WHISPERING GALLERY MODE OF COATED MICRO-BOTTLE RESONATOR USING ACRYLATE POLYMER FOR HUMIDITY SENSING

MEISAM PARSA POUR

FACULTY OF ENGINEERING
UNIVERSITY OF MALAYA
KUALA LUMPUR

2018

WHISPERING GALLERY MODE OF COATED MICRO-BOTTLE RESONATOR USING ACRYLATE POLYMER FOR HUMIDITY SENSING

MEISAM PARSA POUR

RESEARCH REPORT SUBMITTED IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF TELECOMMUNICATION ENGINEERING

FACULTY OF ENGINEERING
UNIVERSITY OF MALAYA
KUALA LUMPUR

2018

UNIVERSITY OF MALAYA

ORIGINAL LITERARY WORK DECLARATION

Name of Candidate: Meisam Parsa Pour

Matric No: KQH 160012

Name of Degree: Master of Telecommunication Engineering

Title of Research Report: Whispering gallery mode of coated micro-bottle resonator using acrylate polymer for humidity sensing

Field of Study: Optical Fiber Sensor

I do solemnly and sincerely declare that:

(1) I am the sole author/writer of this Work;
(2) This Work is original;
(3) Any use of any work in which copyright exists was done by way of fair dealing and for permitted purposes and any excerpt or extract from, or reference to or reproduction of any copyright work has been disclosed expressly and sufficiently and the title of the Work and its authorship have been acknowledged in this Work;
(4) I do not have any actual knowledge nor do I ought reasonably to know that the making of this work constitutes an infringement of any copyright work;
(5) I hereby assign all and every rights in the copyright to this Work to the University of Malaya ("UM"), who henceforth shall be owner of the copyright in this Work and that any reproduction or use in any form or by any means whatsoever is prohibited without the written consent of UM having been first had and obtained;
(6) I am fully aware that if in the course of making this Work I have infringed any copyright whether intentionally or otherwise, I may be subject to legal action or any other action as may be determined by UM.

Candidate's Signature Date:

Subscribed and solemnly declared before,

Witness's Signature Date:

Name:

Designation:

ABSTRACT

In recent years, Micro-Bottle Resonator (MBR) has attracted an excessive attention on account of its various applications such as sensors, lasing and filters. Compared to the other Optical Micro-Resonators (OMRs) it has some advantages of fast tunability through the strain application, better control over the coupling by optical tapered microfiber and in the spectrum the probability of attaining a great number of equally-spaced modes. The MBR was fabricated with an SMF-28 silica optical fiber by “soften-and-compress” method which created a bulge area on the fiber to become formed as bottle shape. In this research report used two method of MBR. First method: we have successfully studied the comparison of three the different size of tapered microfiber through Micro Bottle Resonator (MBR) for humidity sensing. A “soften-and-compress” technique has used to form the MBR with midriff 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 experiment conducted in the sealed chamber with humidity range is controlled from 40% to 95% RH for each different tapered microfiber. The performance of sensor analysed from toward different diameter of taper microfiber with the MBR coupled for diverse humidity level. Firstly, the size of MBR was 2µm by tapered then is followed with 4µm and 8µm tapered. The Q-factor succeeds to have around 10^4 for all size of tapered microfibers of MBRs. However, the size of 2µm MBR is finally found successful in most of the parameters. The p-value for all size of diameter tapered microfiber were $> 10^{-5}$, which is consider data collected in correct way. At the end, the results showed the best data collection by 2 µm tapered microfiber while coupled with the MBR managed to have higher in sensitivity, linearity and standard deviation value, compare with other sizes of tapered microfiber. Second method: An investigation has studied the comparison of the different coated optical micro-bottle resonator for humidity sensing. The MBR characteristic is firstly defined by employing a 2µm tapered bare fiber before being suppressed to humidity range of 40% - 95% with two different coated MBR. The MBR firstly coated with PMMA (Poly Methyl Methacrylate) then is followed with PVA (polyvinyl-alcohol) coating, which is purposely used for sensing characteristic. The Q-factor for the non-coated MBR is 1.451×10^5 which is higher than both the MBR-PMMA coated with values of 3.881×10^4 and the MBR-PVA coated of 2.534×10^4. However, the MBR-PVA coated is finally found successful in most of the parameters. The p-value which is $> 10^{-5}$ for all MBRs is ensuring that these data have been collected correctly and eventually, the MBRs are undergoing a 60-second stability test with a specific 65% RH humidity level. Truley, this indicates that the PVA coated MBR performed better than both non-coated MBR and the PMMA coated MBR as a humidity sensor.

Keywords: Whispering gallery mode (WGM), optical micro-bottle resonator, PMMA, PVA, humidity sensing.

ABSTRAK

Sejak akhir-akhir ini, Resonator Botol Mikro (MBR) telah menarik perhatian dalam pelbagai aplikasi seperti penderia, pelaras dan penapis. Berbanding dengan Resonator Mikro (OMRs) yang lain, ia mempunyai beberapa kelebihan melalui aplikasi terikan, kawalan yang lebih baik terhadap gandingan oleh microfiber optik dan berada dalam spektrum yag boleh mencapai sejumlah besar mod bersamaan. MBR dibuat dengan serat optik silika SMF-28 dengan menggunakan kaedah "lembutan-dan-kompres" yang membentuk kawasan bonjol pada serat untuk dibentuk sebagai bentuk botol. Dalam laporan penyelidikan ini, terdapat dua kaedah MBR. Kaedah pertama: kami telah berjaya mengkaji perbandingan tiga saiz microfiber tirus yang berbeza melalui Resonator Botol Mikro (MBR) untuk mengesan kelembapan. Teknik "lembutan-dan-kompres" telah digunakan untuk membentuk MBR dengan diameter midriff $D_b = 190\ \mu m$, diameter batang $D_s = 125\ \mu m$ dan panjang botol $L_b = 182\ \mu m$. Eksperimen yang dijalankan di ruang tertutup dengan kadar kelembapan dari 40% hingga 95% RH bagi setiap microfiber tirus yang berbeza. Prestasi sensor dianalisis dari arah diameter yang berbeza dari microfiber tirus dengan MBR ditambah untuk tahap kelembapan yang pelbagai. Saiz MBR tirus pertama adalah 2μm kemudian diikuti dengan 4μm dan 8μm. Q-faktor sekitar 10^4 telah dicapai untuk semua saiz microfiber MBRs tirus. Walau bagaimanapun, saiz 2μm MBR akhirnya mempunyai kelebihan dalam kebanyakan parameter prestasi. Nilai p bagi semua saiz diameter microfiber tirus adalah $> 10^{-5}$, yang menunjukkan data dikumpul dengan cara yang betul. Pada akhirnya, keputusan menunjukkan pengumpulan data yang terbaik dengan microfiber tirus 2μm manakala digabungkan dengan MBR berjaya mempunyai sensitiviti, lineariti dan nilai sisihan piawai yang lebih tinggi, berbanding dengan saiz lain microfiber. Kaedah kedua penyiasatan telah mengkaji perbandingan antara resonator botol mikro bersalut berlainan untuk penderiaan kelembapan. Ciri-ciri MBR ditakrifkan dengan menggunakan serat terdedah 2μm sebelum ditekan hingga 40% - 95% dengan dua MBR bersalut berlainan. MBR yang pertama disalut dengan PMMA (Poly Methyl Methacrylate) kemudian diikuti dengan salutan PVA (polyvinyl-alcohol), yang sengaja digunakan untuk mengesan ciri. Q-factor untuk MBR bukan bersalut ialah 1.451×10^5 yang lebih tinggi daripada kedua-dua MBR-PMMA yang bersalut dengan nilai 3.881×10^4 dan MBR-PVA bersalut 2.534×10^4. Walau bagaimanapun, MBR-PVA yang bersalut akhirnya didapati lebih baik dalam kebanyakan parameter. Nilai-p yang $> 10^{-5}$ untuk semua MBRs memastikan bahawa data-data ini telah dikumpulkan dengan betul dan akhirnya, MBR menjalani ujian kestabilan selama 60 saat dengan tahap kelembapan RH spesifik sebanyak 65%. Kesimpulannya, ini menunjukkan bahawa MBR bersalut PVA dilakukan lebih baik daripada kedua-dua MBR yang tidak bersalut dan MBR bersalut PMMA sebagai sensor kelembapan.

Kata kunci: pengaruh mod galeri berbisik (WGM), mikro-botol resonator optikal, PMMA, PVA, penginderaan kelembapan

ACKNOWLEDGEMENTS

At the very first moment, I am expressing my gratitude to Almighty Allah for giving me the patience and competence to complete my research project successfully. In addition, I am thankful to my parents whose allow me to fulfil my dream, inspire me and also support me in every stage of my life. During my research, I acknowledge the inspiration and assistance given by several people and my institute. I would like to thank my honourable supervisor Prof. Ir. Dr. Sulaiman Wadi Harun who motivated and driven me all the way to implement this research project.

Moreover, I am grateful to Mr. Md Ashadi Md Johari who guided me as a mentor during my research. My appreciation goes to Abdullah Al Noman for his helping and advising me. I am also thankful to my fantastic friend Miss Elnaz Salim for her love, patience and underestimated during my research work.

