractive for liquid sensing applications where small refractive index changes need to be detected with high precision.

Honey quality analysis is a growing necessity in food science and consumer protection. Conventional methods such as refractometry, Fourier-transform infrared spectroscopy (FTIR), and electrochemical sensing are widely used but present limitations, including bulky instrumentation, destructive testing procedures, complicated calibration steps, or susceptibility to contamination and electrode fouling. In contrast, optical fibre sensors offer compact, real-time, non-destructive measurements with high immunity to electromagnetic interference. Despite these advantages, the application of MBR-based WGM sensors in honey sensing has not been fully explored. This study addresses this gap by demonstrating an MBR fabricated from SMF-28 silica fibre as a high-performance sensor for honey concentration detection. The aim is to show that MBRs deliver superior sensitivity, repeatability, and stability, highlighting their potential as a novel solution for food quality monitoring and authenticity assurance.

In this research, a micro bottle resonator (MBR) is proposed for sensing honey liquid concentrations. The MBR was fabricated from SMF-28 silica fibre using the soften-and-compress technique and coupled with a tapered microfiber of 2 µm diameter. With the microfiber width fixed at 2 µm, the resulting resonant wavelength exhibited only minor shifts, with a shifting factor of less than 54.23 nm/µm. The decrease in refractive index values directly influenced these wavelength shifts, which in turn contributed to the observation of an unusually large negative thermo-optic coefficient [18,19]. Theoretical analysis suggests that this configuration of the MBR enhances the sensitivity of the sensor for honey concentration measurements [7,20]. Experimental results further confirmed that the MBR exhibited high sensitivity, stable performance, and excellent repeatability across multiple trials, demonstrating its reliability as a practical optical sensing platform [21]

Characterization of MBR

The micro bottle resonator (MBR) was fabricated from standard SMF-28 silica fibre using the soften-and-compress technique. During fabrication, the silica fibre was locally heated with an electric arc while compression was simultaneously applied at both ends, forming a bottle-like geometry. The geometry was characterized by three main parameters: bottle diameter (D_b), stem diameter (D_s), and bottle length (L_b). Careful control of the number and duration of arc discharges allowed precise adjustment of these dimensions. In this study, the MBR was fabricated with D_b = 200 µm, D_s = 125 µm, and L_b = 110 µm, consistent with optimized dimensions reported in earlier works. The fabricated structure is shown in Figure 1.

The "softened-and-compress" method is used to create MBR from a standard silica fibre SMF28. WGMs then use this MBR to control spectral characterisation. After being heated with an electrical arc, the SMF28 is held and compressed on both sides in an inward direction using the Furukawa Electric Fitel S178A splicing machine. The size of the bottle in the heated fibre's middle will depend on how many arcs are applied. With respect to three parameters—the bottle diameter D_b, the stem diameter D_s, and the neck-to-neck length L_b, **Figure 1** illustrated the physical structure characteristic of MBR. The MBR size for D_b diameter in this work was fixed at 200 µm, in line with earlier research. The MBR uses microfiber that was created by flame brushing and has a waist diameter of 2 µm.

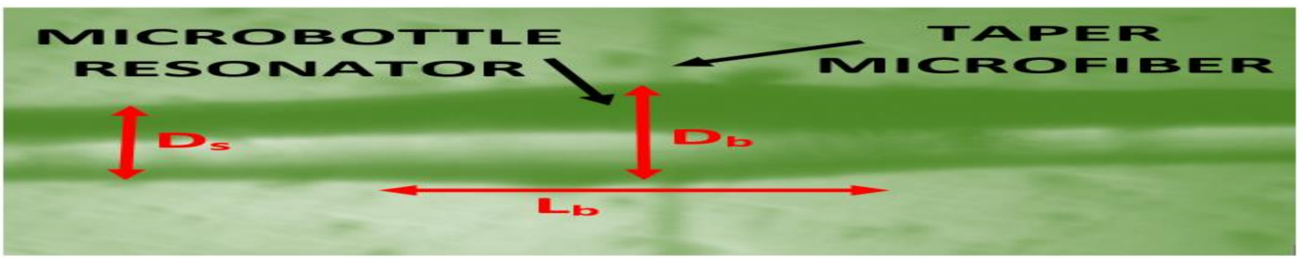


Figure 1: Fabricated microbottle resonator (MBR) with bottle length L_b = 110 µm, bottle diameter D_b = 200 µm, and stem diameter D_s = 125 µm. The dimensions were measured under an optical microscope with ±2 µm accuracy.

