Carbon dioxide gas sensor based on self-assembled WGM microbottle resonator coated with polymethyl methacrylate

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In this study, researchers looked into how coating MBRs with polymethyl methacrylate (PMMA) affected their performance as a carbon dioxide gas sensor. Using a "soften-and-compress" technique, SMF28 produced the MBR shape, which was then coated in a PMMA solution to provide the three different conditions of single, double, and cascade. All forms of MBRs, even the most advanced cascade MBR-PMMA with a Q-factor of 7.47×10^5, were distinguished by the presence of microfibre. Sensitivity, linearity, stability, and repeatability of a carbon dioxide gas sensor were evaluated using MBR-PMMAs. Between 10% and 60% of carbon dioxide gas was consumed. Transmitted power analysis and wavelength shifting analysis were then compared to see which provided more accurate results. The results for Cascade MBR-PMMA were outstanding in every category. Here, the MBR with PMMA coating is arranged in a cascade, which may have an effect on the WGMs and therefore increase the MBR's adsorption capabilities as a sensor.

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1. Introduction

Fibre optics have recently caught a lot of interest in research, including communication, sensor, laser, and plasmonic devices [1, 2]. As a new invention to the sensor industry, a sub-class of fibre optic called as optical microresonator (OMR) appeared [3]. Manipulation of the resonator's whispering gallery modes (WGMs) may improve the resonator's function as a sensor [4, 5]. For this use, several OMRs have been developed, including the microring, microloop, microdisc, and microball resonator [6, 7]. Here, the WGMs on OMR are seriously investigated with many preferences such as quality factor, intrinsic losses, and assembly method, where all of them may yield fantastic results [8, 9]. However, this paper proposes the use of an OMR structure to investigate WGMs as a gas sensor. Based on the appearance of the bottle structure, the microbottle resonator may receive a variable contribution of WGMs to this OMR structure as a sensor [8, 10]. The WGMs can easily cross the MBR axis surface, making this resonator suitable for use as a sensor [4]. As a result, as additional criteria, the MBR may provide a high quality factor with a reasonable free-spectral range, making this OMR structure useful for sensing applications [11, 12].

Polymethyl methacrylate (PMMA) is a transparent thermoplastic used in sheet form as an alternative to glass. [7, 13]. The structure is shatter-resistant, translucent, and lightweight, and has long been employed in a variety of industrial applications [14]. This substance has a variety of applications, including casting resin and coatings [15]. PMMA's reflective index is nearly same to the MBR used of PMMA, which may increase the size of the MBR bottle size [16]. According to prior studies, the size of the resonator may influence its Q-factor [7]. As a result, it would be the most compelling rationale to employ PMMA as a covering material with the MBR.

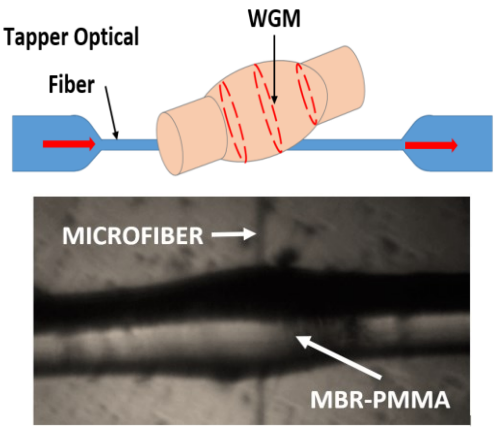
This study looked at the impact of PMMA coating on MBRs use for carbon dioxide (CO_2) gas sensors. As part of a sensing application, the coated MBR may be able to detect each gas level. The was first experiment employed PMMA coated MBR as a carbon dioxide (CO_2) gas sensor, and no other similar research was conducted. The MBR was created using the "soften-and-compress" process and then coated with PMMA using the "drop-casting" technique [11, 17]. Three form of MBR-PMMAs were subsequently constructed named as single,double and cascade of MBR-PMMA. The MBR-PMMAs were then characterised by being linked with a 2 m diameter microfibre. For sensing activity, carbon dioxide (CO_2) gas used in ranging from 1% to 6% ppm. The specified parameters used to determine the performance of MBR-PMMAs as sensors are sensitivity, linearity, stability, and repeatability. These results are generated by comparing transmitted spectrum and wavelength shift analysis for the optimum performance.