At last, I would like to express gratitude towards the University of Malaya from giving me such platform where I can explore and expand my knowledge which will help me in my future.

Thank you very much.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF SYMBOLS AND ABBREVIATIONS

D_b	:	Diameter Bottle or bottle distance
D_s	:	Diameter Stem or stem width
L_b	:	Neck to diameter or neck to neck length
ARC	:	A direct current
CMOS	:	Complementary Metal Oxide Semiconductor
CO_2	:	Carbon Dioxide
CQED	:	Cavity Quantum Electro Dynamic
DMR	:	Disk Micro-Resonator
DSR	:	Dielectric Sphere Resonator
DUV	:	Deep Ultra Violet
EBL	:	Electron Beam Lithography
FBT	:	Flame Brushing Technique
FSR	:	Free Spectral Range
LHO	:	Linear Harmonic Oscillator
m	:	Azimuthal
MBR	:	Micro-Bottle Resonator
MCR	:	Micro-Fiber Coil Resonator
MF	:	Micro-Fiber
MKR	:	Micro-Fiber Knot Resonator
MLR	:	Micro-Fiber Loop Resonator
MMF	:	Multi-Mode Fiber
MR	:	Micro-Resonator
MSR	:	Micro-Sphere Resonator
NIL	:	Nano-Imprinting Lithography

OMF	:	Optical Micro-Fiber
OMR	:	Optical Micro-Resonator
p	:	Polarization
PMMA	:	Poly Methyl Meth Acrylate
PVA	:	Polyvinyl Alcohol
Q	:	Quality factor
q	:	Axial mode number
R	:	Radius
RH	:	Relative Humidity
RPM	:	Revolutions Per Minute
SiN_3	:	Silicon Nitride
SiO_2	:	Silicon Dioxide
SMF	:	Single Mode Fiber
TMR	:	Toroid Micro-Resonator
V	:	Mode Value
WGM	:	Whispering Gallery Mode
XeF_2	:	Xenon Difluoride
λ	:	Resonant wavelength
μ	:	Micro

CHAPTER 1: INTRODUCTION

1.1 Background

The optical fiber sensing developed in during the past 3 decades, which that become powerful and preferable in the applications of sensing technologies and optical fiber (Lou, Wang, & Tong, 2014). Recently, besides the developed in the nanotechnologies and micro by the huge demand on the optical fiber sensors, and the developer uses optical fiber sensor, because of the optical fiber sensor have some characteristics such as high performance and versatility. One of the best choices of the optical fiber sensor is the spatial miniaturization versatility. Decreasing size of the optical fiber makes an essential step in the design of sensor structure to provide the sensor faster response, higher spatial resolution, low power, and higher sensitivity. With these characteristics, the optical fiber will be one of the best candidates for these ideas (Guo, Ying, & Tong, 2013; Tong & Sumetsky, 2011; Wu, 2013).

Ordinarily, the Optical Micro-Resonators (OMR) have a different shape such as a knot, a coil, and a loop, the quality of the optical fiber is great and they are used as a laser and modern filter for the promising application (Zhe Chen & Xiaoqing, 2011). The optical fiber sensors are increasing to use in many technology fields. Due to the requirements and requests of the application, high interest went towards the microfiber. Various type of optical fiber sensor design presented and illustrated and the sensors based on the microfibers are simple device and defined compared to other sensors because they have expensive fabrication procedures and require complex (Allwood, Wild, & Hinckley, 2017; Tong, 2018).

The Micro-Fiber (MF) sensors play the role of the modern society technology, because of their adaptability is mostly based on their inexpensive and speed. Also, they are well to do supporting technology of optical such as photodiodes, light sources, and optical fibers. One of the characteristics of light is that defining it in a dielectric microstructure to interfere with itself, a small range of frequencies can pass and resize inside the cavity without noticeable losses. However, the next generation of optical fiber sensors is based on the use of resonant small power loss like interfering micro-cavities where that have very high performance.

One of the classifications of resonant optical fiber sensors those based on microcavities where supports Whispering Gallery Modes (WGMs), these have produced the highest level of advantages because it gives the highest level of sensitivity (Matthew & Foreman, 2015). Mode of a wave field or WGMs are special resonances inside a given cavity with smooth edges. They supported through the cavity surface during continuous total internal reflection and round the cavity correlate with wave circling that fulfils the requirement of the resonator. These type of resonances of the resonator cavity depends greatly upon the geometry (Feron, 2004).

The term WGM waves were used by Lord Rayleigh for the first time in the 19th century. It was established in London under the dome of St, which defines the phenomenon of the WG by Paul's Cathedral. It was known if a whisper (a sound) announced at the opposing side of the dome was able to hear the sound loudly despite quite far away from the source. However, the gallery with smooth curved inside the cathedral's dome with the Radius (R), which provides the sounds waves above, its surface for reflection by the circumference (hrec ·m = 2nr) of an integer fraction (m) (Kringlebotn, Archambault, Reekie, & Payne, 1994; Lott et al., 2000; Nasir, Yusoff, Al-mansoori, Rashid, & Choudhury, 2009).

The light describes with optical microcavities frequent reflection across a long time period to transform into either linear cavities or circular cavities, Earlier utilization in electromagnetic waves the application programs of WGMs. The light-limiting characteristics of resonators depend on the mode value (V) and the Quality factor (Q). In order to gain high $\frac{Q}{V}$ ratio, the principles of WGMs applying into several numbers of optical micro-cavities which have been expressed since the conception by Richtmyer was moved into the electromagnetic wave's domain (Richtmyer, 1939).

1.2 Objective

The principal aim of this experiment area is to investigate the influences of micro-bottle resonators for humidity sensing by tapered Optical Micro-Fibers (OMFs) and examine the effectivity of the resonators. The objectives which are given below must meet:

a. To understand the fundamental of optical micro-resonator (micro-bottle) regarding humidity sensing.

b. Conduct an experiment for humidity sensing using the coated micro bottle resonator.

c. Analyses the performance of the coated micro-bottle resonator on humidity sensing.

1.3 Problem statement

Nowadays, WGM resonators are contributing in many applications such as sensors, filter, micro-laser, Cavity Quantum Electro-Dynamics (CQED) and optical delay lines (Matsko & Ilchenko, 2006; Vahala, 2003). Generally, several shapes of micro-resonator have been discovered like as toroid's, cylinders, spheres and disks, which they have the rationally symmetric configuration being generally used.

Various work has been done regarding liquid sensing with different kind of Micro-Resonators (MRs). WGMs with microspheres resonator has been applied for the optical biomolecules sensing with the Q-factor of ~10^5 whereas sensitivity and reliability were not effective for biomolecules sensor (Nadeau, Illchenko, Kossakovski, Bearman, & Malkei, 2002).

Microspheres resonator with WGMs has been used the optical biomolecules sensing with the Quality factor of ~10^5, while reliability and sensitivity were not efficient for biomolecules sensor (Nadeau et al., 2002). A slot-waveguide micro-ring resonator established an integration biochemical sensing for the use of the biomedical sensor. For that work, the MR was fabricated by silicon dioxide (SiO_2) and silicon nitride (Si_2N_3) which operated at the wavelength of 1.3μm (Barrios et al., 2007).

In this day a new type of OMR is Micro-Bottle Resonator (MBR), which these types of MR taking the consideration compared to the other OMRs, because of it is distinct specification. In among other MR, MBR has several benefits such as best control over the coupling through optical tapered microfiber, in the spectrum the possibility of achieving a great number of equally-spaced modes and fast tunability by the strain application. To date, as we notice that a broad range of investigation has been done by several type of technique for humidity sensing.

1.4 Report outline

The research report is ordered into five chapters, each of which is then subdivided into sections and subsections. Chapter one presented an introduction of this work comprising the background study, problem statement, and aims of the research study. Chapter two explained the fundamental of micro-resonators, their properties and the characterizations of different types of micro-resonators. The fabrication process of MBR, use of MBR along with bare MF and compression of different diameter of tapering bare MF used with the MBR for humidity sensing in terms of performance are briefly described in chapter three. Chapter four demonstrated the effects of different bare fibers with MBR coated for the humidity sensing. In the end, the overall summary was stated in chapter five along with references.

CHAPTER 2: LITERACTURE REVIEW

2.1 Introduction

Historically, many efforts have been made to transmit information by optical waves. In 1790s, the Chappe brothers invented a light telegraph that could send messages from one tower to another. Also, in 1845s, a British physicist named john Tyndall proved that light can flow through a curved water flow, so the optical signal can be broken.

In 1880s, Alexander Graham bell discussed the technology of fiber optics by recording a device called Photophone, which later became known as Radiophone. This device transmitted audio through the optical fiber. The device emitted light in the air. But, unfortunately, up to 200 meters had the ability to transfer information, so it was not welcomed. After Alexander Graham Bell, a lot of efforts were made to transfer information by optical waves in the form of a hardware platform. With the invention of laser radiation, in early 1960s, a new valve was opened in fiber optic communication. In 1966s, Charles K. Kao and George A. Hockham introduced the use of glass for the first time as a light emission environment. Following the presentation, Corning Glass's Robert Maurer, Donald Keck, and Peter Schultz, researchers in the 1970s announced the construction of the first single-mode fiber optic cable.

