Micro-ball and micro-bottle resonators for relative humidity sensing

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We compare the performance of two whispering gallery mode optical resonators; optical micro-ball (MBaR) and micro-bottle resonators (MBR) as a relative humidity (RH) sensor. The MBaR and MBR are fabricated via the so-called ``soften-and-compress" method to create a ball or bulge structure. The MBaR and MBR is then optically excited by using a 8μm optical microfiber and was found to have a Q-factor of >105. The MBaR and MBR was then employed as a humidity sensor with a RH range of between 40% to 100% and the performance is compared for both resonator. The MBR RH sensor was found to have a sensitivity of 0.2973 dB/%, linearity >90% and is superior to the MBaR microfiber in all measured parameters. The MBR RH sensor was also found to have good repeatability and stability compare to MBaR.

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1. Introduction

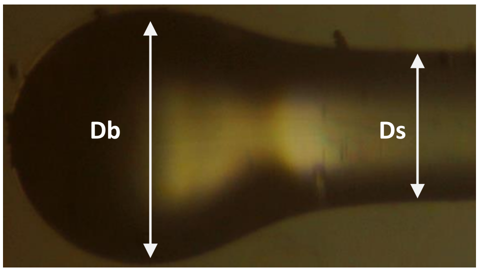
Micro-resonators have been widely investigated in recent years due to their many advantages including their ability to confine light with high quality factor (Q) and in a small modes volume [1-2]. They are typically associated with circular-path resonant cavities such as micro-ring, micro-disc and micro-toroid geometry and these resonators can support whispering gallery mode (WGM) operation by creating continuous internal reflection at specific resonant wavelengths [3-12]. According to the geometrical optic principle, a WGM can be represented by an optical ray transmitted exclusively near the micro-resonator surface due to grazing-angle total internal reflection [13]. When light is evanescently coupled into the micro-resonator via a microfiber, very narrow resonance dip with a full width half maximum (FWHM) on a level of pm appears in the transmission spectrum. The optical WGM device can be applied in many areas including optical sensing [14-15].

On the other hand, optical fiber based relative humidity (RH) sensors have been widely studied due to their advantages such as feasibility of long-distance sensing, real-time monitoring, and immunity to electromagnetic interference. Various techniques including tapered optical fiber, hetero-core optical fiber, and fiber grating have been reported previously for RH sensors [16–20]. In this paper, we proposed and experimentally demonstrated a RH sensor using a WGM based micro-resonators. We compare the performance of the RH sensor for two different probes; micro-ball resonator (MBaR) and micro-bottle resonator (MBR). WGM resonators, in particular, have been extensively studied due to several advantages including ease of fabrication, high Q factors and low intrinsic losses [12,13]. The proposed resonators are also compact in size, fast in response, and low in cost..

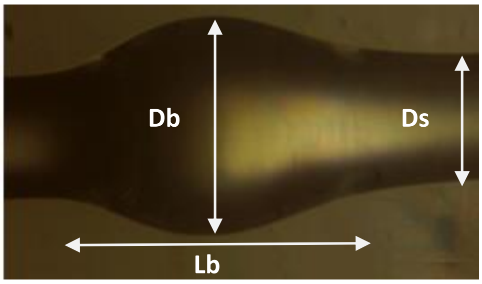
2. Experimental setup

Two types of micro-resonator namely micro-ball resonator (MBaR) and micro-bottle resonator (MBR) were fabricated by the soft-compress technique. At first, a micro-ball structure was fabricated by placing a single mode fiber (SMF) in a manually controlled fiber fusion splicer (Furukawa Electric Fitel S178A) so that the fiber can be heated through plasma arcing. Through multiple arcing process, a micro-ball structure was formed at the end of edge fiber. On the other hand, a micro-bottle structure was fabricated by clamping a continuous length of SMF on two sides in a manual splicer where a small section is heated under a plasma arc. This high temperature was finely changed the molecule chain of the silica fiber and ready for compress procedure. Simultaneously, the two ends of the two fibres are compressed inward in the direction of the plasma arc, resulting in a bottle-like structure. This softening and-compressing procedure yields increasing pronounced bulge along the fibre with each number of arcs performed [2]. The size of bottle was depending on numbers of arc applied during the process. Fig. 1 shows images of the fabricated micro-ball and micro-bottle structures with 10 times arc. As shown in Fig. 1(a), the diameter of micro-ball, Db was 213 μm with the stem diameter, Ds = 125 μm. The fabricated micro-bottle attains neck-to-neck distance, Lb = 355 µm, bottle diameter, Db = 175 µm and stem diameter, Ds = 125 µm as illustrated in Fig. 1(b).

