Experimental study on the sensing performance of optical microbottle resonator with polymethyl methacrylate coating $C_6H_9NaO_7$ (Sodium Alginate) sensor

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This research explored the effect of polymethyl methacrylate (PMMA) coating on the Microbottle Resonator (MBR) that is used for sodium alginate concentration sensors. The MBR form by SMF28 used the "soften-and-compress" technique, which was further coated with PMMA solution and formed three different sizes. The MBR-PMMAs are characterised by tapered microfiber and managed to have Q-factor $> 10^5$ for all sizes, where MBR-PMMA-C is the highest at $5.723\, x\, 10^5$. The MBR-PMMAs experienced a sodium alginate concentration sensor with sensitivity, linearity, stability and repeatability observed as a measured parameter. The sodium alginate liquid concentration was between 1% ppm and 6% ppm. The results were then compared between transmitted power and wavelength shifting analysis. The biggest size of the coated resonator, MBR-PMMA-C, managed to have excellent performance from all measured parameters. Here, the size of the bottle structure of MBR with PMMA coating may influence the whispering gallery modes (WGMs) to increase the adsorption capability of the MBR as a sensor.

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1. Introduction

Recently, fiber optics captured huge research intention, including communication, sensor, laser, and plasmonic devices [1-7]. Sub-class fiber optics, known as optical microresonator (OMR), became a new invention in the sensor world [8-11]. Manipulating the whispering gallery modes (WGMs) on the resonator may increase the resonator's performance as a sensor [12-14]. Several OMR has been invented for this application, such as microring, microloop, microdisc and microball resonator [11, 15-17]. Here, the WGMs on OMR are seriously explored with different preferences such as quality factors, intrinsic losses, and assembly methods, which may receive tremendous outcomes [14, 18-20]. However, this paper promotes OMR structure to observe the WGMs exploration as a liquid sensor. Named as a microbottle resonator based on the bottle structure appearance, it may receive a different contribution of WGMs towards this OMR structure as a liquid sensor [19, 21-23]. The WGMs may freely cross the MBR axis surface and make this resonator worthy of being used as a sensor [12, 14]. Hence, the MBR may produce a high quality factor with a practical free-spectral range as additional criteria, making this OMR structure suitable for sensing applications [21, 24-26].

The PMMA known as polymethyl methacrylate is a transparent thermoplastic used in sheet form as an alternative to glass [17, 27, 28]. The structure is shatter-resistance, transparent and lightweight, always used in several industrial productions [27]. This material can be used as casting resin and coatings, among many other uses [29]. The reflective index of PMMA is almost similar to the MBR used of PMMA which may increase the size of the MBR bottle size [28]. Hence, the size may influence the Q-factor of the resonator based on previous research [17, 24]. Therefore, it would be best to use PMMA as coating material with the MBR.

This article explored the effect of PMMA coated on MBR use for sodium alginate concentration sensors. Sodium alginate was widely used in food industries with speciality to keep refreshments of the food product such as meat and fish [30, 31]. The coated MBR can perhaps detect each liquid concentration level as part of the sensing application. The first experiment used PMMA coated MBR as a sodium alginate sensor, and non-others research on the previous similar. The MBR is formed by a method known as "soften-and-compress", which is then coated with PMMA by the "drop-casting" technique [23, 24, 32].

Three new MBR-PMMAs have then been formed with different sizes each. The MBR-PMMAs are then characterised by coupled with microfiber 2 μm diameter. The sodium alginate prepared in the range of 1% to 6% ppm for sensing activity. Sensitivity, linearity, stability and repeatability are the listed parameter used to determine the performance of MBR-PMMAs as a sensor. These results are produced by transmitted spectral and wavelength shift analysis, then compared for the best performance.