Nowadays, many designers have developed the laser to be suitable for the high-end applications in different fields, particularly optical communications and sensor technologies. Several benefits offered by the using of fiber sensor over the standard sensor, great sensitivity, small size, lightweight, highly accurate, prevent electromagnetic interferences, geometric flexibility, safe to use it in dangerous environments, and the optical fiber adaptability to communications. The optic fibers sensing system technology is perfect for controlling the structural health of aircraft (load, strain, temperature), Medical and Surgical Maneuvers (Biosensing, vascular procedures, and detection, Placement and monitoring movement of tiny catheters) which is shown in figure 2.1.

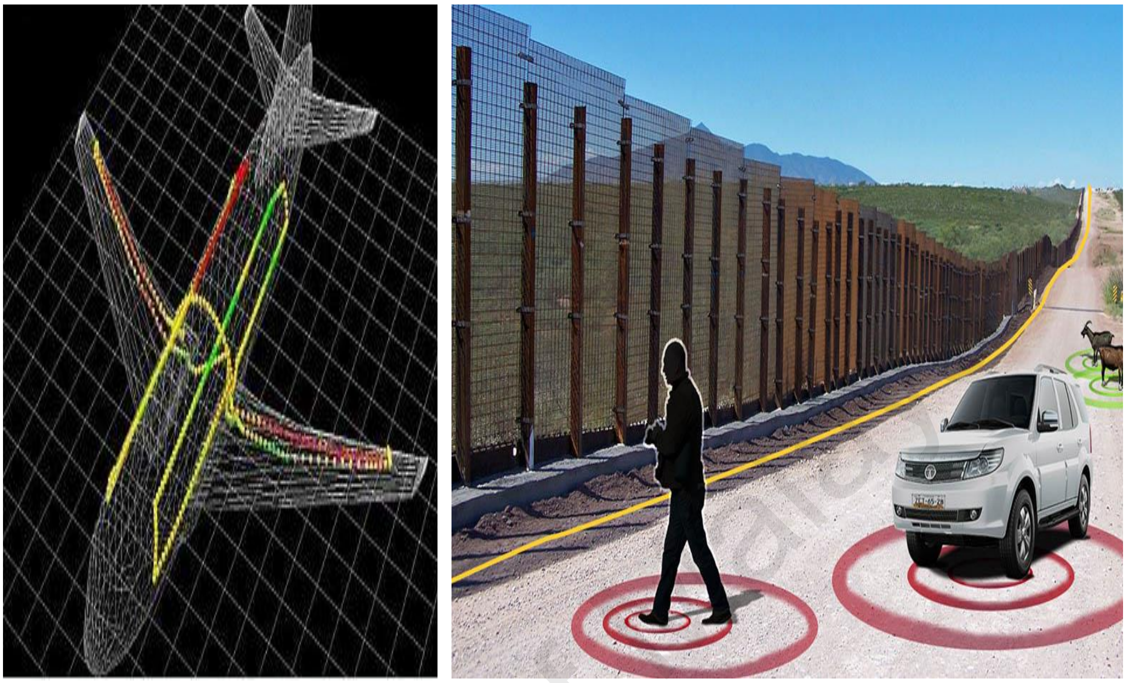


Figure 2.1: Application of optical fiber sensor

2.2 Optical fiber

The optical fiber is tall and thin filaments of very purplish glass that have a size about the diameter of human hair. They are set together in the pack called optical fiber cables and are used to transfer optical signals at many distances.

If you observe exactly at a fiber optic, you'll see that it's created of the following parts:

2.2.1 Core

The core of the central part of the fiber is made of glass and the light goes on in this part.

2.2.2 Transparent layer

A transparent interface that surrounds the core of the fiber optic and reflects the light inside the nucleus.

2.2.3 Protective coating

A plastic sheath that protects the optical fiber against moisture and damage. Hundreds or thousands of these fiber optic fibers are packaged together, which are referred to as optical cables. These bundles of fiber optic fibers are protected with an outer cover called buffer(jacket), which is shown in figure 2.2.

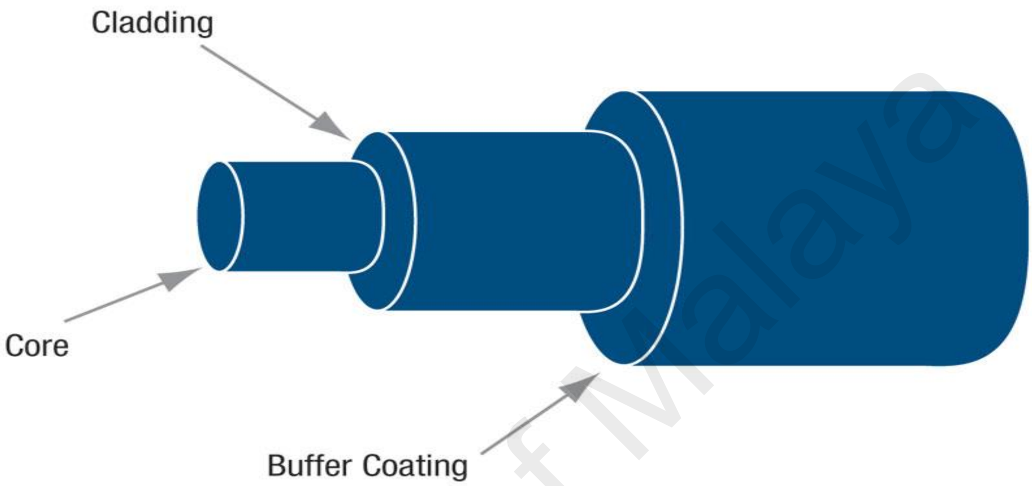


Figure 2.2: Layers of optical fiber

Generally, there are two kinds of optical fibers according to the transmission characteristics (Hoss & Lacy, 1993).

2.2.4 Single-mode-fiber optic (SMF)

These types of fibers are small nuclei (about 4 inches (4), 10 × 3.5 or 9 microns in diameter) and can be transmitted from infrared lasers (wavelengths 1300 to 1550 nm) Do it.

2.2.5 Multimode-fiber optic (MMF)

These types of fibers have larger nuclei (about 10 inches (2.5 inches or 62.5 microns) in diameter) and infrared light from optical diodes called LEDs (with a wavelength of 850 to 1300 nm) are self-guided. Some optical fibers are made of plastic. These fibers are large nuclei (4 cm or 1 mm in diameter) and direct the red luminous eye that comes from LEDs (and wavelengths equal to 650 nm), which is shown in figure 2.3 (Jeunhomme, 1983).

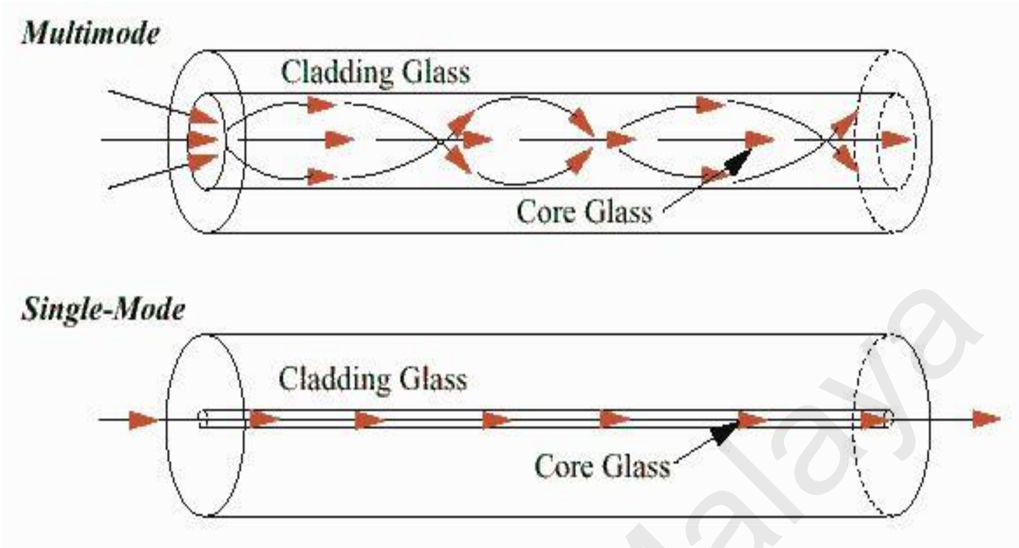


Figure 2.3: Multi-mode and single-mode optical fiber

2.3 Micro-Fiber (MF)

Recently, due to the special features of MFs, they are used in various methods and applications. MFs are also used to develop fiber optic devices. As an example, many studies have been conducted on the development of light resonance using microfiber, including the use of it as light filters in light communication and sensors. The types of resonators are as follows:

- Micro-fiber loop resonator (MLR)
- Micro-fiber coil resonator (MCR)
- Micro-fiber knot resonator (MKR)

The diameter of the MF core is between 100 Nano-meters and a few Micro-meters. To access the blackout due to the removal of the coating by chemical itching or the mechanical sealing process. MF typically has a diagonal diameter with side surface smoothness and a high variance between MF materials such as glass, polymer with surrounding media such as air and water. This kind of microwave or nanoscale waveguide, which drives light with low light scarcity, high mechanical elasticity, light beam enclosure and a large magnetic field, makes it possible for a small platform to measure light with specific characteristics, such as fast response High sensitivity and low power consumption.

