New enhancement method on sensing ability of micro resonator bottle structure using polymer materials drop-casting coating technique

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This experimental paper proposes a new method to enhance the ability of microbottle resonator (MBR) sensor through polymethyl methacrylate (PMMA) and polyvinyl alcohol (PVA). The bottle resonator custom used the "soften-and-compress" technique from SMF28 silica fiber, then coated with PMMA and PVA. Three MBR used are non-coated MBR, MBR-PMMA and MBR-PVA. The coated and non-coated MBRs were then characterized via taper microfiber and achieved to have Q-factor $> 10^5$ for all, MBR-PVA is at the top with $8.624\ x\ 10^5$. The MBRs were then experienced as ethanol gas sensors, with the gas percentages used between 1% to 5% ppm. The sensitivity, linearity and stability are measured parameters via transmitted spectral and wavelength shift. The findings show that the MBR-PVA tremendously outraged every observed parameter. Here, the coating may influence the MBR performance as a gas sensor.

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1. Introduction

Fiber optic recently captured broad attention due to tremendous performance in several applications such as communication, laser technology, and plasmonic device development [1, 2]. One of the new fibre optic classes was invented in the sensor technology, known as optical microresonator (OMR) and applied as a sensor [3]. This new sub-class of fiber can manipulate the rotation of whispering gallery modes (WGMs) and increase the sensitivity of the microresonator as a sensor. This optical microresonator is established by several microloop, microdisc, microring, and microball resonator structures [4-6]. Here, the whispering gallery mode's behaviour has been explored seriously by analysis through several parameters such as quality factor, intrinsic losses, and method of assembly [7]. This paper introduces one micro resonator sub-class known as microbottle (MBR) to be used as a sensor. This structure with a bottle curve is believed to increase the quality of the whispering gallery modes' resonation based on previous research. The high quality of WGMs would increase the sensing capability of the MBR, where the WGMs can freely resonate across the resonator axis. The excellent quality of resonation may lead s to the practical free-spectral range, making this sub-class of resonator sensible to be applied as a sensor [8].

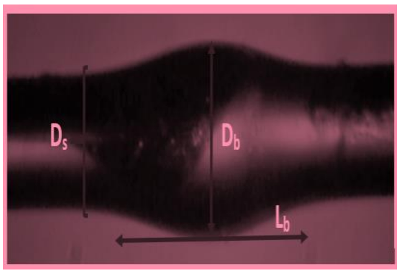
Polymethyl methacrylate (PMMA) is a transparent thermoplastic that is probably an alternative to glass [9-11]. This material has always been used in industrial production for numerous advantages such as lightweight structure, transparency and shatter-resistance [10]. This material is typically used as a coating substance and casting resin [12]. The PMMA is selected as a coating material based on the refractive index value, which is probably close to the MBR and could increase the size of the bottle MBR [11]. The size of the bottle MBR may influence the resonator Q-factor similar to the previous research [9, 13]. A similar reason for the polyvinyl alcohol (PVA) was chosen. The PVA is also known to have a close refractive index value with the MBR and can increase the size of the bottle. However, these materials are known to have different capabilities when it is used as a sensor. The adsorption ability of these materials is different from each other, based on previous research [14, 15].

This research studied the performance of the coating MBR as an ethanol gas sensor and the effect of the PMMA and PVA coating on sensing capability. Ethanol is best known to be used as fuel recently because of its ability to stimulate the engine under the appropriate condition [16, 17]. As part of the sensing method, the coated MBR is believed to detect the presence of ethanol gas particles performed in different densities. This research would be the first ethanol gas sensor using the PMMA or PVA-coated MBR and non-others similar to previous research. The MBR may be formed by the method "soften-and-compress" which allows the silica fiber to bump into the bottle structure, while the PMMA coating procedure uses the "drop-casting" technique; the same goes with the PVA [13, 18, 19]. The MBR was prepared in three conditions:

non-coating MBR, PMMA-MBR and PVA-MBR and then characterized through microfiber 2 μm diameter by coupling it together [20, 21, 22]. The ethanol gas was prepared in five different percentages from 1% to 5% for the sensing medium. Sensitivity, linearity, stability and repeatability are used to measure the MBRs performance as a sensor. These parameters were used to evaluate the data collected during the experiment via transmitted spectral and wavelength shift analysis, then compared for the versions.