2. Characterisation of MBR-PMMAs

The MBR is created using a method known as "soften-and-compress" from a silica fiber SMF-28 [33]. The splicing machine (Furukawa Electric Fitel S178A) used an electrical arc to heat the fiber's middle area [22]. At the same time, the holder then compressed the fiber in an inward direction [23]. The heated area then bumps and turn into the bottle structure [33]. The size of the bottle is determined by the number of electrical arcs applied during the process. As shown in Fig. 1, the bottle size determined by three parameters as bottle diameter D_b, bottle stem diameter D_s and also bottle length L_b, and this was similar to previous works. The MBR is then characterised by coupling together with 2 μm taper microfiber. Several methods can form a tapered microfiber, where the "flame brushing" technique would be chosen based on the time consumption and handling matters. Prepared with three different sizes, as shown in Table 1, the MBR then experienced the coating procedure with PMMA solution using "drop-casting". Here, the solution will cover the entire bottle resonator surface, as shown in Fig. 2. The PMMA solution was prepared by mixed 1.0 mg PMMA crystal with 10 ml isopropanol liquid. The mixed solution then heated at 100 ^{0}C on a hot plate and stirred at 700 rpm for 1 hour. The coating MBR is now known as MBR-PMMAs, and the coating thickness measured to have 10 μm in all size.

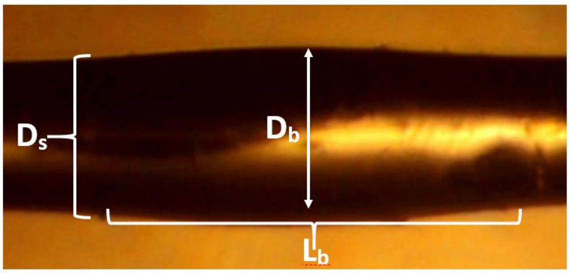


Fig. 1. Three parameters named bottle diameter D_b, bottle stem diameter D_s and bottle length L_b for the MBR (color online)

Table 1. Three sizes of bottle resonator known as MBR

Parameter	Bottle stem diameter D_s	Bottle diameter D_b	Bottle length L_b
1st MBR	125μm	170μm	182μm
2nd MBR	125μm	180μm	183μm
3rd MBR	125μm	190μm	184μm

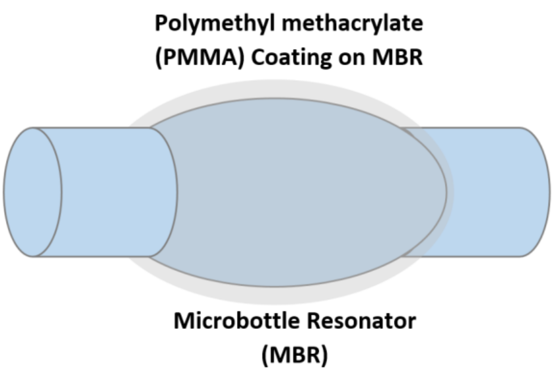
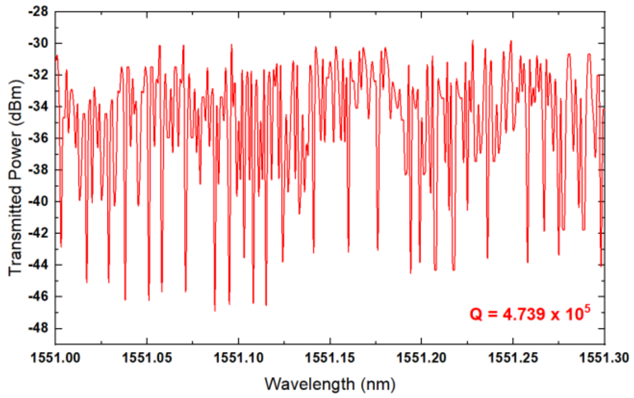
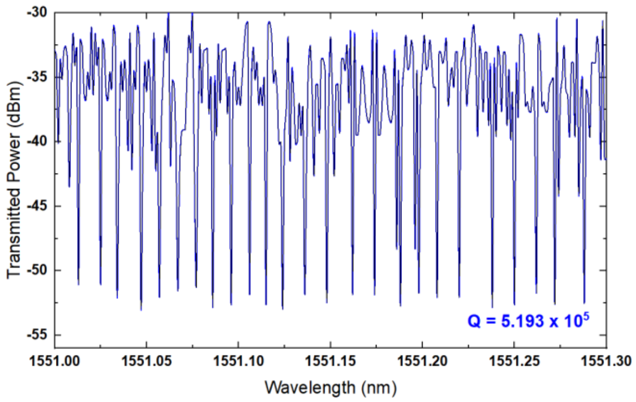