To couple light efficiently into the resonator, a tapered microfiber with a 2 µm waist diameter was fabricated using flame brushing. The microfiber was aligned near the waist of the MBR, where the strongest evanescent field interaction occurred. The experimental setup employed a tuneable laser source (ANDO AQ4321D), which covers a wavelength range of 1520–1620 nm. For characterization, the laser was scanned between 1550 and 1555 nm in fine steps of 0.001 nm, and the output was recorded by a THORLABS S145C optical power meter. The transmission spectra exhibited sharp resonance dips characteristic of WGMs, with insertion loss maintained below –10 dBm when coupling alignment was optimized as shown in **Figure 2**.

The Q-factor of the resonator was determined from the full-width half-maximum (FWHM) of resonance peaks using Lorentzian fitting, with calculations performed in Origin software. A maximum Q-factor of 1.586×10^5 was obtained, confirming the resonator's low-loss performance. This high Q-factor demonstrates that the MBR provides strong confinement suitable for refractive index sensing. Calibration was performed using air and pure water to establish reference baselines before introducing honey solutions, ensuring measurement accuracy and stability.

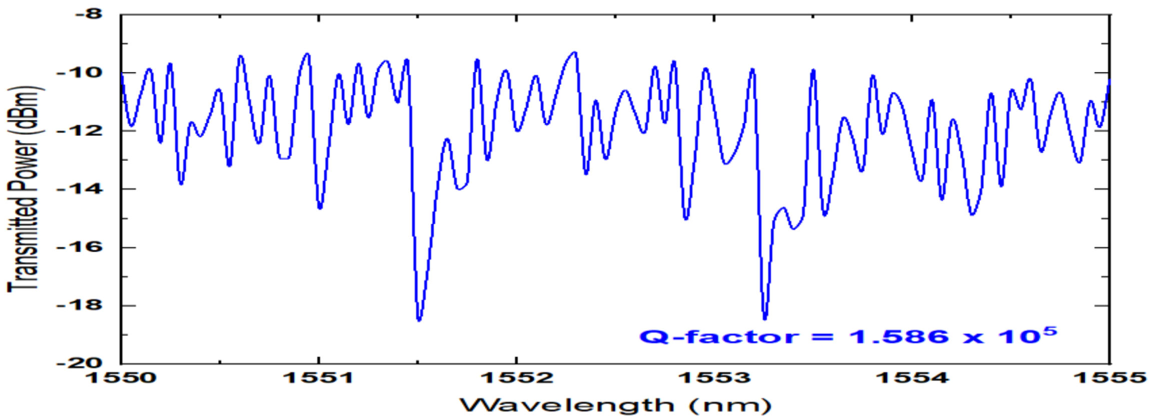


Figure 2: Transmission spectrum of the MBR coupled with a 2 µm tapered microfiber in the wavelength range 1550–1555 nm. Multiple sharp WGM resonances are visible, confirming a high Q-factor (1.586×10^5). Power is measured in dBm, with insertion loss exceeding –10 dBm.

Performance of MBR Honey Concentration Sensor

The experimental setup for honey concentration sensing is shown in **Figure 3**. The tapered microfiber was positioned at the waist of the MBR, with one end connected to the tuneable laser and the other to the optical power meter. Honey solutions with concentrations of 10%, 20%, 30%, 40%, 50%, and 60% (v/v) were prepared by diluting pure honey with deionized water, ensuring precise volumetric measurements. Baseline calibration was performed with pure water before each set of measurements. Each concentration was tested three times, and results were averaged. Error bars representing standard deviation were added to the sensitivity and linearity graphs to account for experimental uncertainty.

