Microbottle resonator for temperature sensing

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Abstract. The whispering gallery mode on the surface of the microbottle optical resonator (MBR) was studied in this research paper as a relative temperature sensor. The MBR is formed by a technique known as "soften-and-compress" allowed SMF-28 silica fiber to be formed in bottle structure with a bottle diameter $D_b = 190 \mu m$, stem diameter of $D_s = 125 \mu m$ and bottle length of $L_b = 182 \mu m$. The Q-factor of the MBR is defined by excited with bare microfiber with 2 $\mu m$ diameter and managed to have $>10^5$. The range of temperature between 40°C to 100°C is then employed to the MBR as a temperature sensor for analysis purpose. The performance of the MBR is promising with sensitivity 0.0149 dB/°C with linearity 94% and P-value $>10^{-5}$ which is defined as a good sensor. The sensitivity value from the wavelength shift is 1.3 pm/°C. The repeatability and stability of the MBR can be employed as a temperature sensor.

1. Introduction

Recently, whispering gallery modes (WGMs) optical microresonator (OMRs) have captured significant interest due to their potential applications as optical sensors, lasers and related plasmonic devices [1-6]. OMRs confine light in spatially and temporally, allowing the production of high optical intensities, large-quality factor and extending photon lifetimes in the resonator structure and have been realized in a variety of different geometries such as microdisks, micropillars, microrings and photonic-crystal cavities [7-17]. WGMs OMRs have also been intensively studied, exhibiting the advantages of a number such high-quality factor, low intrinsic loss and simple fabrication methods [2, 18-20].

The microbottle resonator (MBR) is a sub of OMR which is made from the silica fiber by changing the fiber structure into a bump, which looks like a bottle. For the operation of MBR, the WGMs is used to circulate around the MBR surface continuously perpendicular from the bottle axis. The electromagnetic field was located around the MBR surface which is useful for sensing application [21, 22]. This concept is similar to the electromagnetic field on surface plasmon-polaritons (SPPs) [23-29]. Though the MBR has been suggested to be ideal for silica-based OMR sensors as they have very high-quality factor and free spectral range (FSR) [2, 30].
In this paper, we proposed to use the MBR for temperature sensing. The MBR structured from SMF-28 silica fiber by "soften-and-compress" technique which then coupled with the taper microfiber with 2µm wrist diameter to performed sensing [31-33]. As the diameter of the taper microfiber is maintained at 2µm, it experienced small wavelength shifting with the shifting factor < 55.25nm/µm. Hence, the decreased of the external refractive index influenced the wavelength shift and contributed to the high negative thermo-optic coefficient. As per the theoretical analysis, the MBR in the setup will increase the sensitivity of the temperature sensor. The vacuum oven is used to provide a closed environment with a range of temperature between 40°C to 100°C. The purposed MBR is observed to have high sensitivity, stability with consistence repeatability.

2. Characterization of MBR

A standard silica fiber SMF28 is used to form MBR using technique known as "softened-and-compress", which by then used by WGMs in regulating spectral characterization [34]. The splicing machine (Furukawa Electric Fitel S178A) is used to hold and compressed on both sides of SMF28 in inward direction after being heated with an electrical arc. The number of arcs applied will determine the size of the bottle in the centre of heated fiber [30]. Figure 1 shows physical structure characteristic of MBR with three parameters, as known as the bottle diameter \(D_b\), the stem diameter \(D_s\) and the neck-to-neck length \(L_b\). In this work, the size of MBR was set at 190 \(\mu m\) for \(D_b\) diameter which is similar to other work previously [30]. The MBR is employed with microfiber with 2 µm of waist diameter fabricated using flame brushing method [35].

![Figure 1. Sample fabricated MBR of \(L_b = 182 \mu m, D_b = 190 \mu m\) and \(D_s = 125 \mu m\)](image)

The MBR which employed with 2 µm tapered microfiber, is firstly characterized by launched wavelength range between 1551 nm to 1560nm from a tuneable laser source (ANDO AQ4321D) into it. The tuneable laser source used in this experiment is able to produce a laser with a wavelength range between 1520 nm until 1620 nm, which is compatible with the proposed experiment. The wavelength interval of 0.001 nm was tuned from laser source collected by an optical power meter (THORLABS S145C) as output transmitted power. Figure 2 shows the transmission spectra of MBR, where numbers of sharp resonance were defined clearly and used as a quality factor [36]. The MBR and the tapered microfiber manage to have the insertion loss for more than -5dBm and its may accede by controlling the position of microfiber and MBR as mention in previous research [37]. The Q-factor for the MBR is defined by calculation and also by Lorentzian fitting where both are found to have 1.555 x 10⁵ which is similar than previous work [30]. The calculation of Q-factor is defined by \(\Delta \lambda / \lambda\) where \(\lambda\) is the resonant wavelength and the Lorentzian fitting is from the Origin software application. The insertion loss of the entire MBR and the microfiber diameter contributes to the value of Q-factor.
3. Performance of MBR Temperature Sensor