Fig. 2. The PMMA coated on the MBR by the "drop-casting" method

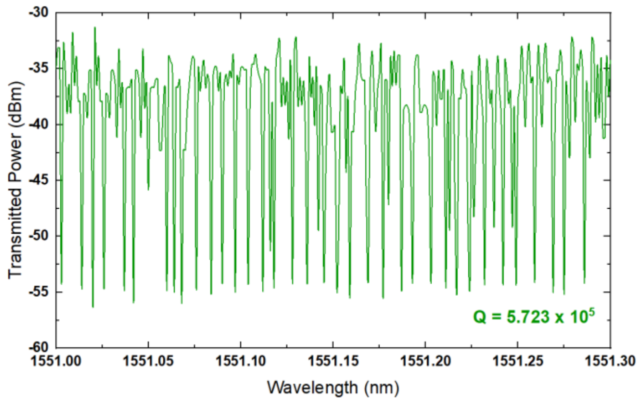
The MBR-PMMAs are then characterised for Q-factor and FSR results before apply for sensing purposes. The tunable laser source (ANDOAQ4321D) supplied the wavelength from 1551.0 nm until 1551.3 nm with a 0.001 nm interval. This tunable laser source (TLS) can provide a wavelength between 1520 nm and 1620 nm, perfectly suitable for this procedure. The optical power meter (THORLABS S145C) is then used to capture transmitted spectral and record it in the computer. Fig. 3 shows the transmitted spectral from three sizes of MBR-PMMAs with Q-factor values. The insertion loss may change for each coated resonator size, caused by the coupling gap between the resonator with the microfiber and the coating thickness on the MBR-PMMAs. Hence, free-space radian modes and numbers of partial overlapping could become the reason for the insertion loss condition. The smallest size MBR-PMMA-A managed to have -30 dBm, which is higher than the bunch. Furthermore, the sizes of the MBR-PMMAs would influence the depth of the resonation of the MBR-PMMAs.



MBR-PMMA-A



MBR-PMMA-B



MBR-PMMA-C

Fig. 3. The transmitted spectral produced by MBR-PMMAs during the characterisation procedure for Q-factor and insertion loss (color online)

The Q-factor was determined by the equation estimation and Lorentzian fitting and managed to have $> 10^5$ for all coated resonators, similar to the previous. By the estimation of $\lambda/\Delta\lambda$, where λ describe as the resonant frequency, the Q-factor seem to have a different value for each MBR-PMMAs. As shown in Fig. 3, the biggest MBR-PMMA-C managed to have the highest Q-factor with 5.723×10^5 and the smallest size MBR-PMMA-A able to have 4.739×10^5. Here, the Q-factor may drop with the decreasing size of the MBR-PMMAs.

3. Performance of MBR-PMMAs as sodium alginate sensor

As shown in Fig. 4, the experimental setup used in the sodium alginate sensor with the position of MBR-PMMAs is physically in contact with the liquid while coupled with the microfiber. The WGMs were then deployed, crossing the resonator axis to part of the sensing mechanism. The microfiber 2 μm diameter is then connected to the TLS for wavelength supplied and the optical power meter for transmitted power data collection. The setup may operate in the sealed chamber for humidity and temperature level control. The temperature remained 25^0C during the process to reduce external error throughout the process. The sodium alginate concentration used is 1% to 6% ppm, placed inside the container. Furthermore, the optical power meter may record transmitted power for every percent of concentration used. The same procedure was repeated in three cycles and remained 60 minutes for each cycle. It would reduce random error while data collection and may optimise the sensor performance simultaneously. Although the MBR-PMMAs may experience the same procedure, the wavelength used as supplied will differ for each resonator seize, based on the resonating depth in Fig. 3. The MBR-PMMA-A used 1551.087 nm, MBR-PMMA-B used 1551.047 nm, and MBR-PMMA-C used 1551.020 nm as input wavelength. The wavelength used is determined by the deepest depth recorded by the MBR-PMMAs during the characterisation procedure.