A microfiber with a waist diameter (W) of 8 µm, a waist length (L1) of 0.1 mm, and a length of the stretching (L2) of 1 mm (see Fig. 2) was fabricated by using a flame-brushing method. This microfiber is used to launch light into the fabricated structure and form a resonator. Fig. 3 shows the image of the MBaR and MBR coupled to a microfiber at the centre position with 1550 nm lasing light launched through the microfiber. We have used a quite thick tapered fiber (8 um waist) for ease of handling. The use of a thinner microfiber may improve the coupling of light to the WGM resonators. The fiber was in physical contact with the resonator.



(a)



(b)

Fig. 1. Images of the fabricated (a) micro-ball (b) micro-bottle structure

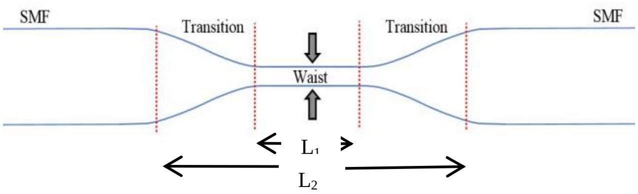
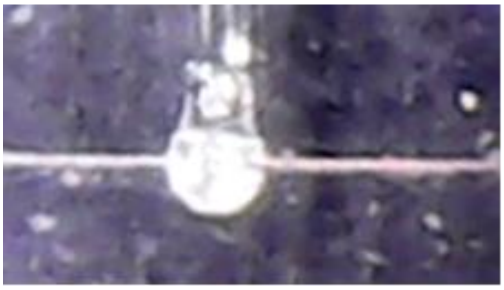
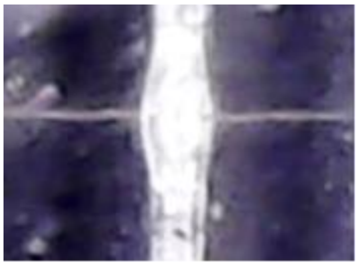


Fig. 2. Illustration of a microfiber structure



(a)



(b)

Fig. 3. Images of the microfiber coupled to the (a) micro-ball (b) micro-bottle

Fig. 4 shows the experimental setup of the relative humidity measurement using a MBaR or MBR as a probe coupled with a microfiber with 8µm waist diameter. The resonator was excited with a laser light from a tunable laser source (TLS) via the microfiber connected to a power meter on the other end, as shown in Fig. 4. Both the sensor probe and the microfiber are placed in a sealed chamber, with the humidity being monitored by a hygrometer (RS 1365). The performance of each configuration was measured independently for 5 times to reduce any random errors. The entire experiment conducted in room temperature 25^{o}C.

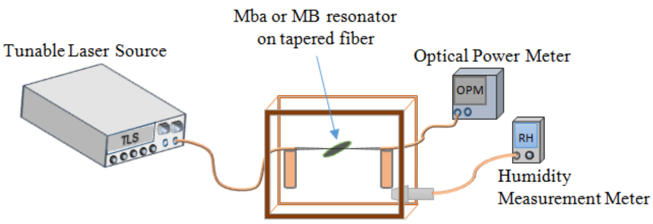
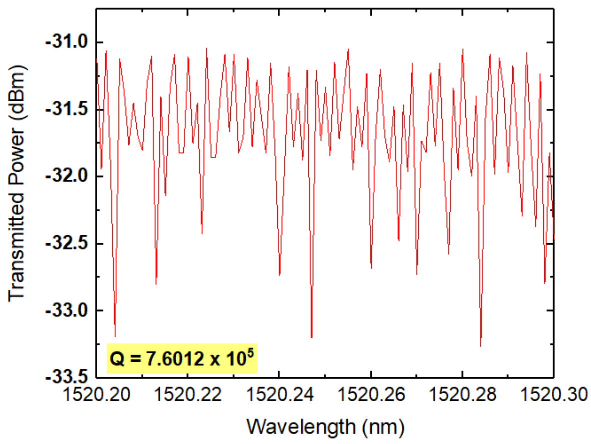


Fig. 4. Experimental setup of the humidity measurement with a 8 µm microfiber coupled to MBaR/MBR probe

