A study of relative humidity sensor on micro-ball resonator

U U M Ali¹, M A M Johari¹, Z Jusoh², H A Rahman³, S W Harun¹

¹ Department of Electrical Engineering, University of Malaya, 50603 Kuala Lumpur, Malaysia.
² Faculty of Electrical Engineering, University Teknologi Mara (Terengganu), 23000 Dungun, Terengganu, Malaysia
³ Faculty of Electrical Engineering, Universiti Teknologi Mara, 40450 Shah Alam, Selangor, Malaysia

umairah.ali@gmail.com

Abstract. We investigate the use of a class of whispering gallery mode optical resonators, namely, optical micro-ball resonator (MBR) as a relative humidity (RH) sensor. The MBR is fabricated using fusion splicer at the tip of standard optical fibers; single-mode fibers (SMF-28). The MBR is then optically excited by using an 8μm optical microfiber and was found to have a Q-factor of >10⁵. The MBR was then employed as a humidity sensor with an RH range of between 40% to 100%. The MBR RH sensor was found to have a sensitivity 0.284 dB/%, linearity >90% and is superior to the bare microfiber in all measured parameters. The MBR RH sensor was also found to have good repeatability and stability compared to bare microfiber.

1. Introduction

Microresonators (MRs) have been widely studied due to their advantage of confining the light with high-quality factor (Q) and in a small volume [1-2]. The MRs have many geometries such as microring, microdisk and microtoroid and this MRs supports whispering gallery mode (WGM) [3-11]. MR operates by creating continuous internal reflection at specific resonant wavelengths.

A WGM MRs is typically associated with circular-path resonant cavities, formed e.g. by micro-ball [12]. The most commonly used WGM microresonators for sensing are micro-ball, due to their straightforward fabrication and very high Q-factors. In micro-ball resonators, WGMs are resonant modes with small mode volumes and high-Q factors. In terms of geometrical optics, a WGM can be represented by an optical ray transmitted exclusively near the microresonator surface due to grazing-angle total internal reflection [13]. This transmission can occur if a light is evanescently coupled into the tapered fiber. A very narrow resonance dip with a full width half maximum (FWHM) on a level of pm appears in the transmission spectrum of the taper due to coupling light into the WGM.

Optical fiber-based relative humidity (RH) sensors have been widely studied due to their advantages such as the feasibility of long-distance sensing, real-time monitoring, and immunity to electromagnetic interference. Various techniques including tapered optical fiber, heterocore optical fiber, and fiber grating have been reported previously [16–20]. In this work, we proposed and experimentally demonstrated a novel differences RH fiber sensor by using a micro-ball resonator (MBR) and bare fiber. Whispering gallery modes (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 resonator also compact in size, fast in response, and low in cost.
2. Experimental set-up
In this paper, we microresonator namely micro-ball resonator (MBR) and this MBR was fabricated at the tip of standard optical fibers; single-mode fibers (SMF-28). A single-mode fibre (SMF) was placed in a manually controlled fibre fusion splicer (Furukawa Electric Fitel S178A) of the fibre was heated through plasma arcing. One of the two clamped-ends compressed the fibre in the direction of the arcing-region. This softening and-compressing procedure yields increasing pronounced bulge along the fibre with each number of arcs performed [2]. Figure 1 shows the fabricated of MBR resonator with 10 times arc. As shown in Figure 1, the diameter of MBR Db=213 μm and stem diameter Ds = 125 μm.

![Figure 1. Fabricated micro-ball resonator](image1)

In these experiments, a taper 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 Figure 2) was fabricated. The insertion losses of this taper were 13 dB for λ =1310 nm (a standard communication wavelength). Figure 3 shows the image of the MBR coupled to a tapered fiber at the centre position with 1550 nm lasing light launched through the tapered fiber.