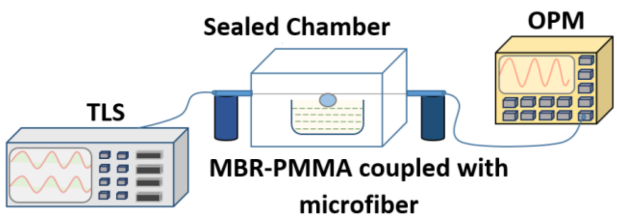
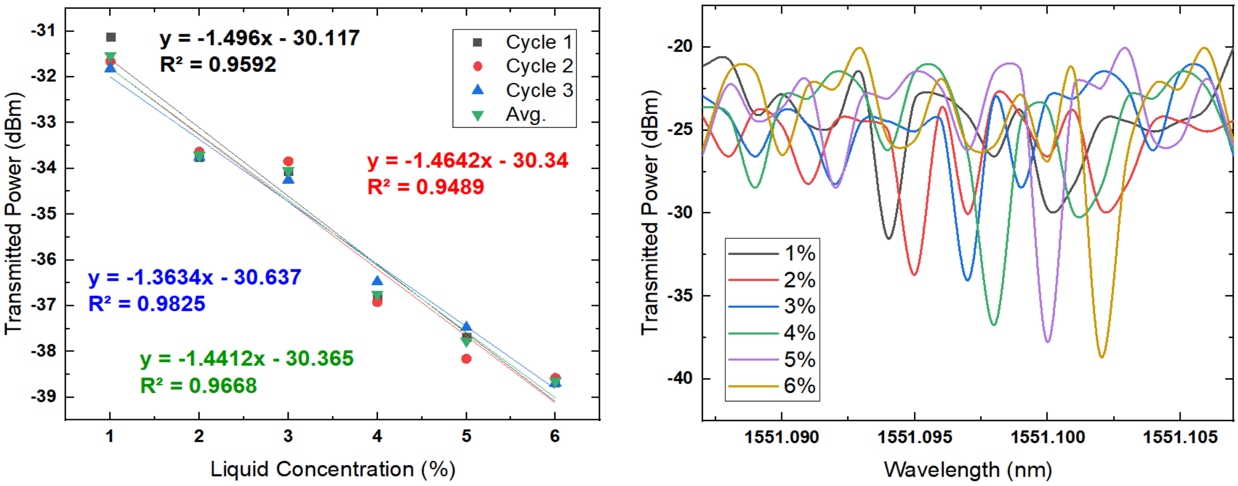
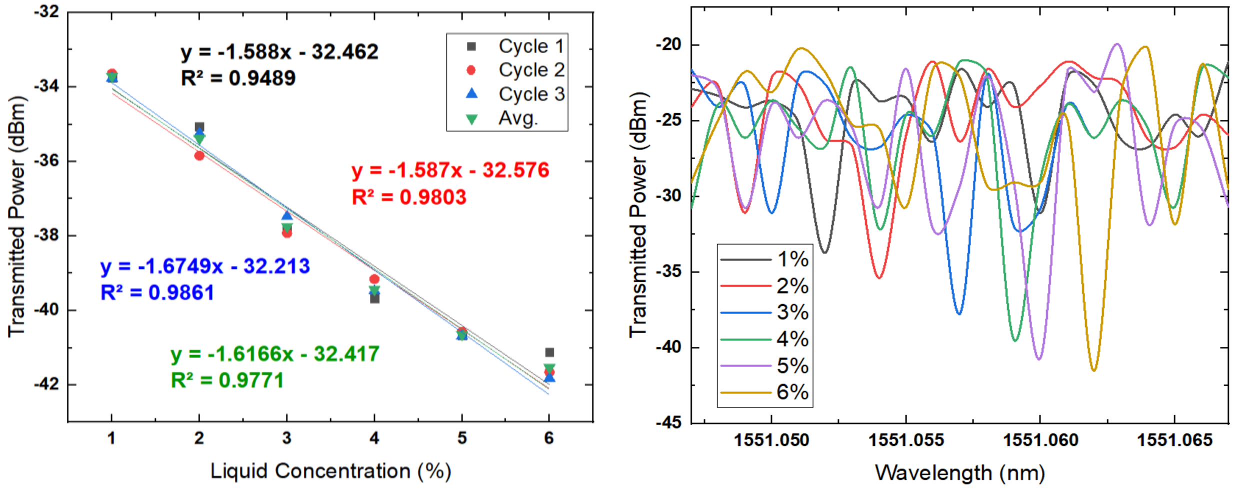


