Optik - International Journal for Light and Electron Optics 185 (2019) 558–565

Contents lists available at ScienceDirect

Optik

journal homepage: www.elsevier.com/locate/ijleo

Original research article

Whispering gallery modes on optical micro-bottle resonator for humidity sensor application

Md Ashadi Md Johari[a,b,*], Muhammad Imran Mustafa Abdul Khudus[c], Mohd Hafiz Bin Jali[a,d], Abdullah Al Noman[a], Sulaiman Wadi Harun[a]

[a] *Department of Electrical Engineering, Faculty of Engineering, University of Malaya, 50603 Kuala Lumpur, Malaysia*
[b] *Faculty of Engineering Technology, Universiti Teknikal Malaysia Melaka, 76100 Melaka, Malaysia*
[c] *Department of Physics, Faculty of Science, University of Malaya, 50603 Kuala Lumpur, Malaysia*
[d] *Faculty of Electrical Engineering, Universiti Teknikal Malaysia Melaka, 76100 Melaka, Malaysia*

ARTICLE INFO

Keywords:
Microfiber optic
Optical Micro-resonator
Humidity sensor

ABSTRACT

We investigate the use of a class of whispering gallery mode optical resonators, namely, optical microbottle resonators (MBR) as a relative humidity (RH) sensor. The MBR is fabricated via the so-called "soften-and-compress" method to create a bulge (bottle) structure with a bottle diameter D_b = 190μm, stem diameter of D_s = 125μm and bottle length of L_b = 182μm. The MBR is then optically excited by using a 2 μm optical microfiber and was found to have a Q-factor of > 10^4. The MBR was then employed as a humidity sensor with a RH range of between 40%–80% and the performance is compared with a no-MBR microfiber. The MBR RH sensor was found to have a sensitivity 0.0487 dB/%, linearity > 90% and P-value > 10^5 and is superior to the no-MBR microfiber in all measured parameters. The MBR RH sensor was also found to have good repeatability and stability over a period of 60 s. The wavelength shifted for the MBR is 0.03 nm greater than no-MBR.

1. Introduction

Optical microresonator (OMRs) has been garnered significant interest recently due to its wide potential applications in optical sensors, lasers and plasmonic devices [1–5]. OMRs operate by creating continuous internal reflection at specific resonant wavelengths and has been realized in several structure such microdisks, miropillars, microrings and photonic-crystal cavities [6–14]. 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 [15,16]. Lord Rayleigh was the first to discover whispering gallery resonance phenomenon in the dome of the St. Paul's cathedral in London [17]. He observed that sounds could be hear at specific points along the circumference of the dome length, indicating that the sound waves form so-called whispering gallery modes within the dome structure. The same concept of the sound reflection along the cathedral dome may be translated in the optical domain by OMRs the similar geometries, thus exhibiting similar resonance features for whispering gallery mode.

One subclass of WGM resonators, the microbottle resonator (MBRs), has recently been shown to have one of the highest Q factors and FSR for silica based resonators [16,18]. These advantages make them ideal for silica-based sensors. WGM resonators have been employed successfully in a variety of sensing environments and has the advantage of being unperturbed by high external electromagnetic fields [19,20]. Indeed, the WGM optical sensors exhibited high sensitivity, high accuracy and speed with minimal optical

* Corresponding author at: Department of Electrical Engineering, Faculty of Engineering, University of Malaya, 50603 Kuala Lumpur, Malaysia.
E-mail address: johariashadi@gmail.com (M.A. Md Johari).

https://doi.org/10.1016/j.ijleo.2019.03.111
Received 1 January 2019; Received in revised form 19 March 2019; Accepted 19 March 2019
0030-4026/

Table 1
List of reported research using optical micro resonators for humidity sensing.