2. Characterisation of MBRs

The silica fiber SFM-28 was used as the main material to form the bottle structure of MBR using the "soften-and-compress" method [1]. Silica fiber was placed on a splicing machine (Furukawa Electric Fitel S178A), and an electrical heat arc was applied to the midriff fiber area [2]. During the heating, the fiber is then compressed by the holder inwardly and turned into the bottle structure [1, 3]. The electrical arc numbers applied through the process will determine the bottle size. Three parameters limit the bottle structure as bottle length L_b, bottle diameter D_b and bottle stem diameter D_s as shown in Fig. 1, which then similar to previous works [4, 5, 23]. The MBR is then coupled with taper microfiber 2 μm for characterization, where the "flame brushing technique" is used to form the microfiber [24]. Among other methods, this technique seems to have the most convenient in handling and time consumption. The MBR then coating with PMMA and PVA by "drop-casting" technique and the size was then recorded in Table 1. As shown in Fig. 2, the technique allowed the coating material to cover the whole bottle surface with the thickness $of\ < 10\ \mu m$ [6]. The PMMA coating solution prepared by mixing 10 ml isopropanol liquid with 1.0 mg PMMA crystal was then stirred at 700 rpm for one hour long and heated on a hot plate at 100 ^{0}C at the same time [6]. The PVA coating solution was prepared by mixing 12 ml distilled water with 5 mg PVA powder and using an ultrasonic cleaning machine (GT SONIC-P2) for a stirred process for 6 hours long [7]. The coating of PMMA and PVA on the MBR surface was measured to have <10 μm in all sizes.



(a)

(b)

Fig. 1. The size of the MBR with bottle diameter D_b, bottle stem diameter D_s and bottle length L_b (a) and the MBR coupled with microfiber for characterization (b) (color online)

Table 1. Size of three coating and non-coating MBR

Parameter	Coating MBR-PVA	Coating MBR-PMMA	Non-coating MBR
D_s	125μm	125μm	125μm
D_b	220μm	220μm	190μm
L_b	181μm	181μm	220μm

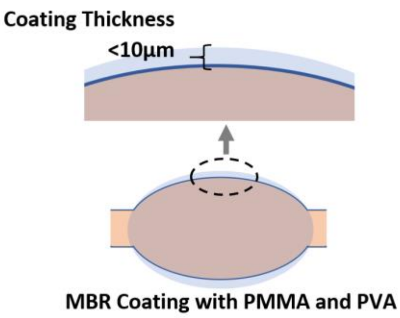


Fig. 2. The PMMA and PVA coated on the MBR by the "drop-casting" method with a thickness of less than 10 µm (color online)

The coating MBRs then characterized by coupling with the taper microfiber for Q-factor and FSR results, which are then useful for sensing purposes. The laser source (ANDOAQ4321D) supplied a range of wavelengths from 1520.00 nm until 1520.20 nm with a 0.001 nm interval. This kind of laser source can normally produce a huge range of wavelengths from 1520 nm to 1620 nm, which is suited to the experiment requirement. The characterization procedure revenue three transmitted spectra with different Q-factor as in Fig. 3. The insertion loss may differ for each MBRs caused by the coating thickness, coating material, and the coupling gap between the resonator with taper microfiber. Free-space radian modes and numbers of overlapping partial would be an additional cause of insertion loss. The MBR-PVA have the lowest insertion loss with -36 dBm than other MBR.