Fig. 4. The experiment setup for MBR-PMMAs for sodium alginate liquid sensor (color online)

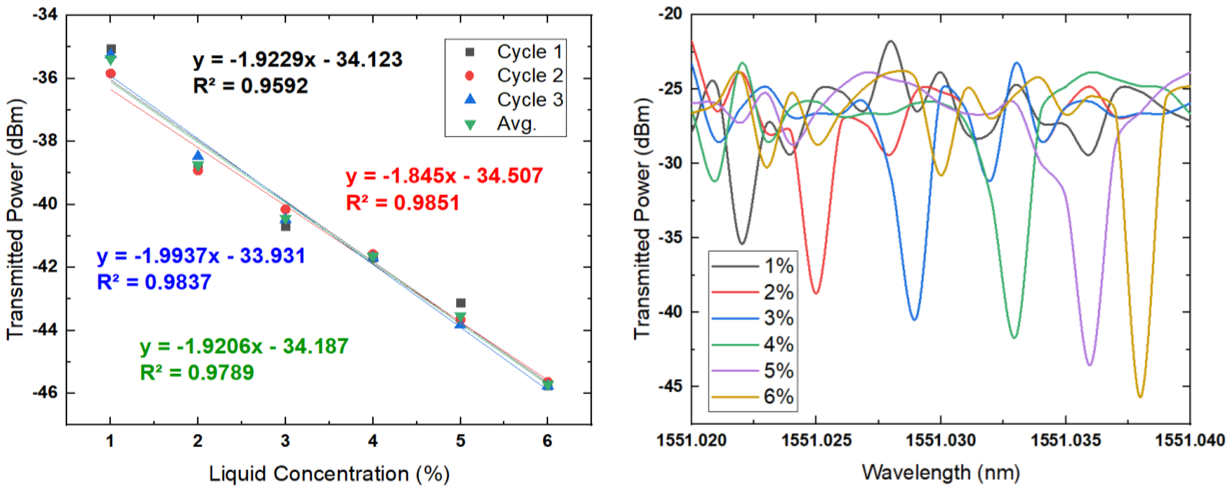
Sensitivity, linearity, repeatability and stability are the listed parameter used to determine the sensor performance. These results may then be collected from transmitted power and wavelength shift, which are then compared for synchronisation. By transmitted power results, the value decreased by increasing the level of liquid concentration used. As shown in Fig. 5, the wavelength may shift close to the right while different concentrations change during the procedure for all MBR-PMMA. To begin with, the MBR-PMMA-A is the smallest size of coating resonator, the sensitivity and linearity recorded as the lowest of the bunch with 1.4412 dB/%ppm and 98.3% only. In addition, the wavelength shift recorded is slightly small from 1551.094 nm to 1551.102 nm with only a 0.008 nm interval.



MBR-PMMA-A



MBR-PMMA-B



MBR-PMMA-C

Fig. 5. The sensitivity linearity and repeatability results of MBR-PMMAs as sodium alginate sensors by transmitted power analysis. The wavelength shift showed different resonant depths for every concentration (color online)

The middle size MBR-PMMA-B manage to have a sensitivity of 1.6166 dB/%ppm with linearity of 98.8%, respectively. As a result, the wavelength shifted from 1551.052 nm to 1551.062 nm with a 0.01 nm interval. These results are based on the transmitted power and wavelength shift data analysis considered average. However, the MBR-PMMA-C marked as the biggest coating resonator is high in sensitivity of 1.9206 dB/%ppm and 98.9% of linearity. Hence, the wavelength shifted from 1551.022 nm to 1551.038 nm with a 0.016 nm interval. By these results, the size may have influenced the coating MBR to perform well as a sodium alginate concentration sensor. Furthermore, the MBR-PMMAs were then analysed for sensitivity and linearity by the wavelength shift results. Undoubtedly, the MBR-PMMA-C manage to have high in both results with 3.3 pm/%ppm with 99.5% of linearity, as shown in Fig. 6. On the other hand, the MBR-PMMA-A only had a 1.6 pm/%ppm for sensitivity and 99.4% for linearity, while MBR-PMMA-B managed to have a 2.0 pm/%ppm sensitivity of 99.0% for linearity. Regarding these results, doubtless, to mention, the MBR-PMMA-C performed tremendously as a sodium alginate concentration sensor after all.