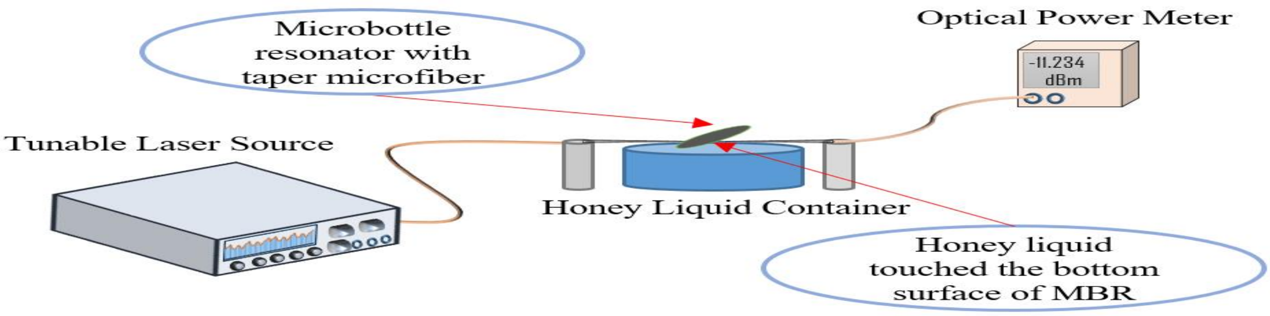
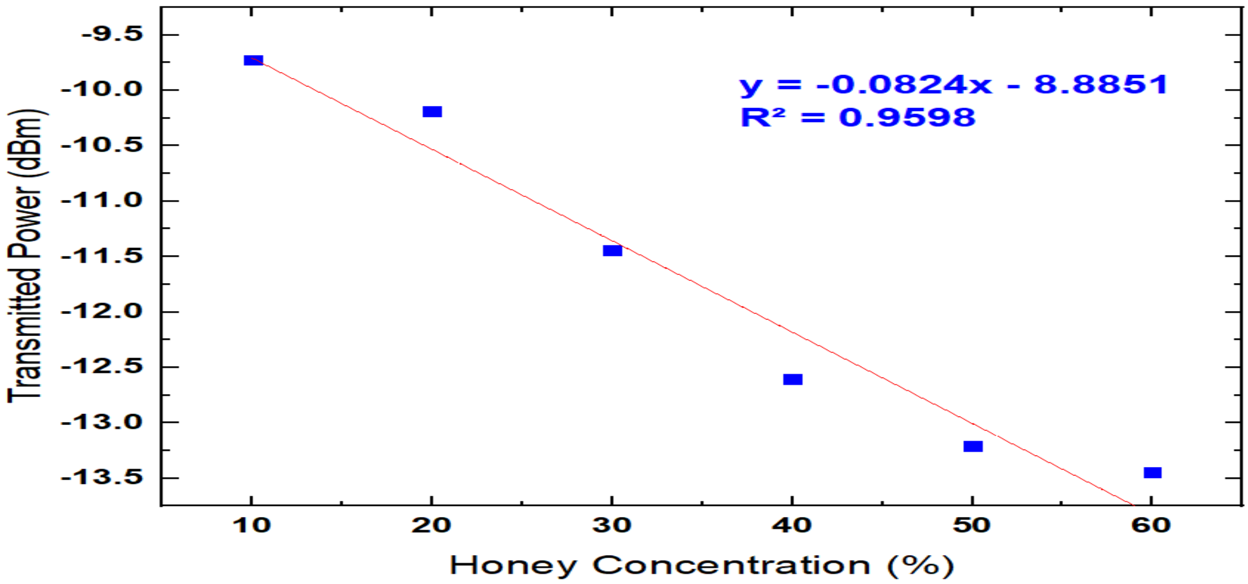


Figure 3: Experimental setup for honey concentration sensing using the MBR. The tunable laser source was set at 1550 nm with 0.001 nm resolution, while transmitted power (in dBm) was recorded using an optical power meter (THORLABS S145C)..