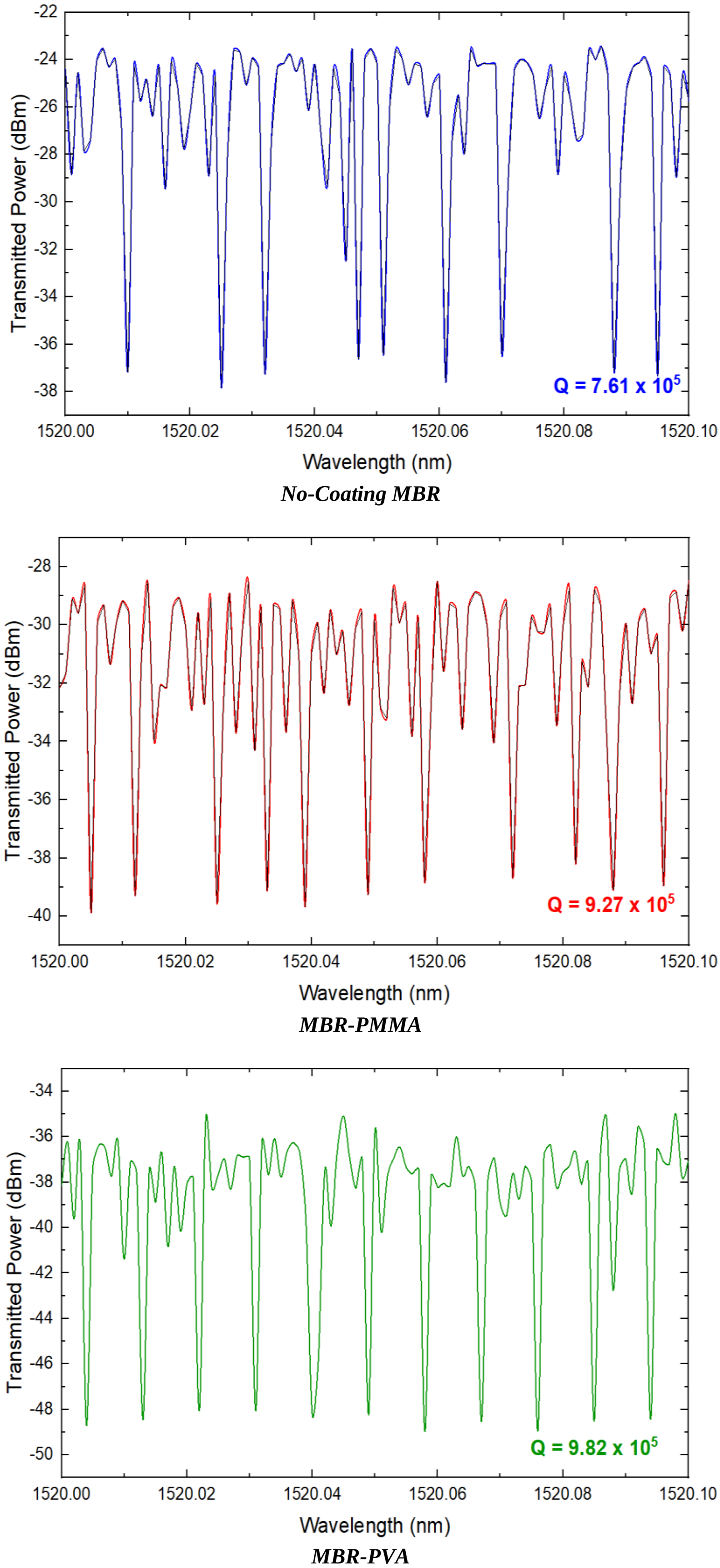


Fig. 3. The transmitted spectral by No-Coating MBR, MBR-PMMA and MBR-PVA (color online)

The Lorentzian fitting was then used to determine the Q-factor value and managed to have $> 10^5$ for all resonator conditions, which is similar to the prior research. The Q-factor may also be defined by the estimation of λ/Δλ where λ is the resonant frequency, which is different for each MBR condition. As Fig. 3 showed, the MBR-PVA marked the highest Q-factor with 9.82×10^5 of the bunch. It may demonstrate that the material used in coating influenced the Q-factor value.