3. Result and discussion

The light source in this investigation is a TLS which its operating wavelengths are in the range of 1520 nm to 1620 nm with an average output power of 1dBm. This TLS is launched into the MBaR and MBR via a microfiber with a waist diameter of 8μm. The laser was tuned from 1520.2 nm to 1520.3 nm with wavelength interval 0.001nm and the output is collected by using an optical power meter (THORLABS S145C). Figs. 5(a) and (b) show the transmission spectrum of MBaR and MBR, respectively, where sharp resonant peaks can be clearly observed. The insertion loss for both resonator devices are around 27.5 dB to 33 dB while the Q-factor loss may be optimized by controlling gap between MBaR/MBR and bare microfiber. The Q-factor of the resonator, defined as $\Delta\lambda/\lambda$, where $\Delta\lambda$ is the full width half maximum (FWHM) of the resonant wavelength and λ is resonant of the wavelength, is found to be smaller than other previous works [20-22]. This is thought to be due to the microfiber, which contributes significantly to the insertion loss of the entire resonator ensemble. The Q-factor for MBaR and MBR is approximately 7.6012×10^5 and 7.6013×10^5, respectively. Both Q-factors are almost similar.

The variation of the transmitted light against the relative humidity for both resonators was investigated. In the experiment, the TLS was fixed at 1520.285 nm wavelength. This wavelength was chosen since it provides the highest resonance depth as shown in Fig. 5. The performance of a bare microfiber (without the resonator) as humidity sensor was also investigated for the comparison purpose. The humidity level was varied between 40% and 100%, and the variation of transmitted power of the three devices is shown in Fig. 6 and collated in Table 1. In general, the transmission is reduced with increasing humidity in all three sensor probes. This result is similar to previous work, and is thought to be caused by additional scattering losses due to adsorption of water particles by the microfiber or ball or bottle device which changes in the resonator refractive index. The value sensitivity, linearity, standard deviation and p-value of the MBR are significantly better as compared to the bare micro-fiber and MBaR. For the bare micro-fiber, the sensitivity is obtained at 0.152 dB/%, with a slope linearity of 38.99% and limit of detection of 20.197%. The microfiber coupled with MBaR shows sensitivity of 0.2840 dB/% with a slope linearity of more than 97.80% and a limit of detection of 19.132%, while for MBR produces sensitivity at 0.2973 dB/%, with a slope linearity of more than 99.46% and a limit of detection of 18.3781%. It is found from the results that MBR has much better efficiency regarding humidity sensing than MBaR. This is most probably due to the MBR, which has a larger surface area. The surface interacts with the water molecules to reduce the resonator loss and thus significantly increases the sensitivity of the sensor.



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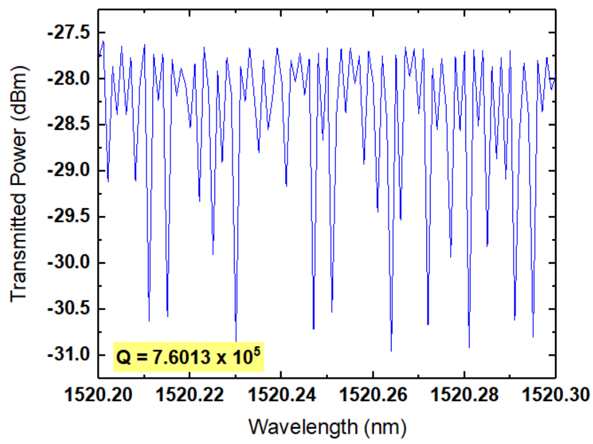


(b)

Fig. 5. Transmission spectrum of (a) micro-ball resonator and (b) micro-bottle resonator