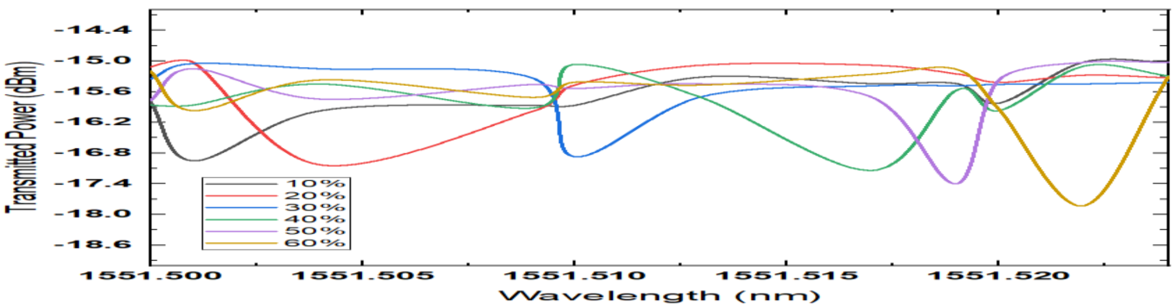
Figure 4(a) shows the transmission spectra for varying honey concentrations, and **Figure 4(b)** illustrates the corresponding resonance wavelength shifts. As concentration increased, the transmitted power decreased consistently, and the resonance wavelength shifted linearly. From transmitted power analysis, the sensor exhibited a sensitivity of 0.0824 dB/% with a linearity of 97%. Wavelength-shift analysis provided an additional sensitivity value of 4.0 pm/%. These results confirm that the MBR can accurately detect refractive index changes caused by honey concentration variations.

The sensitivity and linearity are key parameters used to evaluate the performance of the MBR in sensing honey concentrations. Remarkably, the MBR demonstrated impressive performance across all these parameters. For sensitivity, the MBR achieved 0.0824 dB/% with a linearity of 97% in the transmitted power over honey concentration graph. However, by the analysis from the wavelength shift showed the sensitivity is 4.0 pm/%. In the analysis of wavelength shift, the tuneable laser source transmitted wavelengths ranging from 1550 nm to 1555 nm. An optical power meter and computer were employed to monitor and record each wavelength at various honey concentration levels. The MBR successfully shifted the transmitted spectral wavelength from 1551.500 nm to 1551.524 nm, as illustrated in **Figure 4(b)**.

Repeatability testing, shown in **Figure 5(a)**, involved three measurement cycles for each concentration. The results demonstrated excellent consistency, with sensitivity values ranging from 0.080 to 0.0815 dB/% and linearity consistently above 92%. Stability was further assessed through continuous monitoring over 60 seconds for each concentration, with 60 readings collected per condition. **Figure 5(b)** shows that only minimal fluctuations were observed, confirming the MBR's short-term stability.



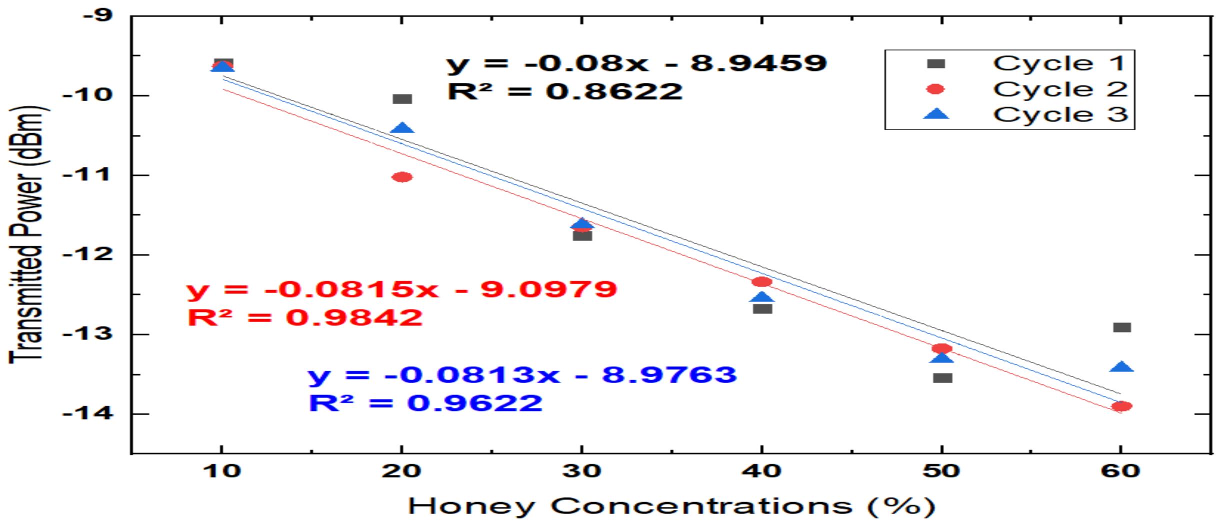
(a)