3. Performance of Coating and Non-Coating MBRs as Sensor

As shown in Fig. 4, the MBRs set up in the sealed chamber, which is then used for the ethanol gas sensor. The MBR coupled together with the taper microfiber 2 μm, which allowed the transmitted spectral from the laser source to circulate on the MBRs surface, which was part of the sensing mechanism. The circulation of the modes perpendicular to the MBRs outer surface may be disturbed by the ethanol gas molecule, which is believed to be adsorbed by the MBRs surface. One end of the taper microfiber is connected to the optical spectrum analyser (OSA, Anritsu MS9710C) to observe the power changes during the process. The changes may represent several wavelengths which are then analysed to view the performance of the MBRs as ethanol sensors. The wavelength used as an input source may differ for each MBRs, depending on the characterization results in Fig. 3. The non-coating MBR and MBR-PVA used a 1520.06 nm input source, which is the most deeply resonant depth on the characterization graph, while the MBR-PMMA used 1520.04 nm with a similar motivation. The sealed chamber helps the setup to keep the temperature in room condition at 25^0C. The ethanol gas was consistently channelled through the chamber from 1% to 5% of concentration. MBRs may experience 30 minutes stability test to increase the accuracy of data collection and help to minimize random error.

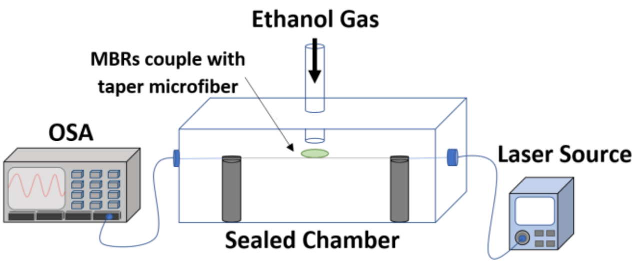


Fig. 4. The experiment setup for no-coating and coating MBRs for ethanol gas sensor (color online)

Three main parameters are used to observe MBRs performance as ethanol sensors; sensitivity, linearity and stability. The transmitted power and the wavelength shift from the optical spectrum analyzer will then be analysed for these parameters as determinant results. Every MBRs condition may produce a different power value for each ethanol gas percentage. The analysis from the transmitted power showed a decreased trend when the level of gas percentage increased, respectively, as shown in Fig. 5. The sensitivity of the MBR-PVA showed the highest with 3.362 dB/%, even though the linearity is slightly lower than MBR-PMMA with a 3.99% difference. The PVA as a coating material may influence the adsorption ability of the MBR as an ethanol gas sensor.

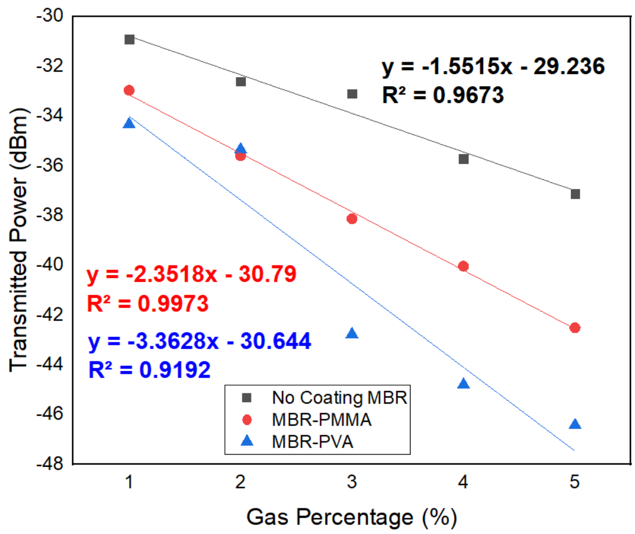
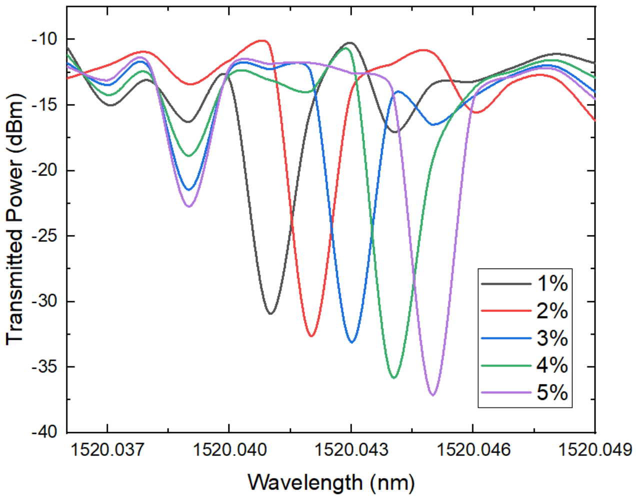
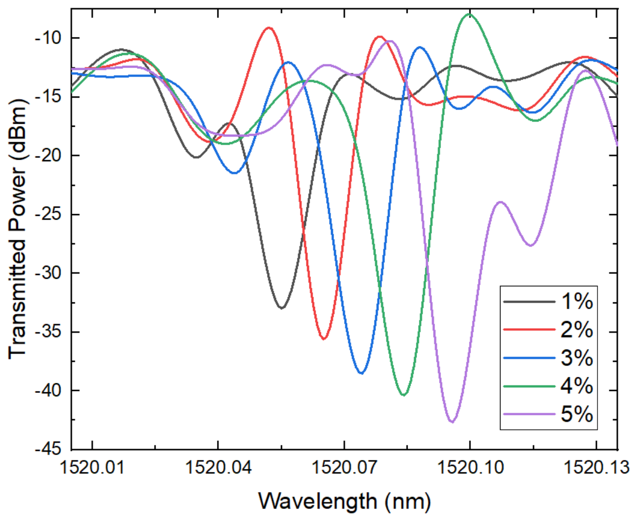