No.	Title	Main Author	Publish Date	Type of Optical Resonator	Sensitivity
1	Integrated humidity sensor based on su-8 polymer microdisk microresonator	M. Ery¨urek	2017	Microdisk	108 pm/% RH
2	PMMA Solid bottle optical microresonator for measure relative humidity	D A Avila	2017	PMMA	0.032 nm /% RH
3	Sensitivity of a PMMA polymer capillary microresonator for measuring relative humidity	D A Avila	2017	Capillary micro resonator	0.07 nm/% RH
4	Relative Humidity Sensor Based on a Few-mode Microfiber Knot Resonator by Mitigating the Group Index Difference of a Few-Mode Microfiber	Anh Duy Duong Le	2017	Knot Resonator	1.53 nm/%.
5	A high-sensitivity optical fiber relative humidity sensor based on microsphere WGM resonator	Lei Liang	2017	Microsphere	0.11 dB/%RH
6	Agarose coated spherical micro resonator for humidity measurements	Arun Kumar Mallik	2016	Microsphere	518 pm/%RH

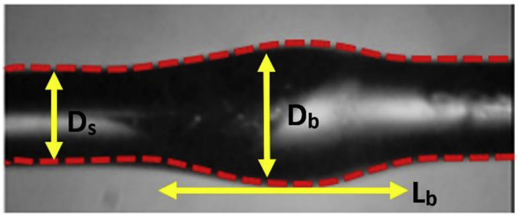


Fig. 1. Optical MBR fabricated with $L_b = 182\ \mu$m, $D_b = 190\ \mu$m and $D_s = 125\ \mu$m.

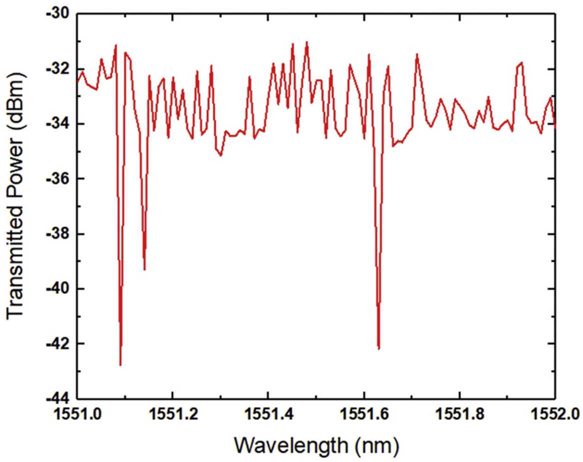


Fig. 2. MBR WGM transmission modes of micro-bottle resonator coupled on micro-tapered fiber 2 µm diameter.

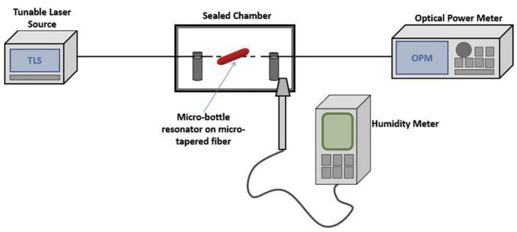


Fig. 3. Micro-bottle resonator attached on micro-tapered fiber 2 µm diameter.

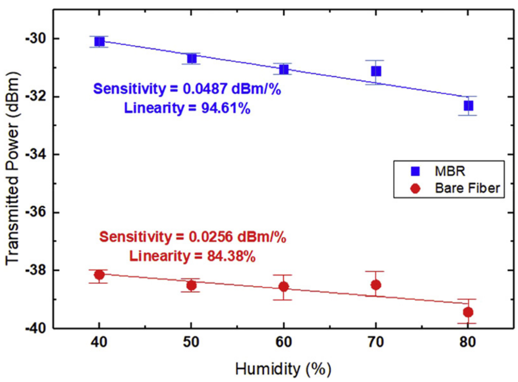


Fig. 4. Transmitted power value for MBR and no-MBR microfiber varies with percentage of humidity.

loses [21].

This paper studies the performance of MBR based humidity sensors. Several research papers on humidity sensing with OMRs are given in Table 1 [22–27]. In this work, the performance between the MBR with no-MBR humidity sensor is compared. The MBR was fabricated by the so-called “soften-and-compress” technique from a standard SMF28. The MBR is first characterized by using a 2 μm

Table 2
Analysis of MBR and no-MBR microfiber performance in humidity sensing activity.