The small diameter of the MF can be exploited by using several techniques, such as the production of fibers from glass materials (Tong et al., 2006), chemical etching (Zhang, Lou, & Tong, 2011), and the growth of silica nanomaterials and from tapered optical fibers by scratching and heating which is shown in figure 2.4 (Naqshbandi, Khan, Rizwan, & Khan, 2012).

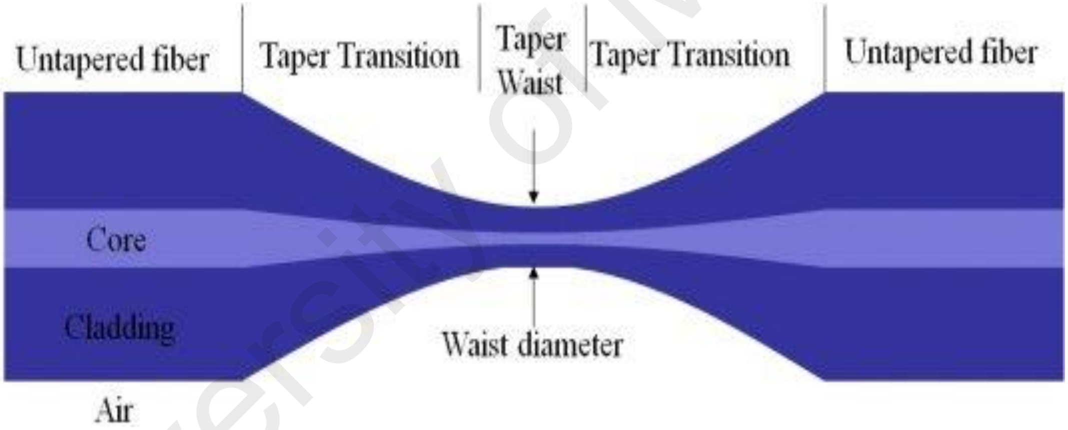


Figure 2.4: Tapered fiber

2.3.1 Flame Brushing Technique (FBT)

Typically used to produce a fiber coupler is a method of FBT. With this technique, the MF dimensions can be carefully designed. Also, the FBT produces bipolar tapered fibers that can be connected to the SMF and can be made MF based devices by using this tapered fiber. The following figure shows 2.5 how to make tapered fibers by using this technique.

As can be seen, the initial coating of the SMF is removed (as much as a few centimeters) and the SMF is kept constant by two fiber holders. The torch moves uniformly and heated the uncoated fiber. When it is stretched together by the fiber.

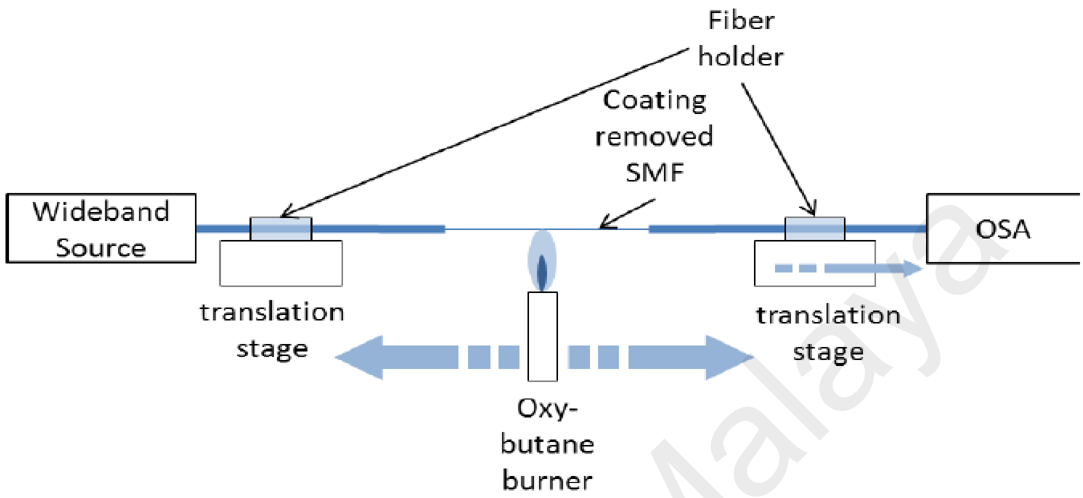


Figure 2.5: Flame brushing technique

2.4 Optical Micro-Resonator (OMR)

The Optical Micro-Resonator (OMR) is the combination of mirrors that create a resonator cavity in which incident light wave forms a standing wave. The light is confined in the cavity and is reflected many times by the mirrors generating the standing waves for certain resonance frequencies. There are different types of OMR that can differ from each other by the two mirrors focal length and the space between them Normally for the designer are not used flat mirror because the alignment of them to the exact position is difficulty also, types of the resonator are designed for other criteria, like the focal a point out of the cavity and minimum beam waist.

Many investigations work has on the develops of OMR based on MFs, which are beneficial for various applications in optical sensors. The OMR based on MFs are susceptible to variation in the surrounding, because of the major magnetic field in the MF

(Chen, Xu, & Lu, 2011; Jiang, Chen, Vienne, & Tong, 2007; Yoon, Kim, Brambilla, & Han, 2012; Zeng, Wu, Hou, Bai, & Yang, 2009).

2.5 Parameter of OMR

Micro-resonator has two important parameters.

- Quality-factor
- Free spectral range

2.5.1 Quality-factor (Q-factor)

Q-factor is used to determine the damping strength of the corresponds and oscillations to the light confinement inside the resonator and the Q-factor of MR is a unit-less parameter. This defines usually described like the stored energy ratio to the power loss and how long inside a cavity or resonator a photon can be stored is also measured by (Jung, Brambilla, & Richardson, 2010):

$$Q = 2\pi \frac{stored\ energy}{power\ loss\ per\ roundtrip} \tag{2.1}$$

To overall Q-factor of whispering gallery mode micro-resonator calculated by:

$$\frac{1}{Q_{total}} = \frac{1}{Q_{WGM}} + \frac{1}{Q_{mat}} + \frac{1}{Q_{cont}} + \frac{1}{Q_{ss}} + \frac{1}{Q_{coupling}} = \frac{1}{Q_{coupling}} + \frac{1}{Q_{intrinsic}} \tag{2.2}$$

In where Q_{total} is the total cavity of Q-factor, the combination of four parameters is intrinsic Q-factor, that four parameters are:

- Q_{WGM}: Q of radiation loss because of the dielectric cavity curvature
- Q_{mat}: Q of material losses
- Q_{ss}: Q of surface scattering
- Q_{cont}: Q of contamination over the resonator

And where $Q_{coupling}$ has defined the energy loss because of the input or output coupling. Based on the OMR mechanisms it can affect values of Q-factor by the radiation losses due to roughness scattering of the surface or waveguide bending and the material intrinsic absorption. Externally the tapered fiber and MR, Q-factor can be measured(Nasir, Murugan, & Zervas, 2016b; Vahala, 2003). Through following way:

$$Q_e = \frac{m\pi}{k^2} \tag{2.3}$$

The Q-factor of the resonator also associated with the resonance Δ_λ linewidth at operating wavelength λ and the lifetime of a photon inside cavity τ by:

$$Q = \frac{\Delta\lambda}{\lambda} = \omega_0 \tau \tag{2.4}$$

Here ω_0 ($\omega = \frac{2\pi c}{\lambda}$) represents the optical frequency.

2.5.2 Free spectral range (FSR)

Generally, for the FSR of cavity measured is as the spacing of frequency of its axial cavity modes. However, for the increased FSR used by the decreased size of the resonator. It means they are inversely proportional to each other. The consecutive modes that have the specific structure of transverse mode, it defines of the mode of FSR. The azimuthal ($\Delta_{vm} = v_{m+1,q} - v_{m,q}$) and axial ($\Delta_{vq} = v_{m,q+1} - v_{m,q}$) FSRs can be extracted from the wave function eigenvalues $k_{m,q}$. They can be estimated by:

$$\Delta_{vm} = \frac{c}{2\pi n} \left(k_{m+1,q} - k_{m,q} \right) \approx \frac{c}{2\pi n R_0} \tag{2.5}$$

$$\Delta_{vq} \approx \frac{c\Delta k}{2\pi n} \tag{2.6}$$

2.6 Different type of OMR

To date, immense of micro-resonator has been developed. Some of them used for environment applications such as temperature, strain etc. and some of them for industrial applications. Among all the micro-resonators most useful resonators are toroid micro-resonator, disk, cylinder and ring micro-resonator, dielectric sphere resonator and micro-bottle resonator which are given below:

2.6.1 Toroid micro-resonator (TMR)

A toroid micro-cavity is prepared by a dielectric material. The shape of dielectric material is a solid toroid. The light can be distributed inside of solid toroid through stable bouncing by the air interface of the toroid with total internal reflection which is shown in figure 2.6 (Kippenberg, 2004). The solid toroid uses the WGN conception, almost the same for the disk, ring and ball micro-resonators. WGMs planarity shares a greater portion of the amenities of employing such resonators rather than spherical ones. The part of fabrication TMR is more involved coupling than ring or disk resonators.