![Figure 2. Illustration of tapered fiber](image2)

![Figure 3. Tapered fiber coupled at the center of MBR](image3)
3. Results and discussion

The light source in this investigation is a tuneable laser source (TLS) which operating wavelengths in the range of 1520nm to 1620nm with an average output power of 1dBm. This TLS is launched into the tapered fiber 8µm coupled to a micro-ball resonator. The laser was adjusted wavelength between 1520.2 nm to 1520.3 nm with wavelength interval 0.001nm and the transmitted power is collected by using an optical power meter (THORLABS S145C). Figure 4 shows the transmission spectrum for a tapered fiber couple with micro-ball resonator (MBR). The insertion loss for MBR around 27.5dBm to 33 dBm, the Q-factor loss could be effective by varying the position or space in between MBR with bare microfiber. The Q-factor identified by \( \Delta \lambda / \lambda \), whereas \( \Delta \lambda \) is the full width half maximum (FWHM) resonant wavelength and \( \lambda \) is resonant of the wavelength, is discovered to be miniature compared to the previous work [20-22]. The Q-factor for micro-ball resonator is \( 7.6012 \times 10^5 \)dBm. The fact behind this due to the non-adiabaticity microfiber which amenities notably towards the insertion loss of the full micro-resonators ensemble.

![Figure 4](image1.png)

**Figure 4.** Transmitted Power of micro-ball resonator varies with wavelength

Figure 5 shows the experimental setup of the MBR used to detect relative humidity using the tapered fiber 8µm. The setup consists of a TLS, the proposed resonator, RH measurement meter (humidity), and optical power meter (OPM). Both ends of the tapered micro-fiber are connected to the TLS and OPM, respectively. The TLS is launched into the tapered fiber coupled with MBR placed in a sealed chamber with a dish filled with a saturated salt solution.

![Figure 5](image2.png)

**Figure 5.** Experimental setup of micro-ball resonator coupled with tapered fiber 8 µm

Figure 6 shows the variation of the transmitted light against the relative humidity for bare micro-fiber and MBR on the tapered fiber. It is observed that the intensity of the transmitted light through the
bare micro-fiber and MBR on the tapered fiber increases as relative humidity increases from 40% to 100%. The performance characteristics of the bare micro-fiber and MBR are summarized in Table 1. The value sensitivity, linearity, standard deviation and p-value of the MBR are significantly better as compared to the bare micro-fiber. For the bare micro-fiber, the sensitivity is obtained 0.152 dB/%, with slope linearity of 38.99% and limit of detection of 20.197% while the tapered fiber coupled with MBR shows sensitivity 0.2840 dB/% with slope linearity of more than 97.80% and a limit of detection of 19.132%. The outcome of the investigation is that MBR has much better efficiency regarding humidity sensing than bare micro-fiber. One of the cause is surface absorption in transmitted insertion loss of the resonator whereas the losses increasing along with the higher humidity levels. Although losses in the resonator were noticed due to the light circulation inside the resonators, power loss with each pathway of the circle thus significantly increased the sensitivity.

![Graph](image)

**Figure 6.** Performances of bare micro-fiber and MBR for the different humidity level

The repeatability of the setup was studied by repeating the experiment three times for MBR and bare microfiber [22]. As showed in Figure 7, the results were consistent for MBR and bare microfiber, with similar values of sensitivity – more than 0.25 dB/% for MBR and less than 0.2dB/% for the bare microfiber, respectively. The linearity values for MBR microfiber was 97.8%, as depicted in Table 1. Therefore, in general, the MBR performed much better as a humidity sensor as compared to the bare microfiber.
Table 1. Performance of the resonator in humidity sensing activity.

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

Figure 7. Repeatability performance of (a) bare micro-fiber and (b) MBR varies with a humidity level

4. Conclusion

We have investigated the use of a class of whispering gallery mode optical resonators, namely, optical micro-ball resonator (MBR) as a relative humidity (RH) sensor. The MBR was employed as a humidity sensor with an RH range of between 40% to 100%. The MBR RH sensor was observed to have a sensitivity of 0.284 dB/%, linearity >90% and showed relatively good repeatability and stability.