Parameters	No-MBR	With MBR
Linearity (%)	84.38%	94.61%
Sensitivity (dB/%RH)	0.0256	0.0487
Standard deviation (dBm)	0.2972	0.3044
P-value	8.40×10^{-6}	2.07×10^{-5}
Linear Range (% RH)	40 - 80	40 - 80

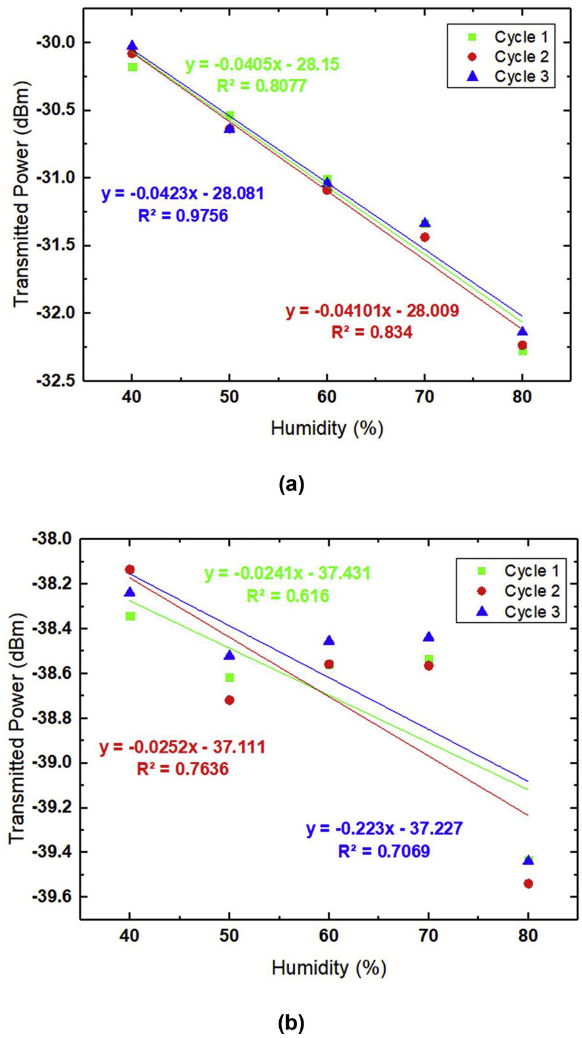


Fig. 5. Repeatability performance of (a) MBR and (b) no-MBR microfiber varies with humidity level.

microfibre before the being employed for a humidity range of 40–80%, and then compared with no-MBR microfiber for sensing performance. [28,29].

2. Experimental setup

The WGM employed in this work was fabricated from a standard SFM-28 by using the so-called “softened-and-compress” method [30]. A continuous length of SMF-28 fiber is manually clamped in a manual splicing machine (Furukawa Electric Fitel S178A) before being heated with an electrical arc and compressed inwards from both ends of the fiber. This creates a bulge in the centre of the fibre, with the size being determined by the number of arcs employed [18]. The resulting MBR structure is then physically characterized by three parameters, namely, the bottle diameter D_b, the stem diameter D_s and the neck-to-neck length L_b, as show in Fig. 1. In this work, D_b was set at $190\,\mu m$, similar to previous works [18]. A biconical optical microfibre with a waist diameter of $2\,\mu m$, fabricated by the

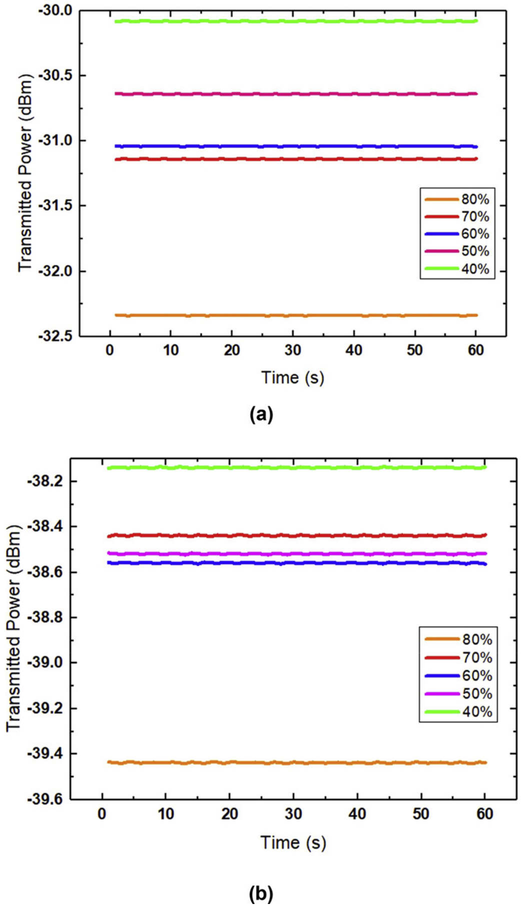


Fig. 6. Stability performance of (a) MBR and (b) no-MBR microfiber varies with time.