2. Theoretical analysis

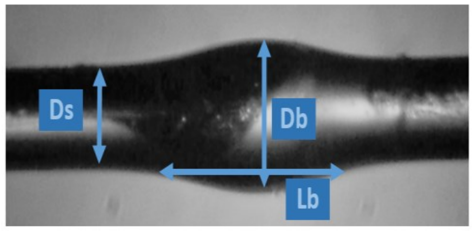
The WGM microbottle resonator has a high Q value and excellent sensitivity, allowing it to confine light at precise frequencies for cyclic resonance. Excitation of WGMs using a microbottle resonant cavity linked to a tapered fibre is depicted schematically in Fig. 1(a). There will be evanescent waves on the outer surface of the medium and dips in the output spectrum when light from the tapered fibre is coupled into the microbottle resonator, because light of certain wavelengths that satisfy the resonant conditions will be continuously and totally reflected along the surface of the cavity medium [18, 19].

3. Characterisation of MBR-PMMAs

The MBR is made using a "soften-and-compress" process from a silica fibre SMF-28. The splicing machine (Furukawa Electric Fitel S178A) heated the fibre centre area with an electrical arc [20]. Simultaneously, the holder crushed the fibre in an inward direction. [21]. The heated area then bumping and turn to the bottle structure. The amount of electrical arcs used during the procedure determines the size of the bottle. As indicated in Fig. 1(b), the bottle size was governed by three parameters: bottle diameter Db, bottle stem diameter Ds, and bottle length Lb, which was consistent with earlier research. The MBR was then coated with a PMMA solution via a "drop-casting" method. As indicated in Fig. 2, the solution will cover the full surface of the bottle resonator. PMMA solution was made by combining 1.0 mg PMMA crystal with 10 mL isopropanol solvent. The mixed solution was then heated at 100 °C on a hot plate for 1 hour while being agitated at 700 revolutions per minute. MBR coatings are currently termed as MBR-PMMAs, and coating thickness is measured to be 15 µm in all sizes using the specific microscope (SPZHT-135 Trinocular Stereo Zoom Microscope). The MBR-PMMAs was then characterised by connecting with a 2 µm taper microfibre. Several methods can be used to create a tapered microfiber, with the "flame brushing" technique being chosen based on time constraints and handling issues.



(a)



(b)

Fig. 1. Tapered fibre stimulated resonator shown in WGM schematic (a). The MBR has three parts: the length Lb (182 µm), the diameter Db (170 µm), and the diameter Ds (125 µm) of the bottle stem (b) (color online)

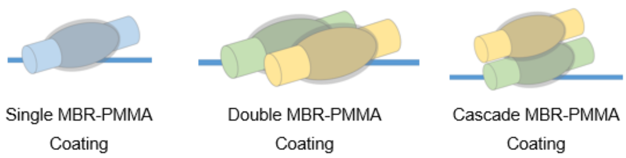
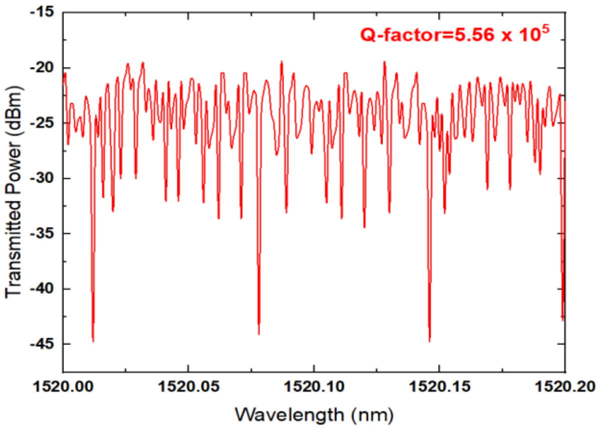
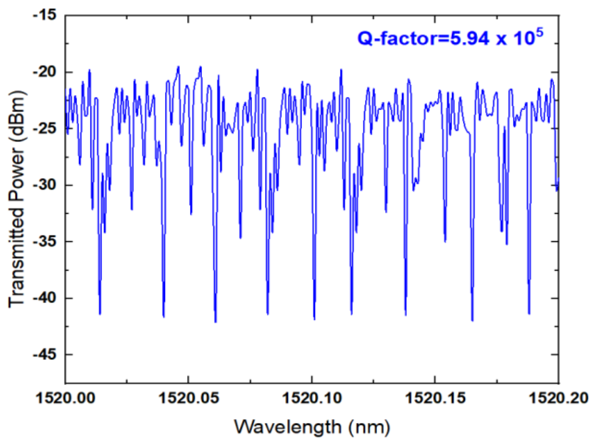