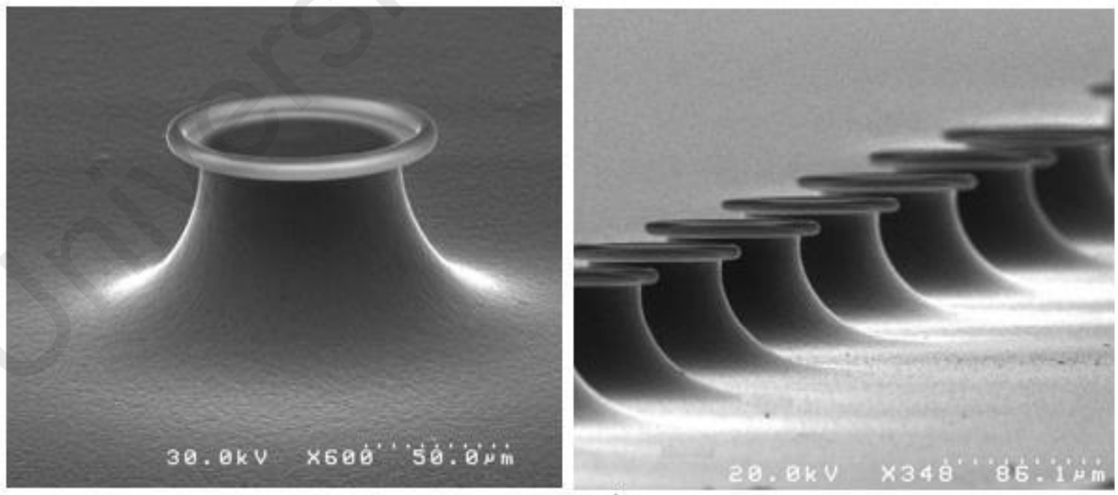


Figure 2.6: Fabricated a TMR from a thermal oxide (left) and an alignment of TMR (right)

TMR has a lot of potential advantages. Compared to another resonator are they able to Ultra-Q factors gain in the sequence of $\sim 10^8$ and $\sim 5 \times 10^8$, its one of important advantage(Armani & Vahala, 2007; Kippenberg, 2004). Compared to sphere microresonators because of the conduct of the surface during their fabrication which presents them a numerous magnitude and quiet soft surface orders which is bigger than the disk resonator Q-factor. While sharing simplest fabrication of utmost advantages and integration of the resonators which is disk.

2.6.1.1 Fabrication

The constructing method for designing a TMR is illustrated in figure 2.7, which is shown below.

Step 1: a circular silica (SiO_2) disk is described by dry etching.

Step 2: a small measure of the silicon under of the disk which shifted by isotropic etching using Xef_2 (Xenon Difluoride) gas to the keeping of the light vertically.

Step 3: by using a CO_2 (Carbon Dioxide) laser the Si finally melted through irradiating process.

Step 4: the melted Si convert into soft toroidal shape using surface strain at the disk edges part. (the interior part does not restructure of the disk while they quickly move their heat through the Si)

Through this process toroid micro made up with the fundamental diameter between 80μm and 120μm, the torus shape diameter of 5μm and 10μm and the Q-factors of $\sim 10^8$. The fabrication progress provides simply manage of the size of specific TMR fabricated than the method of fabrication for made up sphere micro-resonator, planar geometry TMR gives us a combination in the simple process into optical fiber cavity, this process is probable for sphere micro-resonators (Tobin & Dumon, 2010).

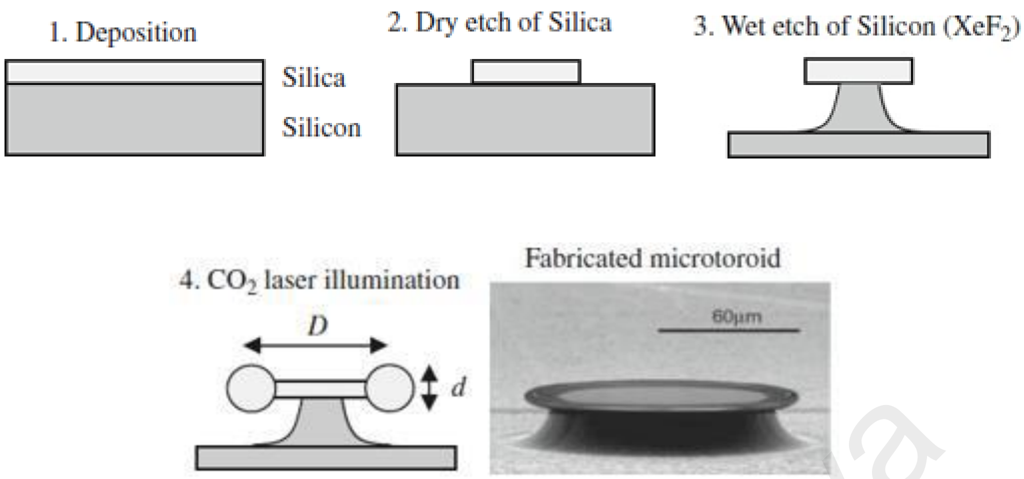


Figure 2.7: Demonstration of the fabrication process of the TMR and a view of completed micro-toroid

2.6.2 Disk, cylinder and ring micro-resonator (DMR)

The dielectric cylinder and DMRs also supported for the WGMs. Almost function of cylinders as sphere according to the WGMs that they support (through a similar process lights radiates over the area of the cylinder to rounding lights nearby the sphere equator). But basics phenomenon is not similar. While the method of the sphere under disturbance away from the distribution, that is equatorial and for cylinders of the dielectric is not accurate in the same process. In a sphere, the polar form with a curve in the surface of the sphere confines and focuses in a light beam of the cylinder of dielectric and in light on the behavior of polar direction which is suitably perturbed surrounding the equator by propagating. They do this so that they can leave over the top or bottom of the dielectric cylinder and therefore, it leaves the micro-resonator (Gomilsek, 2011).

That is hard to fabricate disks with parallelly a spherical resonator, because of the instability of the mode in polar direction on account of the lack of focusing which has the cylinder resonator Q-factors, less surface violence, and DMRs are normally much less than the sphere (Tobin & Dumon, 2010).

However, the fabrication process is more suitable to control, much faster and simpler due to their planar geometry and simple to integrate into an optical integrated network, while the same time considering much lower space than the radii of the microspheres with smaller volumes of the mode. In this method, it can make them so effective according to the practical applications. Ring resonator is the disk with variations of resonators, at the center of disk resonator with a circular hole. Considering WGMs are greatly restricted at cavity air interface ring and it has the same structure of WGM as disks with resonators while high order modes with radial are better suppressed. It has extra benefits; ring resonators allow various times shorter mode volumes in only a part of the volume of material (Gomilsek, 2011).

2.6.2.1 Fabrication

The three processes of the fabrication of ring, cylinder, and disk resonators are:

- Deep Ultra-Violet (DUV):

DUV has maximum throughput, that is simply matched with Complementary Metal Oxide Semiconductor (CMOS), because of the only ~100nm characteristic resolution which creates some surface roughness.

- Electron Beam Lithography (EBL):

EBL has several efficient for approximately packed structures than deep ultraviolet and EBL has resolution characteristic of ~10nm.

- Nano-Imprinting Lithography (NIL):

NIL has great throughput and great characteristic resolution (Tobin & Dumon, 2010).

DUV uses Ultra Violet light and the wavelength for DUV is 193nm or 248nm. From this wavelength, DUV describes the structure of resonator through etching the substrate, while EBL uses speeded or accelerated electrons for etching. Whereas for NIL needed three steps:

Step 1: the structure of resonator which uses DUV lithography or EBL for fabricated.

Step 2: a polymer is solidified and molded around the structure to create a solid mold.

Step 3: this mold can be utilized as a resonator.