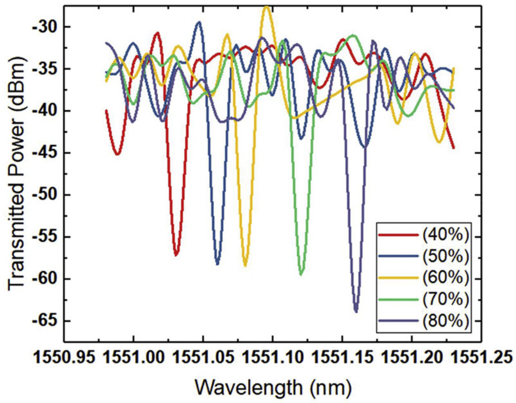
flame brushing method, is employed to optically excite the MBR [31].

The MBR was first characterized by using a tuneable laser source (ANDO AQ4321D) with a wavelength range between 1520 nm and 1620 nm, launched into the MBR via a microfiber with a taper waist of $2\,\mu m$. The laser was tuned from 1551 nm to 1559 nm with a wavelength interval of 0.001 nm and the output is collected by using an optical power meter (THORLABS S145C). The transmission spectral of the MBR is shown in Fig. 2, where sharp resonant peaks can be clearly observed [32]. The insertion loss from both the microfiber and MBR is approximately -30 dBm and is similar when different MBRs of the same size is employed, and may be optimized by controlling gap between MBR and microfiber [33]. The Q-factor of the MBR, defined as $\Delta\lambda/\lambda$ where λ is the resonant wavelength, is found to be 5.4359×10^4 which is smaller than other previous work [34]. This is thought to be due to the microfiber, which contributes significantly to the insertion loss of the entire microbottle ensemble.

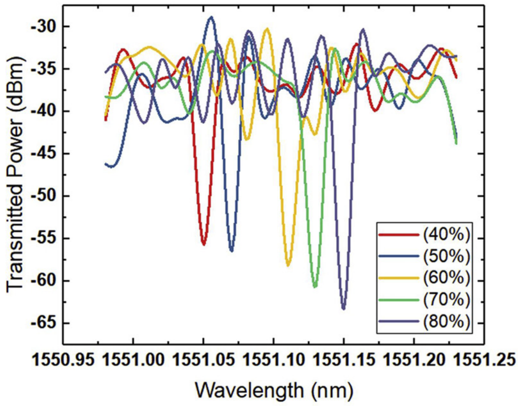
The performance of the MBR and microfiber humidity sensors were then investigated by employing the setup shown in Fig. 3. The MBR and the microfiber are placed inside a sealed chamber, with the humidity monitored by a hygrometer (RS 1365) at ambient room temperature of 25 °C at atmospheric pressure 1.0 atm. One end of the microfiber is connected to the tuneable laser source, with the other end connected to an OPM to measure the transmitted power. The humidity was then varied from 40% to 80% using silica gel. First, the wavelength was set at 1551.1 nm and the transmission of the MBR at different humidity levels are recorded. The experiment was carried out three times to reduce random errors and to investigate the repeatability of the humidity sensor. The MBR was then removed and the humidity sensing performance of a no-MBR microfiber was investigated as a comparison. The stability of the sensor was also studied by recording the transmission at different humidity levels for a period of 60 s.