References

[1] Chiasera, A., et al., Spherical whispering-gallery-mode microresonators. Laser & Photonics Reviews, 2010. 4(3): p. 457-482.
[2] Murugan, G.S., J.S. Wilkinson, and M.N. Zervas, Selective excitation of whispering gallery-modes in a novel bottle microresonators. Optica express, 2009. 17(14): p. 11916-11925.
[3] Little, B.E., et al., Microring resonator channel dropping filters. Journal of lightwave technology, 1997. 15(6): p. 998-1005.
[4] Absil, P.P., Microring resonators for wavelength division multiplexing and integrated photonics applications. 2000.
[5] Kokubun, Y., Wavelength selective integrated device by vertically coupled microring resonator filter. Photonics Based on Wavelength Integration and Manipulation IPAP Books, 2005. 2: p.
303-316.

[6] Armani, D., et al., Ultra-high-$Q$ toroid microcavity on a chip. Nature, 2003. 421(6926): p. 925.

[7] Armani, D., et al., Electrical thermo-optic tuning of ultrahigh-$Q$ microtoroid resonators. Applied physics letters, 2004. 85(22): p. 5439-5441.

[8] Gérard, J., et al., Enhanced spontaneous emission by quantum boxes in a monolithic optical microcavity. Physical review letters, 1998. 81(5): p. 1110.

[9] Sarma, J. and K. Shore, Electromagnetic theory for optical disc resonators. IEE Proceedings J (Optoelectronics), 1985. 132(6): p. 325-330.

[10] Srinivasan, K., et al., Experimental demonstration of a high quality factor photonic crystal microcavity. Applied Physics Letters, 2003. 83(10): p. 1915-1917.

[11] Lee, P.-T., et al., Investigation of whispering gallery mode dependence on cavity geometry of quasiperiodic photonic crystal microcavity lasers. Applied physics letters, 2006. 89(23): p. 231111.

[12] Marcatili, E.A.J., “Bends in optical dielectric waveguides”, Bell System Techn. J. 48, 2103-2132 (1969).

[13] Braginsky, V.B., Gorodetsky, M.L., and Ilchenko, V.S., “Quality-factor and nonlinear properties of optical whispering-gallery modes”, Phys. Lett. A 137, 393-396 (1989).

[14] Lee, P.-T., et al., High quality-factor microcavity lasers realized by circular photonic crystal with isotropic photonic band gap effect. Applied physics letters, 2007. 90(15): p. 151125.

[15] Bianucci, P., Optical microbottle resonators for sensing. Sensors, 2016. 16(11): p. 1841.

[16] X. Wang, J. Zhang, Z. Zhu, J. Zhu, Humidity sensing properties of Pd2+ doped ZnO nanotetrapods, Appl. Surf. Sci. 253 (2007) 3168.

[17] L. Zhang, F. Gu, J. Lou, X. Yin, and L. Tong, “Fast detection of humidity with a subwavelength-diameter fiber taper coated with gelatin film,” Optics Express, vol. 16, no. 17, pp. 13349–13353, 2008.

[18] X. Dong, T. Li, Y. Liu, Y. Li, C. Zhao, and C. Chan, “Polyvinyl alcohol-coated hybrid fiber grating for relative humidity sensing,” Journal of Biomedical Optics, vol. 16, no. 7, Article ID 077001, 2011.

[19] Q. Wu, Y. Semenova, J. Mathew, P. Wang, and G. Farrell, “Humidity sensor based on a single-mode hetero-core fiber structure,” Optics Letters, vol. 36, no. 10, pp. 1752–1754, 2011.

[20] T. Li, X. Dong, C. Chan, C. Zhao, and P. Zu, “Humidity sensor based on a multimode-fiber taper coated with polyvinyl alcohol interacting with a fiber bragg grating,” IEEE Sensors Journal, vol.12, no. 6, pp.2205–2208, 2012.

[21] Murugan, G.S., et al., Hollow-bottle optical microresonators. Optics express, 2011. 19(21): p. 20773-20784.

[22] Isa, N.M., et al., Polyaniline Doped Poly (Methyl Methacrylate) Microfiber for Methanol Sensing. IEEE Sensors Journal, 2018.