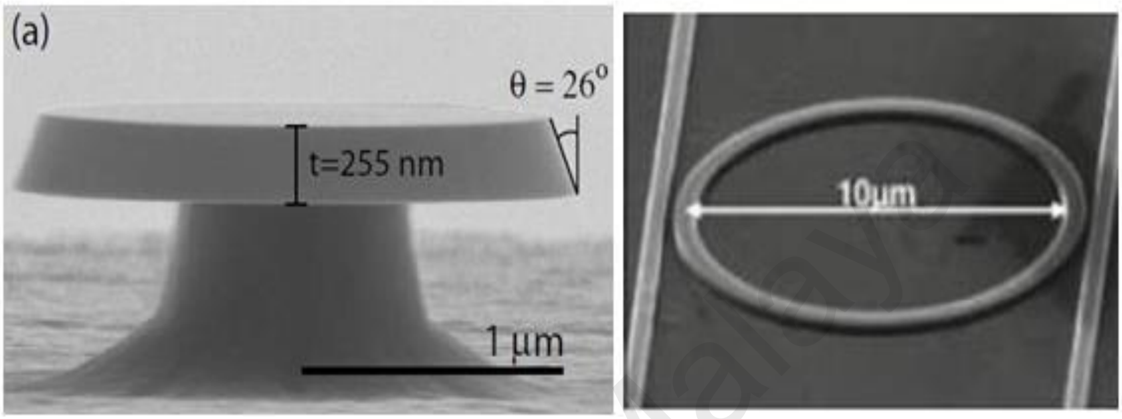


Figure 2.8: Ring resonator (right) and disk resonator (left)

2.6.3 Dielectric Sphere Resonator (DSR)

One of the simple resonators based on the WGMs is dielectric sphere resonator, DSR compared to the surrounding material has a higher refractive index. The viewpoint of geometric optical fiber for the incoming light, that moves almost to the sphere edge is continually reflected. Inside the sphere, this occurs by total internal reflection to the air interface cavity and they cannot come outside of the sphere. So inside of the sphere, the light is caught. That happen means if the light beam distributing reversal to the correct point at the correct phases, it interferes constructively with itself and resonant waves form. This situation is normal for the positioning the coordinate system, so the light beam distributing nearby the sphere. The surface of the sphere also provides to focus the light into the vertical polar direction. Because in the same optical way, the curve of the polar direction of the polar sphere moves, that has efficient for polar sphere travels at the same optical path, it was zigzagging on all direction of the center in place and continues in a straight line which is shown in figure 2.9. This can be understood through a Gouy phase shift from the light polar confinement of gaussian beams, so they can move by their focal points (Little, Laine, & Haus, 1999).

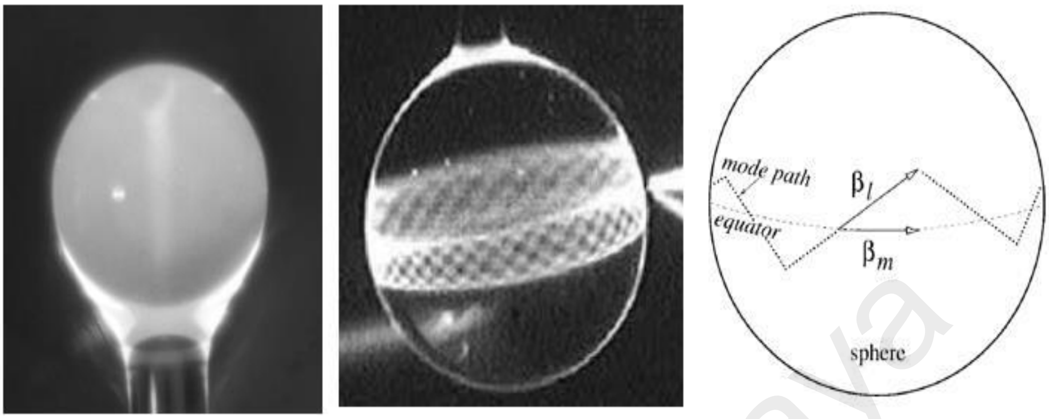


Figure 2.9: Microsphere resonator fabrication by electric arc heating and tuned into a globe (left) modes of the silica microsphere with 300μm (center) and approximation of the geometric optics to WGM propagation (right)

For a spherical MR including resonant performance characterization rather of the definition of geometry using the method of a wave optics essential. For more explanation, assume light provides two primary corrections.

- Correctly light is not bouncing off at the edge inside the sphere. So, it managed easily with sphere edge.
- A wave with total internal reflection at a curve edge is not complete, that means the curve losses and continuously the light leaks out from the sphere with the spherical interface associated (Gomilsek, 2011).

2.6.3.1 Fabrication

For made a Micro-sphere resonator (MSR), usually they are using fabricated by surface tension also MSR is made of materials in liquid, crystalline and that is amorphous structures. It has been expressed by means of spheres. At the initial stage, the OMR is shown easily as a micro (μ) size droplet of liquid along a proximate ideal surface of spherical effected through surface tension (Tobin & Dumon, 2010). Used of droplets are hindered and it has more effective for WGMs. They slowly drying, and it is difficult to manage compared to the solid-state resonators.

Liquid is very efficient in spectroscopy, lasing, fluorescence in dyes for MR, and this already established over the time. Nowadays, droplets of liquid crystal proved to be as far as is feasible two magnitude orders more tunable overheads any MR of solid-state resonators with a max Q-factor of 12.000, which perhaps creating new fields such as sensor and laser (Humar, Ravnik, Pajk, & Muševič, 2009).

Micro-sphere resonator (MSR) was described in fused SiO_2 (silica) for the first time. At first, if the top point of a SiO_2 optical fiber is melted by a flame or an electrical arc, second, that special melted area of a soft sphere of the silica forms which minimizes the surface energy of the sphere. Third, when the arc or flame removed then melted area of silica solidifies into a shape of the MSR where the radius of the sphere managed by modifying the fiber tip size. The size and the shape of the MSR, which is proved diameter of the sphere between 50μm and 100μm on the Q-factor of $\sim 10^9$ and it's reproducible (Tobin & Dumon, 2010). For use MSR with fused silica should be careful to certify an inert atmosphere for the MR, because of MSR with fused silica are very sensitive to the outer polluter, for example, water absorption and -OH absorption. MSR has the measured Q-factor for WGM.

Recently, a record has been made by spherical resonators which are for fused silica Q-factors of 8×10^9 (with the finesse of 2.3×10^6) at λ_0 = 633nm has been measured and for CaF_2 (fluorite) crystalline Q-factors of 3×10^{11} (with the finesse of 2.1×10^7) at λ_0 = 1.55μm also has been described (Savchenkov, Matsko, Ilchenko, & Maleki, 2007).

2.6.4 Micro-Bottle Resonator (MBR)

One of the types of MR is Micro-Bottle Resonator (MBR), MBR made up by the optical fiber (a lengthy dielectric fiber which made of silica or plastic). MBR has a bulge area in the midpoint of MR, compared to the surrounding fiber thickness, the fiber of bottle thickness is a little increased. Incoming light circulates alongside the fiber circumference and perpendicularly to the optical fiber symmetry axis. It is radially confined the light continuously through total internal reflection. Additional axial confinement is gained through the slowly changing of the optical fiber thickness, it is like spherical resonators polar confinement and in opposition with same optical fiber where light is not confined in the direction of axial to allow light guiding down the fiber (O'Shea, Junge, Nickel, Pöllinger, & Rauschenbeutel, 2011).

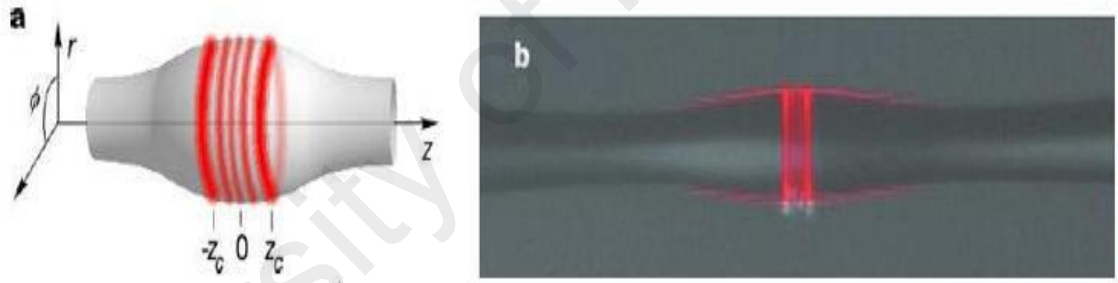


Figure 2.10: Micro-Bottle Resonator

2.6.4.1 Spectrum

Almost parabolic in axial direction z: $R_{(z)} = R_0\,(1 - \frac{1}{2}\,(\Delta k.z)^2)$. The maximum radius of the bottle resonator is $R_0 = R\ (0)$, Δk is the resonator axial curvature. Generally, it is the fiber thickness profile of the optical fibers around the bottle resonator. That has produced effective linear harmonic oscillator (LHO) like as potential in the axial direction. Therefore, complete light confinement inside the resonator is gained which holds in the adiabatic estimation $\left(\left|\frac{dR}{dz}\right| \ll 1\right)$ (O'Shea et al., 2011).

Eigen-modes can be described as coordinates of cylindrical (r, φ, z) inside the fiber in the electromagnetic field. While that using the first kind Bessel functions LHO Eigen-functions Z_q and J_m:

$$\psi_{m,q}(r,\varphi,z) = Ae^{im\varphi}J_m\frac{mr}{R_{(z)}}Z_q(z) \tag{2.7}$$

Where m is azimuthal, q is the axial mode number and they adjacent with polarization p. Which describe the uniqueness of the mode and the multi-index is $\zeta = (\mathrm{m,p,q})$. Also, we can assume visualize in the LHO which light bouncing return to forward in the axial direction which is shown in the figure 2.11. Producing a standing wave in the resonant position is satisfied. Light introduces a caustic in the area which significantly increased intensity. Inside an LHO, there is on the resonance of the resonator at the tuning point ±ZC for classic movement. However, we can think light "bouncing return" in this process, as it hit the mirror (such as fabry-pérot interferometer) (O'Shea et al., 2011).