Fig. 2. The MBR-PMMA Coating by "drop-casting" method (color online)

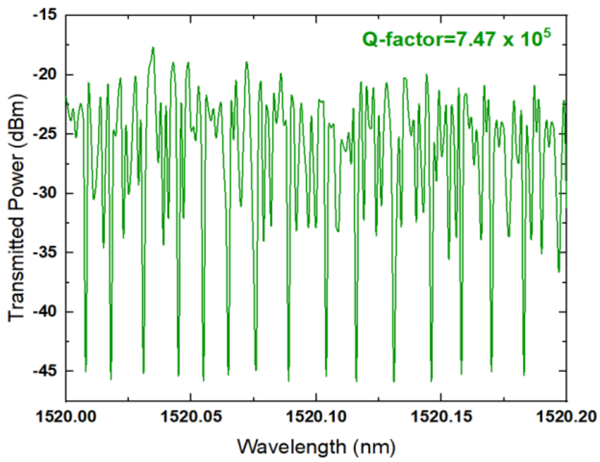
Prior to their use in sensing applications, the MBR-PMMAs were characterised to ascertain their Q-factor results. The ANDOAQ4321D tunable laser source has a wavelength tuning range of 1520.0 nm to 1520.2 nm at a resolution of 0.001 nm. This method is particularly well-suited to the wavelength range (1520 nm to 1620 nm) that can be provided by this tunable laser source (TLS). The transmitted spectrum was measured using a Thorlabs S145C optical power metre and stored in a computer. Three distinct types of MBR-PMMAs and their accompanying spectral transmission and Q-factor values are shown in Fig. 3. The thickness of the coating on the MBR-PMMAs and the coupling distance between the resonator and the microfibre both affect the insertion loss. Therefore, insertion loss may be caused by the presence of free-space radian modes and the degree of partial overlapping. The MBR-PMMAs performed constant signal level at around -20 dBm where couse by same size of experiment setup. In addition, the magnitude of the MBR-PMMAs' resonance would depend on their diameters.



Single



Double



Cascade

Fig. 3. The spectrum transmission generated by coating MBR-PMMAs for Q-factor and insertion loss (color online)

The Q-factor was estimated via equation estimates and Lorentzian fitting, resulting in a value >10^5 for all coated resonators, which is consistent with the prior findings. Based on the calculation of $\lambda/\Delta\lambda$, where λ represents the resonant frequency, it appears that each MBR-PMMA has a distinct Q-factor value. Fig. 3 demonstrates that the cascade MBR-PMMA with the different resonator position achieved the highest Q-factor of 7.47×10^5, while the single MBR-PMMA had a Q-factor of 5.56×10^5. The Q-factor may decrease when the number and position of the MBR-PMMA changed.

4. Performance of MBR-PMMAs as carbon dioxide gas sensor

Fig. 4 depicts the experimental setup used to test the carbon dioxide gas sensor, showing where the MBR-PMMAs are located in relation to the microfibre and the tasted gas. Afterwards, the WGMs were set up so that they would reach the sensing mechanism across the resonator's axis. The transmitted power data was collected by connecting a TLS for wavelength supply to a 2 μm microfibre and an optical power meter. The sealed chamber allows for controlled humidity and temperature to be maintained within the setup. To minimise the possibility of outside interference, the temperature was held constant at 25^0 celsius. The carbon dioxide gas utilised ranges from 1% to 6% ppm, and it is placed within the container. In addition, the optical power meter can keep track of the transmitted power at a given concentration level. The same process was carried out three times, each time lasting 120 minutes. It could improve sensor performance while reducing the chance of error during data collecting. While all MBR-PMMAs will go through the same process, the wavelength employed in its provided form will vary depending on resonator size (as shown in Fig. 3). Input wavelengths for the MBR-PMMAs were 1520.052 nm for single coating, 1520.061 nm for double coating, and 1520.062 nm for cascade coating, respectively. The input wavelength used for every resonator are based on the resonating depth performed by each resonator in Fig. 3. The maximum depth recorded by each MBR-PMMAs form during characterisation establishes the wavelength employed.