3. Performance of MBR and No-MBR microfiber as humidity sensing

The averaged transmission of the MBR and the no-MBR microfiber at different humidity levels is shown in Fig. 4. Overall, the transmission decreases with increasing levels of humidity for both MBR and no-MBR microfiber. However, the sensitivity, linearity, standard deviation and p-value of the MBR is significantly better as compared to the no-MBR microfiber, as recorded in Table 2. Indeed, the sensitivity of the MBR is almost two times greater (0.0487 dB/% as compared to 0.0256 dB/%) with the linearity being almost 10% higher, though the errors in the microfiber is slightly lower, as evidenced in Fig. 4. These results indicate that the MBR



(a)



(b)

Fig. 7. Wavelength shift of (a) MBR and (b) no-MBR microfiber on every humidity level.

humidity sensor significantly outperforms the no-MBR microfiber as a humidity sensor. This may be explained by the fact that there is a higher degree of surface adsorption results on the MBR humidity sensor. This adsorption induced loss is magnified as the light circulates multiple times in the MBR, reducing the power with each round trip, thus significantly increasing the sensitivity [35,36].

The repeatability of the setup was studied by repeating the experiment three times for both the MBR and no-MBR microfiber [37]. As showed in Fig. 5, the results were consistent for both MBR and no-MBR microfiber, with similar values of sensitivity – more than 0.04 dB/% for the MBR and less than 0.03 dB/% for the no-MBR microfiber, respectively. The linearity values for both MBR and no-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 no-MBR microfiber.

Fig. 6 **(a)** and **(b)** showed stability of the MBR and no-MBR microfiber humidity sensor over a period of 60 s. Both the MBR and no-MBR microfiber is remarkably stable over the 60 s interval. The variation in the transmission is less than 0.5% and in the MBR, is only noticeable at humidities exceeding 60%. As adsorption effects are relatively fast, this result indicate that the sensor is very stable over the investigated humidity levels [37].

Experiment continue by defined the wavelength shift for every humidity level. Each of humidity percentage were performed different wavelength based on previous research done recently [38]. Fig. 7 showed the different wavelength shift between the MBR **(a)** and no-MBR **(b)** used in the experiment. The MBR showed batter wavelength shifted than no-MBR where it shifted from 1551.03 nm until 1551.16 nm, with 0.13 nm shifted in between. While no-MBR setup managed to have 0.1 nm shifted where the wave moved from 1551.05 nm to 1551.15 nm. This is another simple proved the ability showed by the MBR for humidity sensing is grater performed than no-MBR.

4. Conclusions

This paper studied the performance of MBR and no-MBR microfiber as humidity sensor. The MBR is fabricated by the "soften-and-compress" method, creating a 'bottle' shape with a bottle diameter of $D_b = 190\mu m$, stem diameter of $D_s = 125\mu m$ and bottle length of $L_b = 182\mu m$. The fabricated MBR is then optically excited by a TLS via a $2\mu m$ optical microfiber and characterized by sweeping the TLS wavelength from 1551 nm to 1552 nm with a step of 0.001 nm. The MBR was found to have a Q-factor of 5.4359×10^4. This is significantly similar to previous work and is thought to be due to the losses from the microfiber. The performance of the MBR as a humidity sensor is then evaluated and compared with a no-MBR microfiber. The linearity, sensitivity, standard deviation and P-value were calculated, and the MBR was found to be superior to the no-MBR microfiber for each parameter. The high p-value ($> 10^{-5}$) indicate that measurements were done correctly. To increase accuracy in data collection, the MBR and no-MBR microfiber undergoing three-time repetition and 60 s stability test for each of humidity level. The wavelength shifted showed by the MBR is higher 0.03 nm than no-MBR, where is showed that the MBR performance is better than no-MBR.

Acknowledgements

The authors would like to acknowledge University of Malaya, Faculty of Engineering Technology, Fakulti Teknologi Kejuruteraan Elektrik dan Elektronik, Universiti Teknikal Malaysia Melaka and Ministry of Education, Malaysia and the University of Malaya for their financial support. [Grant No: BK084-2017 and RF018B-2018]