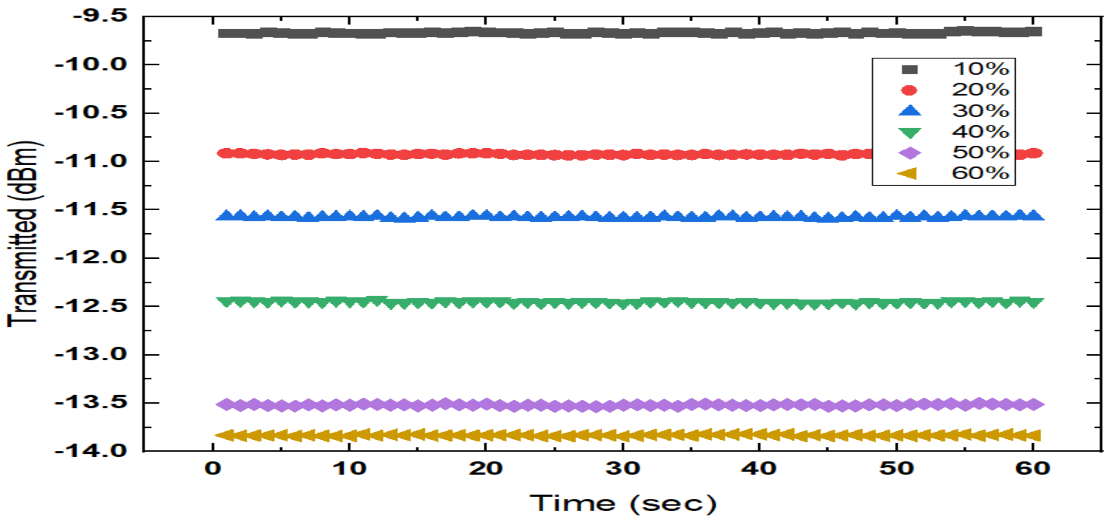
(b)

Figure 4: (a) Transmission spectra of the MBR across honey concentrations from 10% to 60% (by weight). (b) Resonant wavelength shifts as a function of honey concentration, demonstrating sensitivity of 4.0 pm/% and linearity of 97%. Each point represents the mean of three trials, with error bars indicating ±1 standard deviation.

When compared to conventional honey sensing techniques, the advantages of the MBR are evident. Refractometers generally offer sensitivities limited to 0.01 RIU, while FTIR requires complex spectral processing and costly instrumentation. Electrochemical sensors are prone to electrode degradation and sample contamination. The MBR, however, is compact, immune to electromagnetic interference, operates in real-time, and is non-destructive. These strengths confirm the originality and practical significance of using MBR-based WGM sensors for honey quality analysis and broader food safety monitoring.



(a)



(b)

Figure 5: (a) Repeatability test of MBR honey sensing over three measurement cycles, showing consistent sensitivity (~0.08 dB/%). (b) Stability test across 60 seconds per concentration level, confirming long-term reliability with less than ±0.5% variation.

CONCLUSIONS

This study demonstrated the development and performance evaluation of a micro bottleresonator (MBR) coupled with a tapered microfiber for honey concentration sensing. The MBR was fabricated from SMF-28 silica fibre using the soften-and-compress method, producing a resonator with dimensions D_b = 200 µm, D_s = 125 µm, and L_b = 110 µm. The optical characterization confirmed whispering gallery mode operation with a high Q-factor of 1.586×10^5, establishing the device's potential for high-sensitivity applications.

Experimental evaluation using honey concentrations from 10% to 60% revealed a sensitivity of 0.0824 dB/% with a linearity of 97% in transmitted power measurements, and an additional sensitivity of 4.0 pm/% in wavelength shift analysis. The sensor's performance was validated through repeatability testing over three cycles and stability testing over 60-second intervals, demonstrating consistent and reliable operation.

Compared with traditional honey sensing techniques such as refractometry, FTIR, and electrochemical sensors, the MBR-based WGM sensor offers unique advantages in compactness, accuracy, non-destructive measurement, and robustness. These findings underscore the suitability of MBRs for practical applications in honey quality monitoring, authenticity testing, and other food industry contexts. Future research can extend this work by integrating MBR sensors into portable optical platforms and exploring multiplexed sensing architectures for large-scale deployment in food safety and quality assurance.

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