Figure 3 shows the setup of the experiment used to investigate the performance of MBR as temperature sensors. The vacuum oven (GALLENKAMPN 840.3 FT18) used to monitor temperature level with the MBR and the microfiber are placed inside the oven. The MBR is placed at the tapered area where one end of microfiber is connected to tuneable laser source and the other end to OPM to measure transmitted power. First, the wavelength was set at 1555.750 nm, where the most depth resonated wavelength was recorded. The temperature was then increased from 40°C to 100°C and output power were recorded. To investigate the repeatability of the temperature sensor, the experiment was repeated three times on the same day. The transmission spectra at different temperature levels were recorded for 60 seconds to investigate the stability of the sensor. To ensure the best performance, this experiment was compared with different experiment setup.

Figure 3. The MBR was attached with tapered fiber (2μm) for temperature sensing. Optical power meter connected to one end of fiber for final data collection while tuneable laser source supplied wavelength at 1555.750 nm.

The tuneable laser source transmitted a wavelength between the range of 1555.750 nm to 1555.760 nm. The optical power meter and the computer were used to monitor and record the changes of wavelength produced upon changes in temperature. The proposed MBR produce a shift in transmitted spectral wavelength from 1555.750 nm to 1555.758 nm. This is due to the thermo-optic coefficient concept where the MBR conductivity changes drastically with the change of temperature. This work proved that MBR can be used to increase the conductivity of material such as temperature sensing.
Figure 4. Analysis of temperature sensing performances (a) and wavelength shift of the MBR microfiber temperature sensor (b).

Figure 4(a) shows the performance of the transmitted spectra of the MBR with the changes in temperature. Figure 4(b) shows the value of transmitted power plotted by the peak resonant value against wavelength shift. As the temperature changes, the peak value of the resonant wavelength was captured and recorded in the same graft. Based on the plotting, the value of transmitted power (dBm) decreased per unit rise of temperature level. As mentioned in equation (6) where the thermal expansion influenced the sensor performance where transmitted power value decreases with the increase of temperature.

The sensitivity, linearity and standard deviation are listed parameter used to determine the performance of the MBR towards temperature sensing. However, the MBR significantly showed promising performance on all parameter, which is recorded in Table 1. In the sensitivity performance
study, the MBR showed 0.0149 dB/°C with the linearity of 94% respectively for transmitted power over temperature. However, by the analysis from the wavelength shift, the sensitivity is observed at 1.3 pm/°C.

**Table 1.** The analysis results of the MBR microfiber performance in temperature sensing activity

| Parameters                  | MBR       |
|-----------------------------|-----------|
| Linearity (%)               | 94%       |
| Sensitivity (dB/°C)         | 0.0149    |
| Sensitivity (pm/°C)         | 1.3       |
| Standard deviation (dBm)    | 0.3234    |
| P-value                     | $3.886 \times 10^{-8}$ |
| Linear Range (°C)           | 40 - 100  |

The experiment was repeated three times to ensure repeatability and as practised by other earlier research [38]. **Figure 5(a)** shows the repeatability of the proposed work where MBR microfiber shows the same downtrend on every cycle. The MBR is observed to have good sensitivity between the range of 0.014 dB/°C to 0.0155 dB/°C with 0.01 interval between data. For linearity performances, the MBR microfiber shows stable performance which is >80%.

![Graph showing transmitted power over temperature cycles](image-url)
The stability test was carried out for the MBR microfiber temperature sensor and recorded in Figure 5(b). The sensing data was taken for 60 seconds where 60 different transmitted power were produced for the changes in each degree of temperature. These results were used as additional information, to observe the condition of the sensor during the experiment. The MBR microfiber showed stable performance while performing temperature sensing, based on the data collected.

4. Conclusions
This proposed work studied the effect of MBR microfiber towards temperature sensor. The method of “soften-and-compress” was applied on SFM-28 silica fiber with several numbers of arc to create bottle structure with a diameter of $D_b = 190$ µm, stem diameter of $D_s = 125$ µm and bottle length of $L_b = 182$ µm. The characterization of the MBR was defined by the TLS from range of wavelength between 1551 nm to 1560 nm with a step of 0.001 nm via 2 µm optical microfiber. The Q-factor of the MBR was found to have $1.555 \times 10^5$ which is significantly similar to the previous work. The MBR microfiber performance as a temperature sensor is then compared with no-MBR microfiber. The MBR shows better performance than no-MBR based on linearity, sensitivity and standard deviation analysis. The P-value is defined by calculation and needs to be over than $10^{-5}$ indicates that the measurement was finely collected. The experiment was repeated three times to ensure stability and accuracy in data collection.

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