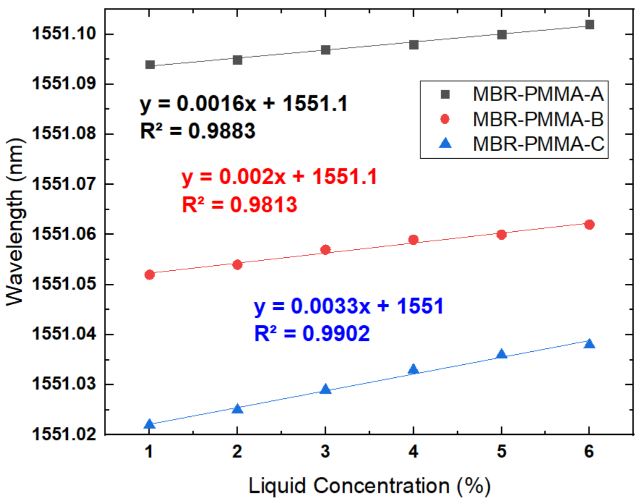


Fig. 6. The sensitivity and linearity results of MBR-PMMAs as sodium alginate sensors from wavelength shift analysis (color online)

In addition, the MBR-PMMAs experienced a stability test for 60 minutes. As shown in Fig. 7, the stability test was collected from the only 6% sodium alginate concentration used as medium sensing. Therefore, the MBR-PMMAs may remain in the same condition for 60 minutes and observed data consistency. The MBR-PMMAs then provide worthy performance for the stability test. Here, the MBR-PMMAs is useful to perform as a sodium alginate concertation sensor.

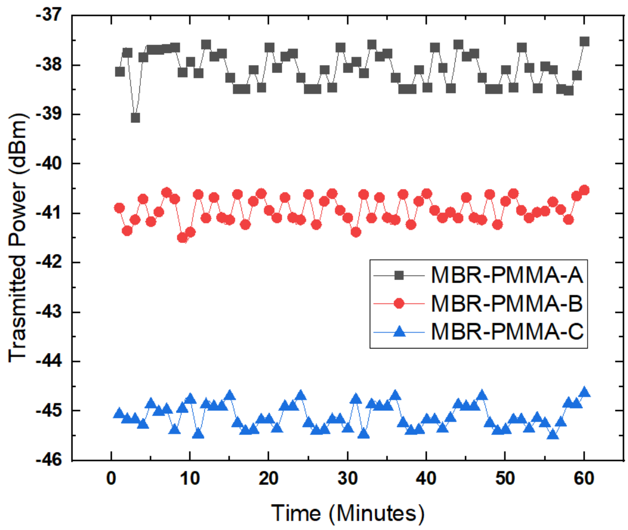


Fig. 7. The stability results of MBR-PMMAs from wavelength shift analysis (color online)

4. Conclusions

This experimental paper investigated the performance of coated MBR as a sodium alginate concertation sensor. The MBR is formed by the technique "soften-and-compress" from the silica fiber SMF-28. The MBR then experienced coating with PMMA using the "drop-casting" method. Three sizes of coated MBR-PMMAs are formed and characterised with microfiber $2\,\mu m$ diameter. The MBR-PMMAs managed to have a Q-factor of $> 10^5$ as remarkable to be applied as a sensor. The MBR-PMMAs were then applied as a sodium alginate sensor where 1% to 6% ppm liquid concentration was used as a sensing medium. The transmitted power and wavelength shift analysis collected sensitivity, linearity, stability, and repeatability results. These parameters then determined the MBR-PMMA-C, which is the biggest resonator to perform tremendously after all. Here, the size may have influenced the resonator performed as a sensor. The biggest coating resonator was performed well than other sizes.

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