Fig. 5. The sensitivity and linearity value based on the analysis of transmitted power results (color online)

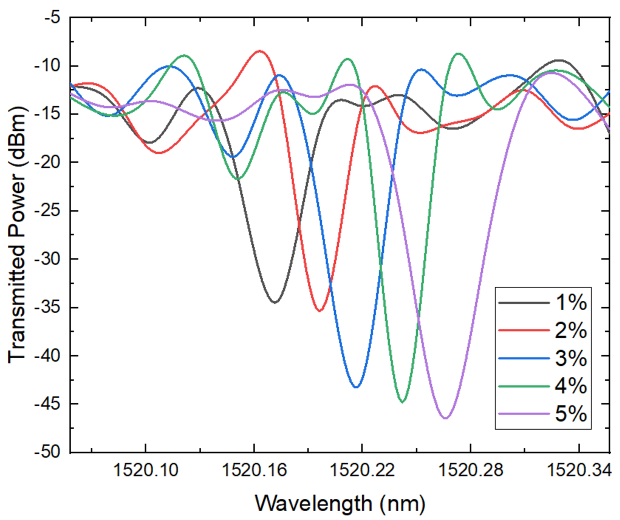
The analysis continued by examining the wavelength shift produced by the MBRs with different ethanol gas concentrations, as shown in Fig. 6. The wave shifted to the right while the gas percentage increased, with the power transmitted value decreasing constantly. The results showed that the coating material didn't hugely impact the wave shifting, whereas the coating and non-coating MBR showed the same trend. However, the coating material may affect the transmitted power value where the no-coating MBR generated fewer power losses with a gap between 1 dBm to 5 dBm, respectively. Hence, the coating MBRs showed less consistency in wave shifting than no-coating MBR. The wavelength shift graph was then analysed for sensitivity and linearity MBRs performance.



No-Coating MBR



MBR-PMMA



MBR-PVA

Fig. 6. The wavelength shift for MBRs for different ethanol gas percentage sensing. The sensitivity and linearity are defined by the wavelength shift (color online)

The analysis of the wavelength shift for sensitivity and linearity results showed in Fig. 7. The wavelength value showed an increasing trend with an additional value of gas percentage. The results were similar to all MBRs conditions, where coating and no-coating marked the same impact on the wave shifting. However, by the sensitivity results, MBR-PVA generated a higher value than others with 0.023 nm/%, flowed by MBR-PMMA with 0.014 nm/% and no-coating MBR with 0.001 nm/%. These may be explained by the coating material proven to enhance the MBR's sensing ability. The linearity results showed slightly different with the no-coating MBR generating the highest linearity at 99.89%, then MBR-PMMA with 99.2% and MBR-PVA with 99.4%. Without any intervention of coating material, the resonator will have linear results. However, the linearity won't represent the overall performance of the MBR as a sensor; it only represents the data collection consistency.