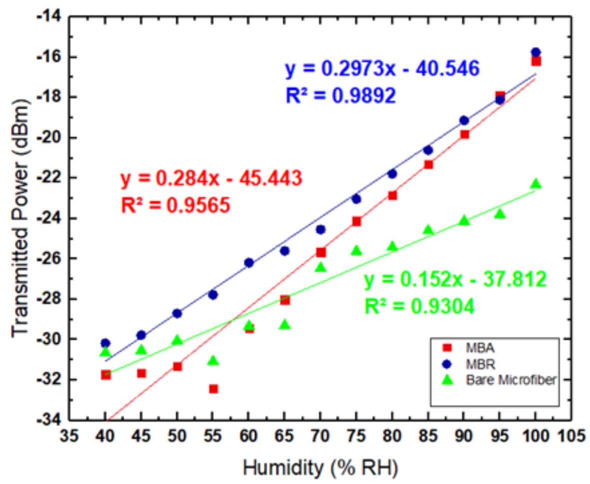
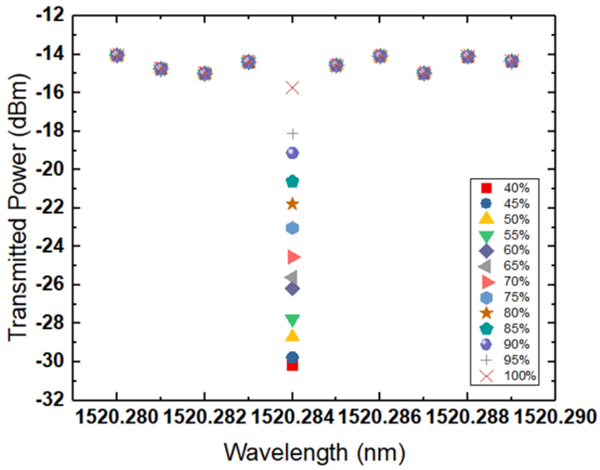


Fig. 6. The RH sensing performances for various probes; bare micro-fiber, MBaR and MBR

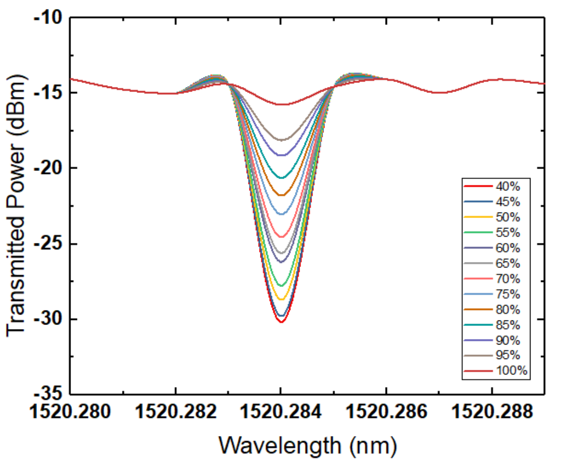
Table 1. Performance of various sensor probes for humidity sensing

Parameters	Bare micro-fiber	MBaR	MBR
Linearity (%)	38.99%	97.80%	99.46%
Sensitivity (dBm/%RH)	0.1520	0.2840	0.2973
Standard deviation (dBm)	3.07	5.433	5.4638
Linear Range Humidity (%)	40-100	40 - 100	40 - 100
Limit of detection	20.197	19.132	18.378

Fig. 7 shows the analysis of the spectra at different RH levels for MBaR based sensor. The actual data was shown in Fig. 7(a). The analysis in Fig. 7(b) was obtained by fitting a Lorentzian curve on the experimental data for clarity. As seen, the resonance wavelength is unshifted with the increase of humidity. However, the resonance broadening was reduced with the increase of humidity. It is also observed that the transmission dip reduced with the increase of humidity. This indicates that the resonator is actually having a role in the detection of water. The existence of water moisture increases the transmission at the resonance wavelength.

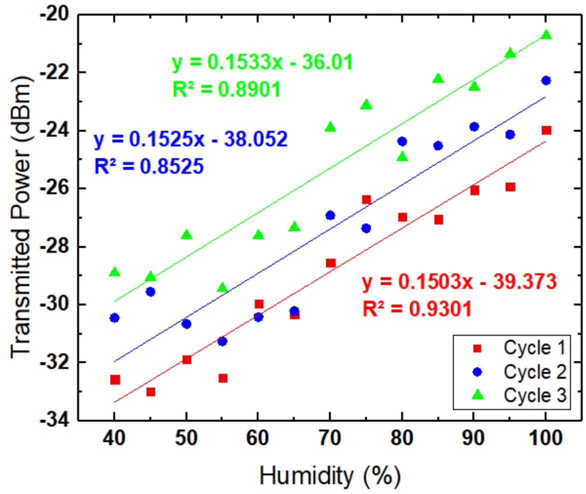


(a)



(b)