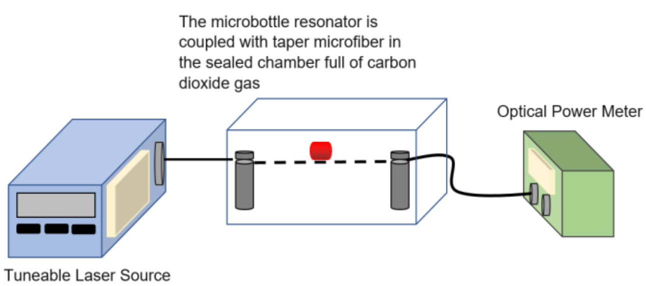
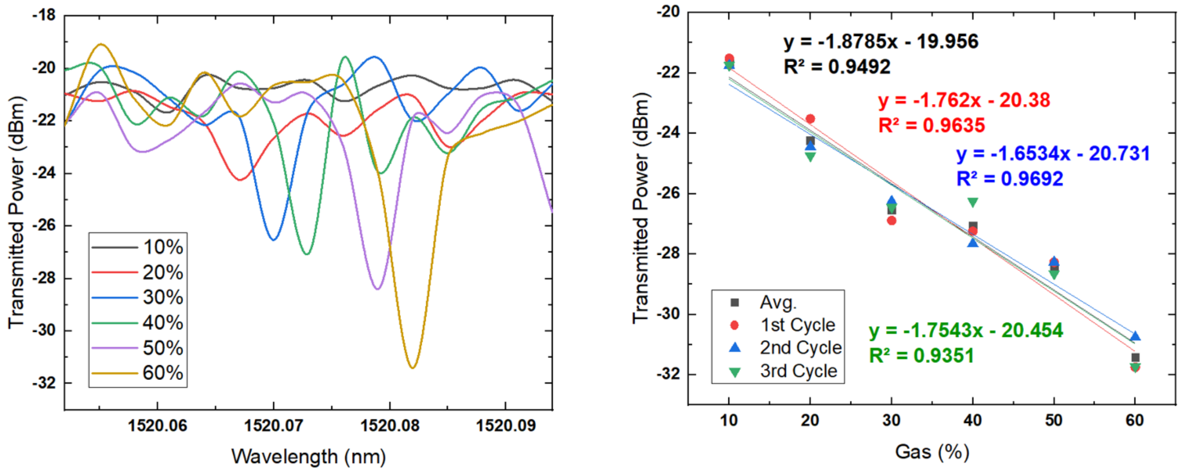
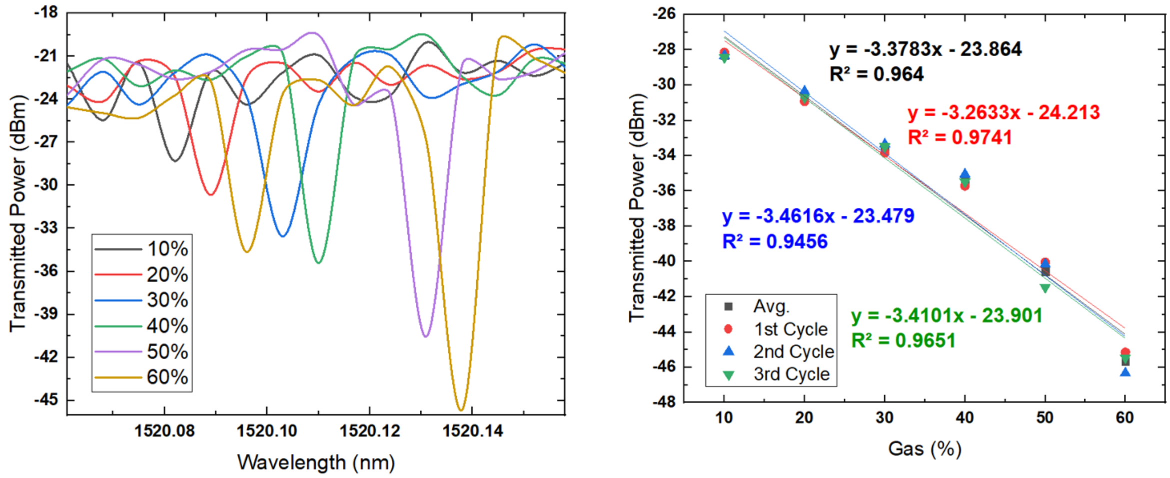