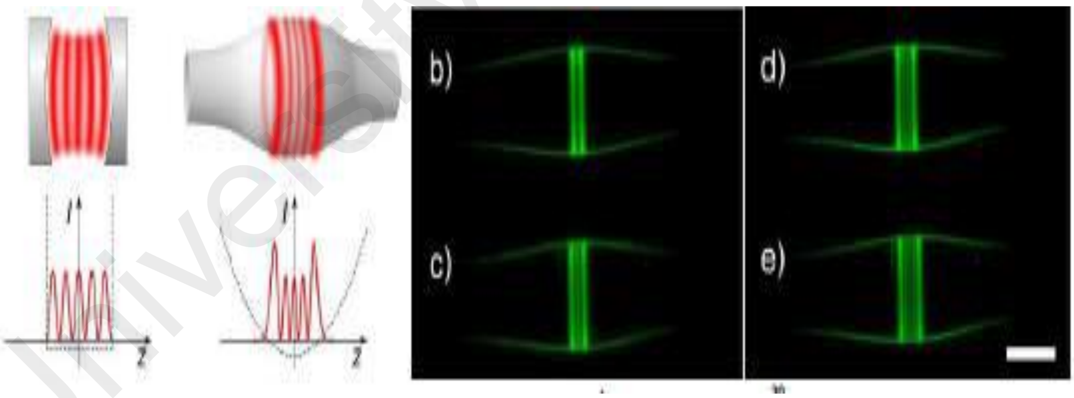


Figure 2.11: Comparison between the OMR and Fabry- Perot resonator and monograph of q = 1,2,3,4 modes

The spectrum of the OMR is given by the number of the wave inside the k_1 as:

$$k_{1,m,q} = \frac{2\pi n}{\lambda_0} = \sqrt{\frac{m^2}{R_0^2} + \left(q + \frac{1}{2}\right)\Delta E_m} = \frac{m}{R_c} \tag{2.8}$$

Here LHO energy spacing is:

$$\Delta E_m = \frac{2m\Delta k}{R_0} \tag{2.9}$$

Where n=$\sqrt{\varepsilon\mu}$ is the optical fiber refractive index, λ_0 is the light wavelength in vacuum and $R_c = R(\pm ZC)$ indicates the bottle radius at the caustic. The radius of the optical fiber getting shrinks due to the higher q and m, and the caustic axial position proportional to the mode numbers (Gomilsek, 2011).

2.6.4.2 Fabrication

The fabrication of MBR has been done through "soften and compress" method. It has some advantages which include simply manufacture process (fibers are easily fabricable and the fiber thickness can straight forwardly be improved through stretching and heating the fiber) and higher tunability (mechanically during stretching process the fiber thickness changes itself and also the MBR frequencies, alternative way is electrical thermo-optic tuning), while also sustaining the typical toroid and spherical resonators ultra-high Q-factor (O'Shea et al., 2011).

2.7 Poly Methyl Meth Acrylate (PMMA)

The first application of PMMA was by Otto Rohm from Germany in 1934s, but in the early 1930s, PMMA was discovered by Rowland Hill from Britain. Poly methyl methacrylate created through Poly (methyl ethylene) and (methoxycarbonyl) from the poly (methyl and methyl propanoate) and the hydrocarbon viewpoint, from the ester viewpoint, the PMMA polymer and MMA monomer illustrated in the figure 2.12:

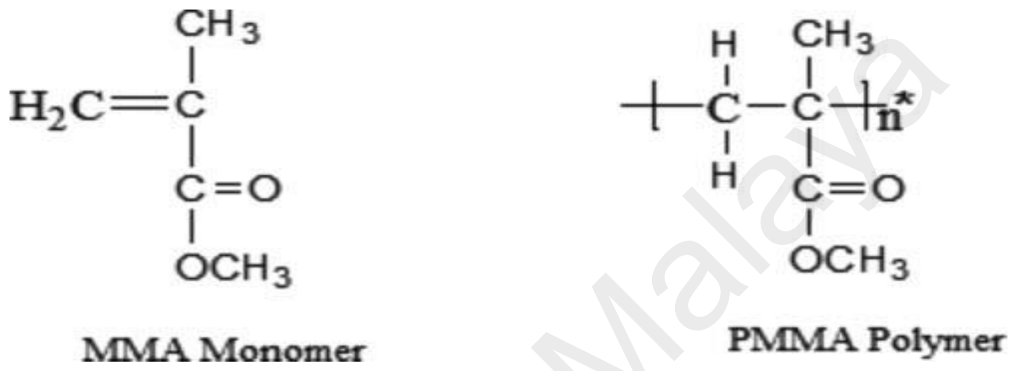


Figure 2.12: The structure of MMA monomer and PMMA polymer

An MMA monomer has advantage as improvement the mechanical and physical properties polymer, in turn and that can lower binder's viscosity. Methyl Methacrylate (MMA) is a colorless liquid and these product through methacrylic acid by oxidization of C4 raffinate-extracted isobutylene at a gaseous state and then esterifying the methacrylic acid with methanol. MMA tends to have excellent transparency, weather resistance, high stability and tolerability (Jin, Yeon, Min, Yeon, & Materials, 2018).

PMMA is an optically clear thermoplastic. Generally, PMMA used for mineral glass as a replacement because it gives the lightweight, exhibits desirable processing conditions, high impact strength, and the shatter-resistant. However, in during world war II, the first major application of PMMA polymer was used as bubble canopies and aircraft windows for gun turrets (Umar , Khairil , Abd, & Nor Aziah, 2015).

2.8 Polyvinyl-Alcohol (PVA)

PVA first time prepared through hydrolysing polyvinyl acetate in ethanol with potassium hydroxide by Hermann and Heahnel in 1924s. The specific physical characteristics and functional properties depend on the degree of hydrolysis and the degree of polymerization. classifieds of PVA into two groups is namely: fully hydrolysed and partially hydrolysed which is shown in the figure 2.13 (Sumetsky, 2004).

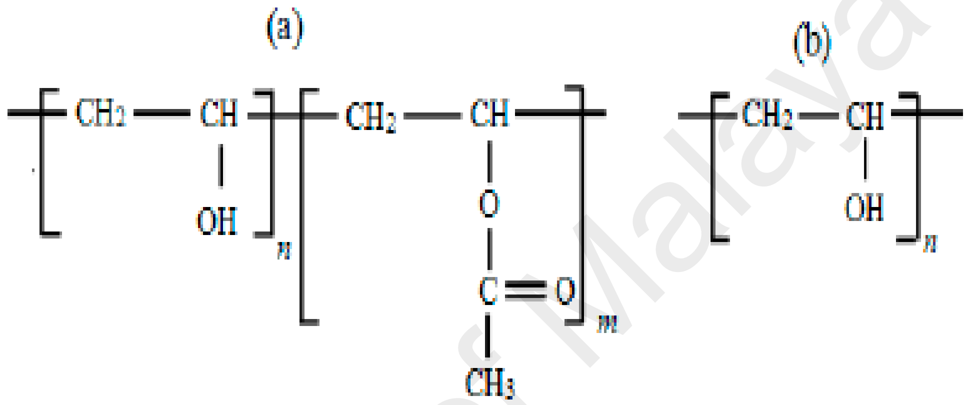


Figure 2.13: Structure formula for PVA, (a) partially hydrolysed, (b) fully hydrolysed

The quantity of PVA determines by the chemical, physical and mechanical characteristics which is highly soluble in water. These is higher rating of polymerization and hydroxylation of the PVA. PVA used for many applications because of the PVA's resistance against organic solvents and aqueous solubility makes it adaptable for many applications. PVA has some advantage as low environmental impact, biodegradability, aqueous solubility and high chemical resistance. Generally, PVA used in the industrial such as food packaging, textile, medical device and paper products manufacturing (Baker, Walsh, Schwartz, & Boyan, 2012).

CHAPTER 3: EFFECT OF MICROTAPER FIBER IN MICRO-BOTTLE HUMIDITY SENSING

3.1 Introduction

Nowadays WGM micro-resonator an increasing number of the article has been published and it has interested growing applications. Because of WGM are especially cylindrical optical fibers, TMR, photonic crystal cavities and etc, however, studying applications from that are easier ones. The traditionally termed of WGM in the optical fiber cavity is the electromagnetic surface oscillation. Generally, this method is regularly assumed as closed-trajectory rays defined through the total reflections. WGMs supported through spheroidal, toroidal-shaped open dielectric resonators and cylindrical. That has high Q-factor which made up them for utilization in experimental physics and optoelectronics (Righini et al., 2011).