Fig. 7. The resonance spectra at different RH for MBaR sensor



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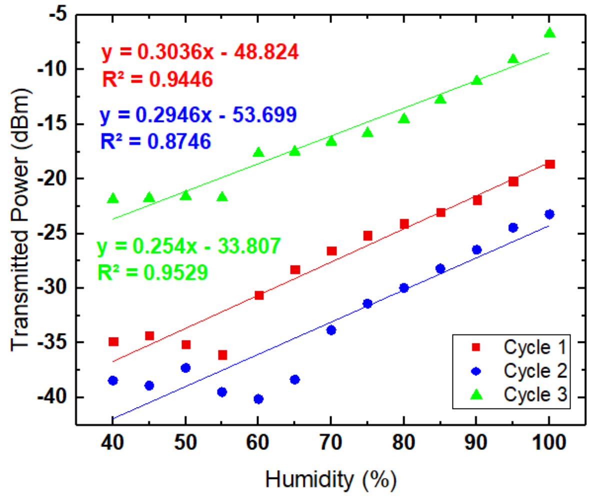

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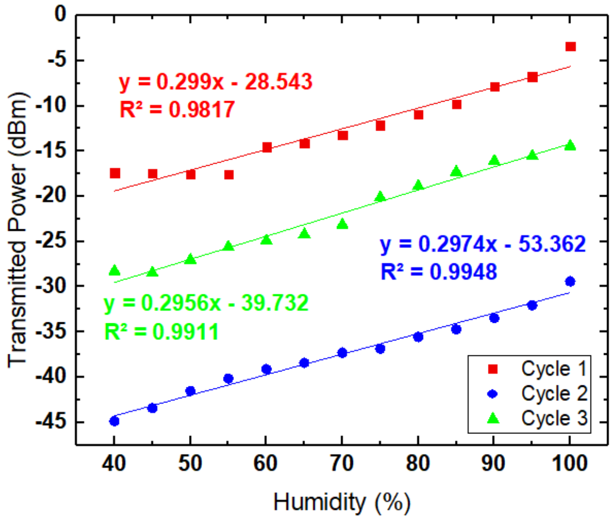

(c)

Fig. 8. Repeatability performance of (a) bare micro-fiber (b) MBaR and (c) MBR

The repeatability of the setup was studied by repeating the experiment three times for both the resonator and bare microfiber [22]. As showed in Fig. 8, the results were consistent for both resonator and bare microfiber, with similar values of sensitivity – more than 0.25 dB/%

for both resonators and less than 0.2dB/% for the baremicrofiber, respectively. The linearity values for MBA and MBR microfiber was also similar, as depicted in Table 1. Therefore, in general, the MBR performed much better as a humidity sensor as compared to the bare microfiber and MBaR. However, each cycle of measurement seems to lose about 10-15 dB in in transmission as shown in Fig. 8(c). This may restrict the application of the sensor. The reversibility of the sensor was also investigated. Fig. 9 shows the hysteresis result for MBR sensor. It was performed by recording data during forward and reverse measurement. It shows a small output difference between forward and reverse results. The temporal characteristic of the sensor should be investigated in future work.

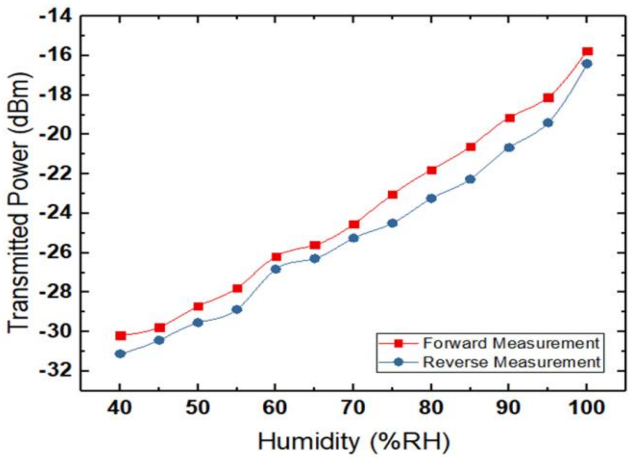

Fig. 9. Hysteresis result for MBR sensor

4. Conclusion

Simple WGM sensors based on micro-ball and micro-bottle resonators were successfully demonstrated for measuring relative humidity. The MBaR and MBR were fabricated via the so-called "soften-and-compress" method to create a ball or bulge structure. The Q-factor for both resonators were observed to be more than 105. The MBaR and MBR were then employed as a humidity sensor by optically exciting by using a 8 μm optical microfiber. It is found that the MBR performed better than MBaR sensor with a sensitivity of 0.2973 dB/%, linearity of more than 99.46% and a limit of detection of 18.3781%.

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