Fig. 4. The experimental configuration for MBR-PMMAs used in the carbon dioxide gas sensor (color online)

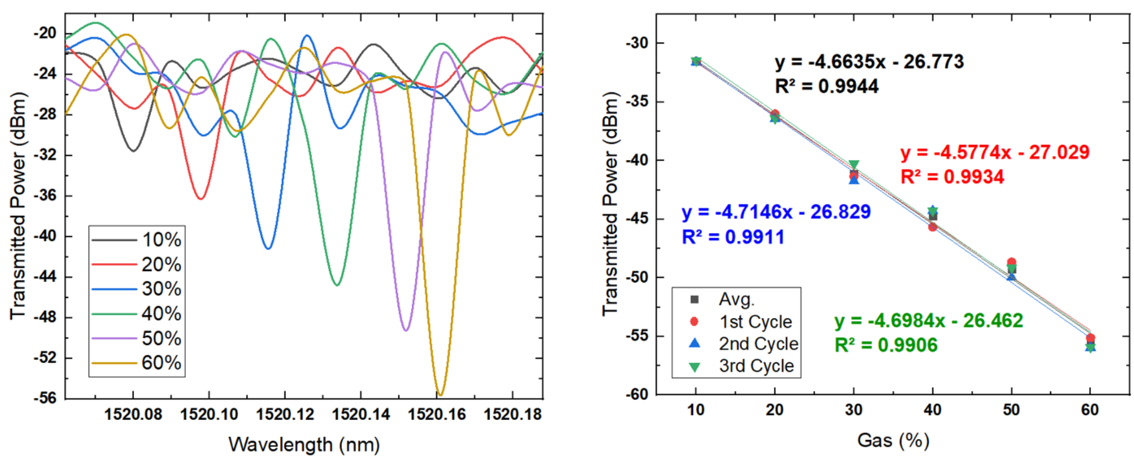
The effectiveness of a sensor can be evaluated according to the aforementioned criteria: sensitivity; linearity; repeatability; and stability. Synchronisation can then be determined by comparing the transmitted power and the wavelength shift. Increasing the gas percentage of the carbon dioxide utilised decreased the value, as measured by the transmitted power. As can be seen in Fig. 5, the wavelength of all MBR-PMMA may shift nearly to the right as the gas percentage are altered during the process. To begin, the sensitivity and linearity recorded for the single MBR-PMMA, were the lowest of the bunch at only 1.8785 dB/%ppm and 97.4%. Furthermore, the observed change in wavelength is rather minor, ranging from 1520.061 nm to 1520.082 nm with only a 0.021 nm gap.



Single MBR-PMMA coating



Single MBR-PMMA coating



Single MBR-PMMA coating

Fig. 5. Transmitted power analysis reveals linearity and repeatability in sensitivity (color online)