References

[1] A. Chiasera, et al., Spherical whispering-gallery-mode microresonators, Laser Photon. Rev. 4 (3) (2010) 457–482.
[2] A. Matsko, et al., Review of applications of whispering-gallery mode resonators in photonics and nonlinear optics, IPN Progress Report 42 (162) (2005) 1–51.
[3] P. Berini, Long-range surface plasmon polaritons, Adv. Opt. Photonics 1 (3) (2009) 484–588.
[4] P. Berini, R. Charbonneau, N. Lahoud, Long-range surface plasmons on ultrathin membranes, Nano Lett. 7 (5) (2007) 1376–1380.
[5] V. Bykov, O. Silichev, Laser Resonators, Cambridge Intl, Science Publ, 1995.
[6] B.E. Little, et al., Microring resonator channel dropping filters, J. Light. Technol. 15 (6) (1997) 998–1005.
[7] P.P. Absil, Microring Resonators for Wavelength Division Multiplexing and Integrated Photonics Applications, (2000).
[8] Y. Kokubun, Wavelength selective integrated device by vertically coupled microring resonator filter, Photonics Based on Wavelength Integration and Manipulation IPAP Books 2 (2005), pp. 303–316.
[9] D. Armani, et al., Ultra-high-Q toroid microcavity on a chip, Nature 421 (6926) (2003) 925.
[10] D. Armani, et al., Electrical thermo-optic tuning of ultrahigh-Q microtoroid resonators, Appl. Phys. Lett. 85 (22) (2004) 5439–5441.
[11] J. Gérard, et al., Enhanced spontaneous emission by quantum boxes in a monolithic optical microcavity, Phys. Rev. Lett. 81 (5) (1998) 1110.
[12] J. Sarma, K. Shore, Electromagnetic theory for optical disc resonators, Iee Proc. J Optoelectron. 132 (6) (1985) 325–330.
[13] K. Srinivasan, et al., Experimental demonstration of a high quality factor photonic crystal microcavity, Appl. Phys. Lett. 83 (10) (2003) 1915–1917.
[14] P.-T. Lee, et al., Investigation of whispering gallery mode dependence on cavity geometry of quasiperiodic photonic crystal microcavity lasers, Appl. Phys. Lett. 89 (23) (2006) 231111.
[15] P.-T. Lee, et al., High quality factor microcavity lasers realized by circular photonic crystal with isotropic photonic band gap effect, Appl. Phys. Lett. 90 (15) (2007) 151125.
[16] P. Bianucci, Optical microbottle resonators for sensing, Sensors 16 (11) (2016) 1841.
[17] L. Rayleigh, CXII. The problem of the whispering gallery, The London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science 20 (120) (1910) 1001–1004.
[18] G.S. Murugan, J.S. Wilkinson, M.N. Zervas, Selective excitation of whispering gallery modes in a novel bottle microresonator, Opt. Express 17 (14) (2009) 11916–11925.
[19] M. Johari, et al., Microbottle resonator for formaldehyde liquid sensing, Optik 173 (2018) 180–184.
[20] M.H. Jali, et al., Applied microfiber evanescent wave on ZnO nanorods coated glass surface towards temperature sensing, Sens. Actuators A Phys. 277 (2018) 103–111.
[21] A.B. Matsko, V.S. Ilchenko, Optical resonators with whispering gallery modes I: basics, IEEE J. Sel. Top. Quantum Electron. 12 (3) (2006) 3.
[22] M. Eryürek, et al., Integrated humidity sensor based on SU-8 polymer microdisk microresonator, Sens. Actuators B Chem. 242 (2017) 1115–1120.
[23] D. Avila, S. Horta, C. Torres, PMMA Solid bottle optical microresonator for measure relative humidity, J. Phys. Conf. Ser. (2017) IOP Publishing.
[24] D.A. Padilla, C.T. Moreno, C.M. Cordeiro, Sensitivity of a PMMA polymer capillary microresonator for measuring relative humidity, J. Phys. Conf. Ser. (2017) IOP Publishing.
[25] A.D.D. Le, Y.-G. Han, Relative humidity sensor based on a few-mode microfiber knot resonator by mitigating the group index difference of a few-mode microfiber, J. Light. Technol. 36 (4) (2018) 904–909.
[26] L. Liang, et al., A high-sensitivity optical fiber relative humidity sensor based on microsphere WGM resonator, Opt. Fiber Technol. 45 (2018) 415–418.
[27] A.K. Mallik, et al., Agarose coated spherical micro resonator for humidity measurements, Opt. Express 24 (19) (2016) 21216–21227.
[28] P. Kronenberg, et al., Relative humidity sensor with optical fiber Bragg gratings, Opt. Lett. 27 (16) (2002) 1385–1387.
[29] L. Xu, et al., Optical fiber humidity sensor based on evanescent-wave scattering, Opt. Lett. 29 (11) (2004) 1191–1193.
[30] G.S. Murugan, et al., Hollow-bottle optical microresonators, Opt. Express 19 (21) (2011) 20773–20784.
[31] K. Lim, et al., Fabrication and applications of microfiber, Selected Topics on Optical Fiber Technology (2012) InTech.
[32] M.N.M. Nasir, G.S. Murugan, M.N. Zervas, Broadly tunable solid microbottle resonator, Photonics Conference (IPC) (2016).
[33] M. Cai, O. Painter, K.J. Vahala, Observation of critical coupling in a fiber taper to a silica-microsphere whispering-gallery mode system, Phys. Rev. Lett. 85 (1) (2000) 74.
[34] M.N.M. Nasir, G.S. Murugan, M.N. Zervas, Spectral cleaning and output modal transformations in whispering-gallery-mode microresonators, Josai Shika Daigaku Kiyo 33 (9) (2016) 1963–1970.
[35] F.J. Arregui, et al., Optical fiber humidity sensor using a nano Fabry–Perot cavity formed by the ionic self-assembly method, Sens. Actuators B Chem. 59 (1) (1999) 54–59.
[36] M. Batumalay, et al., A study of relative humidity fiber-optic sensors, IEEE Sens. J. 15 (3) (2015) 1945–1950.
[37] N.M. Isa, et al., Polyaniline doped poly (Methyl methacrylate) microfiber for methanol sensing, IEEE Sens. J. (2018).
[38] N. Isa, et al., Multi-walled carbon nanotubes doped Poly (Methyl MethAcrylate) microfiber for relative humidity sensing, Sens. Actuators A Phys. 272 (2018) 274–280.