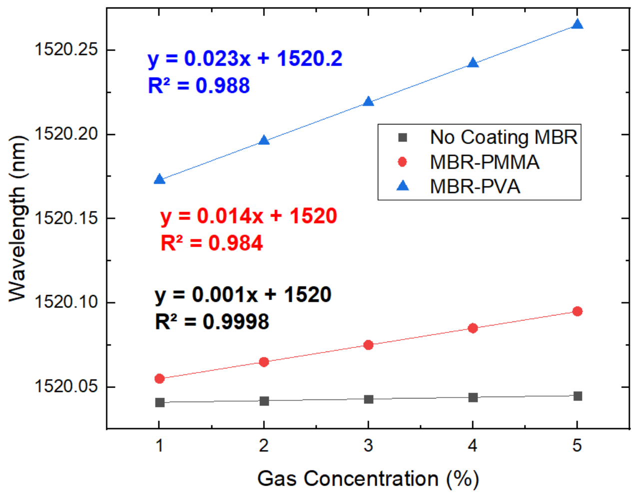


Fig. 7. The sensitivity and linearity from the wavelength shift (color online)

The MBRs are then tested with the stability test for the additional optimization procedure. The MBRs remained in the same condition, where the data are taken 30 minutes from its start. As shown in Fig. 8, the MBRs showed stable performance with less than 2% of transmitted power changes for every minute. This remarkable performance showed that the coating material wouldn't affect the stability much. The consistent results shown by the MBRs may be explained why this kind of resonator captured huge intention from the researcher for future sensor alternatives.

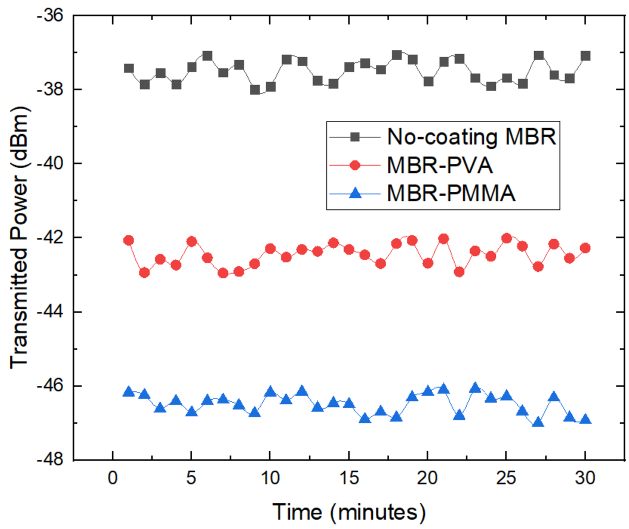


Fig. 8. The stability performance of MBRs as ethanol gas sensors (color online)

4. Conclusions

This experimental paper proposes a new method to increase the sensing ability of the MBR. Introducing the PMMA and PVA as a coating material on the outer surface of the MBR may influence the whispering gallery mode behaviour and leads to tremendous performance as a sensor. The "soften-and-compress" technique was used to form the MBR from silica SMF-28, which was then coated with the PMMA and PVA. Three samples of MBR named no-coating MBR, MBR-PMMA and MBR-PVA are then characterized on the taper microfiber. The Q-factor values which were $> 10^5$ become an indicator showing the MBRs suitable for being used as a sensor. The MBRs then tested with different percentages of ethanol gas as a proven application. By analysing the transmitted power and wavelength shift, parameters such as sensitivity, linearity and stability are then used as performance indicators. The MBR-PVA showed the best performance by all parameters and a remarkable outcome. Additionally, the coating material could be used as an alternative way to increase MBR performance as a sensor.

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