The linearity is 98.2% and the sensitivity is 3.3783 dB/%ppm for the double MBR-PMMA. This caused a 0.056 nm change in wavelength, from 1520.082 nm to 1520.138 nm. These findings are based on an average examination of transmitted power and wavelength shift data. The cascade MBR-PMMA, however, is the most sensitive and has the highest linearity 99.7% of any of the coated resonators. As a result, there was a 0.081 nm change in wavelength, from 1520.080 nm to 1520.161 nm. These findings suggest that the cascade coating MBR's stellar performance as a carbon dioxide gas sensor could be attributed, at least in part, to its position form. The findings of measuring the wavelength shift of the MBR-PMMAs were then examined to determine their sensitivity and linearity. Fig. 6 demonstrates unmistakably that the cascade MBR-PMMA achieves high in both findings, with 1.67 pm/%ppm at 99.6% linearity. The sensitivity and linearity of the single MBR-PMMA-A were only 0.41 pm/%ppm and 99.4%, respectively, whereas those of the double MBR-PMMA were 1.18 pm/%ppm and 98.9%, respectively. As can be seen from these outcomes, the cascade MBR-PMMA proved to be an excellent carbon dioxide gas sensor.

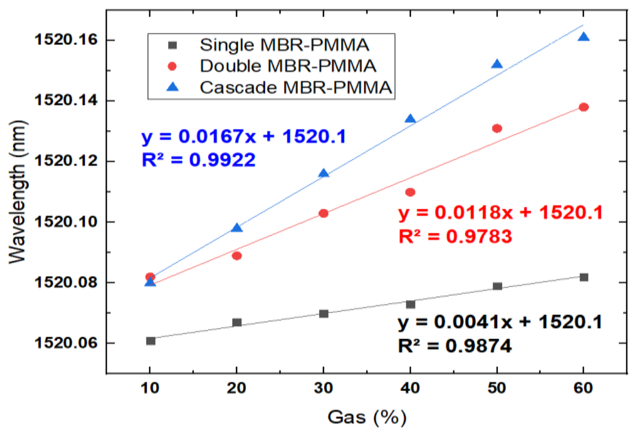


Fig. 6. Analysis of wavelength shifts

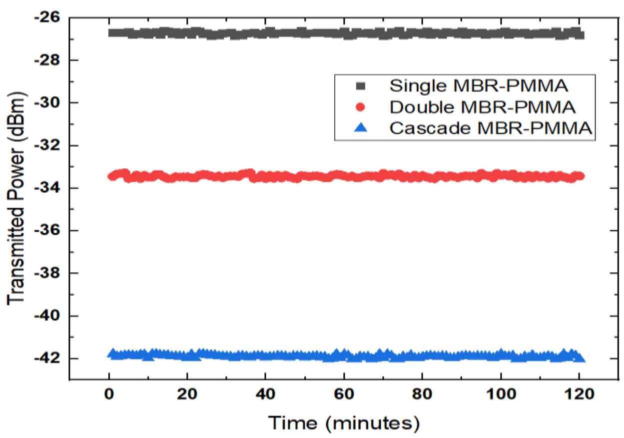


Fig. 7. Wavelength shift of stability (color online)

The MBR-PMMAs were also subjected to a 120-minute stability test. Fig. 7 displays the results of a stability test using data gathered from a medium sensing solution of 30% carbon dioxide gas. That said, it's possible that the MBR-PMMAs will stay in the same state for the full 120 minutes, ensuring reliable data collection. The stability test is passed with respectable results thanks to the MBR-PMMAs. In this application, the MBR-PMMAs is helpful as a carbon dioxide gas sensor.

5. Conclusions

The effectiveness of coated MBR-PMMAs as a carbon dioxide gas sensor was tested in this experimental research. The MBR was created using SMF-28 silica fibre using a "soften-and-compress" process, then arranged in single, double, and cascade forms. Next, a "drop-casting" process was used to cover the MBR with PMMA. Microfibers with a diameter of 2 μm are used to create and characterise three different form coated MBR-PMMAs. The Q-factor of >10^5 achieved by MBR-PMMAs is impressive for their potential use as a sensor. As a carbon dioxide gas sensor, the MBR-PMMAs were employed in a gas range of 10% to 60%. Analysis of transmitted power and wavelength shift yields results about sensitivity, linearity, stability, and repeatability. Based on these factors, the cascade MBR-PMMA, was designed for exceptional performance. In this case, the resonator's position may have affected its sensing abilities, where it has more surface for WGMs circulation. Hance, this position allowed the resonator to have more contect surface with the gas particles and make it more sensitive to the changes that appled. When compared to single and double, the cascade coating resonator fared exceptionally well.

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