Md Ashadi bin Md Johari received degree in electronic engineering (Industry) from Universiti Teknikal Malaysia Melaka, Malaysia, in 2006. Master Degree in Telecommunication Engineering from University Malaya, Malaysia, in 2011.Worked as an QA Engineer at NCMC Malaysia from 2006 until 2009 and as Test Engineer at AEX System from 2009 until 2011. From 2011 end of year, work as lecturer at Universiti Teknikal Malaysia Melaka. Currently a PhD student in photonic research under Nanotechnology and Sensor Laboratory at Faculty of Engineering, University Malaya.

Muhammad Imran Mustafa Abdul Khudus received his B.Sc degree in Physics from Imperial College London in 2010, and his M.Sc. in Physics from University College London in 2011. He then completed his PhD in Optoelectronics from the Optoelectronics Research Centre, University of Southampton in 2016. Since 2017, he has been a Senior Lecturer at the Department of Physics, University of Malaya. His current research interests include nonlinear optics as well as the development of various optical fiber devices including fiber amplifiers, fiber lasers, and fiber-optic sensors.

Mohd Hafiz Jali received the B.Sc. degree in electrical and electronic engineering with first class honours from MARA University of Technology (UiTM), Malaysia in 2007 and completed his Master engineering studies with distinction in Industrial Electronics and Control at University of Malaya (UM), Malaysia. He was with the automotive company, Proton Sdn. Bhd from 2007 to 2010 as a Test Engineer under the Complete Vehicle Testing (CVT) department. In 2012, he was appointed as a Lecturer at Universiti Teknikal Malaysia Melaka (UTeM), Malaysia. He is currently a PhD student in photonic research under Nanotechnology and Sensor Laboratory at Faculty of Engineering, University Malaya.

Mr. Abdullah Al Noman received his Bachelors of Science & Engineering degree in Computer Engineering from Independent University, Bangladesh in 2016. During his undergraduate, he worked as teacher assistant on the microprocessor and digital logic gate. Currently, he is doing his Master of Telecommunications degree at the University of Malaya. Besides his study, he is working in the field of optical sensors in Department of Electrical Engineering, UM.

Sulaiman Wadi Harun received his B.Eng degree in Electrical and Electronics System Engineering from Nagaoka University of Technology, Japan in 1996, and M.Sc. and pH.D degrees in Photonics from University of Malaya in 2001 and 2004, respectively. Currently, he is a full professor at the Faculty of Engineering, University of Malaya. His research interests include fiber optic active and passive devices.