The OMRs has capture recent attention where believed to have promising performance in laser device and other application of photonic. The shape, material composite and size of the OMRs will contribute to determine the performance of resonator (Hanumegowda, White, Oveys, & Fan, 2005; Jali, Rahim, Ashhadi, Thokchom, & Harun, 2018; Krioukov, Greve, & Otto, 2003; Nadeau et al., 2002; Vollmer, Arnold, Braun , Teraoka, & Libchaber, 2003; Vollmer et al., 2002). By choose right combination, high speed with low power of photonics circuit would be developed. OMR where supporting WGMs inside circular structure where the reflecting arrangement could be avoided. The value of Q-factor would be element to use to determine the quality of OMRs. High losses would experience by transmitted power while generating WGM. However, the Q-factor would be defined by calculating the resonance wave interval on WGM selected phase (Michelitsch et al., 2011). The Q-factor of OMR would be in high number by reducing scattering losses and transmitted spectral leakage. Recently, OMRs is widely demonstrated in broad application such as small-scale sensor, filter and micro laser, which is contribute over than fundamental research (Birks, Knight, & Dimmick, 2000; Ilchenko, Gorodetsky, Yao, & Maleki, 2001). By change the rotation of symmetrical OMRs structure, new shape of OMR will be formed where the potential could be explored.

Several structures of OMRs commonly used such as toroid, sphere and disks where the toroid's remained the lowest value of Q-factor than others. However, even-though possess low value of Q-factor, toroid's type still available to use in other application related. Presented in 3D structure form, WGM manage to confine on the bolted area, which is contrast with other OMR structure where formed in quasi-2D (Sumetsky, 2004). Hence, MBR manage to enhance strength of field while demonstrated a non-degenerated WGM. With the absolute arrangement of MBR while in the coupling setup, it will increase the MBR ability on handling variety of modes. This technique allows to form best structure of MBR with large mode density and able to generate complex resonance of WGM spectral.

This chapter presenting a compression of different diameter of tapering bare microfiber used with the MBR for humidity sensing. The SMF-28 silica fiber tapered in three different size which are 2μm, 4μm and 8μm. The "soften-and-compress" technique used to form the MBR using manual splicing machine, were later couple with the taper microfiber for sensing setup. The experiment conducted in the sealed chamber with humidity range is controlled from 40% to 95% RH for each different tapered microfiber. The performance of sensor analyses from toward different diameter of taper microfiber with the MBR coupled for diverse humidity level.

3.2 Micro-Bottle Resonator (MBR)

The MBR is other smaller investigated geometry. An MBR created from a cylinder with deformation. Where for the deformation is the radius rising to maximum, then reduce again. Through the combine, WGMs and MBR with bouncing ball modes, including caustics which bound of the distribution on the axial direction and regularly available Q-factor are on the range of 10^7 (Bianucci, 2016), there is some advantage of the MBR over microsphere, these advantages are:

- using tapered optical fibers to better control over the coupling
- the feasibility of taking many of the equally-spaced modes in the spectrum
- fast tunability by the application of strain (Bianucci, 2016)

3.2.1 Fabrication of MBR

The fabrication process of the MBR for this work has been done through a method which is called "soften-and-compress" (G. S. Murugan, M. Petrovich, Y. Jung, J. Wilkinson, & M. Zervas, 2011). An SMF-28 with continuous length in clamped in a manual splicer on two sides (Furukawa Electric Fitel S178A) while a small section of the fiber is heated under a plasma ARC. At the same time, the two ends of the optical fiber are compressed inward in the plasma ARC direction and as a result, it transforms into a structure of bottle. After the fabrication process, the size of the MBR is physically describes as the bottle distance across D_b is set at 190 µm, the stem width D_s is set at 125 µm and the neck-to-neck length L_b is set at 182 µm, which is shown in figure 3.1 (Johari et al., 2018). The splicing machine was set at 25 second heat time for every heat mode with common arc power at 111 respectively end of silica fiber place on holder while the arc process applied at the middle area of fiber. The numbers or ARC will influence the size of bottle of the MBR (Murugan, Wilkinson, & Zervas, 2009).

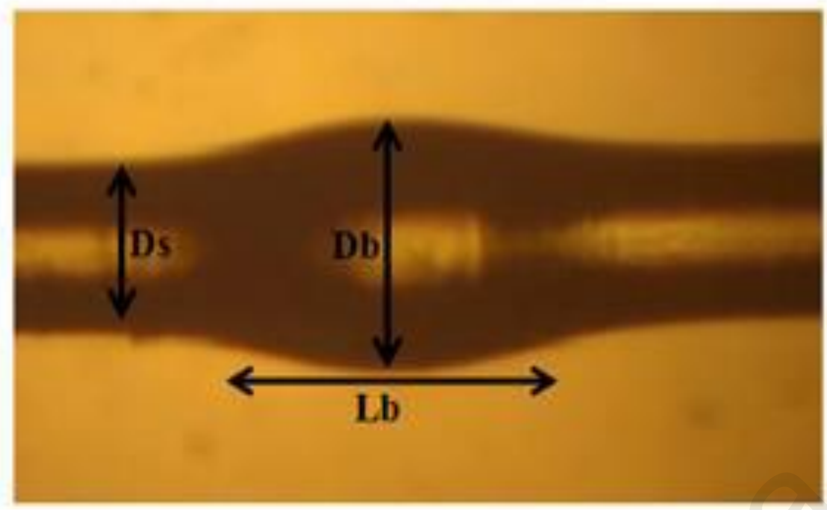


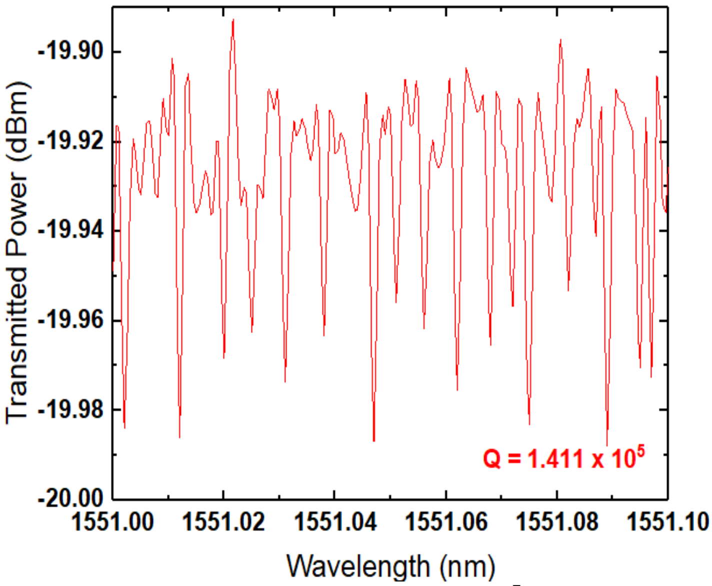
Figure 3.1: The MBR structure with three parameters with $L_b = 182\mu m, D_s = 125\mu m, D_b = 190\mu m$

3.3 Experiment Setup

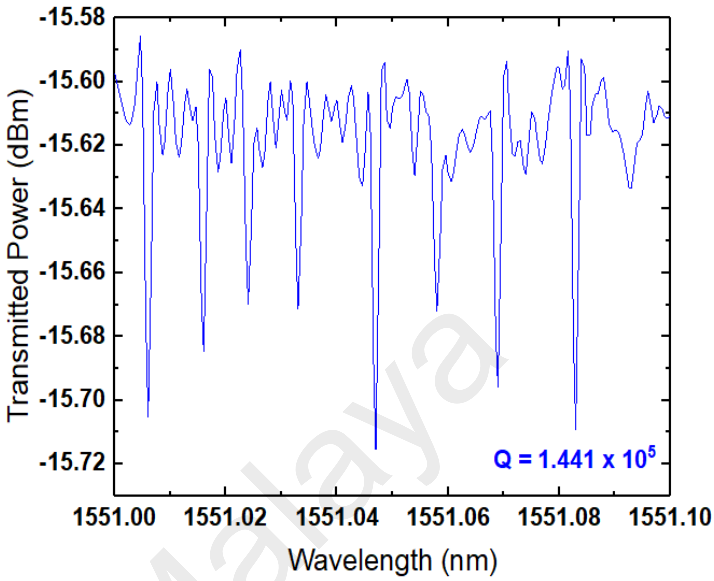
The experiment begins with the forming different diameter size of taper MF using manual tapering machine. The different size of microfiber is formed by flame brushing technique, where the size of SMF-28 silica fiber is minimized and formed 2µm, 4µm and 8µm (Lim, Harun, Arof, & Ahmad, 2012). Continue with the MBR formed process, manual splicing machine is used to bloating the SMF-28 silica fiber with procedure so known as "soft-and-compress" (G. Murugan, S, M. Petrovich, Y. Jung, J. Wilkinson, & M. Zervas, 2011).

The taper microfiber with mention diameter were than couple with the MBR. The distance between the MBR and taper microfiber will be remained 0 µm respectively for all size of taper microfiber. The cross position of the MBR is 90°perpendicular with the tapered microfiber and were placed in the middle area of tapered microfiber.

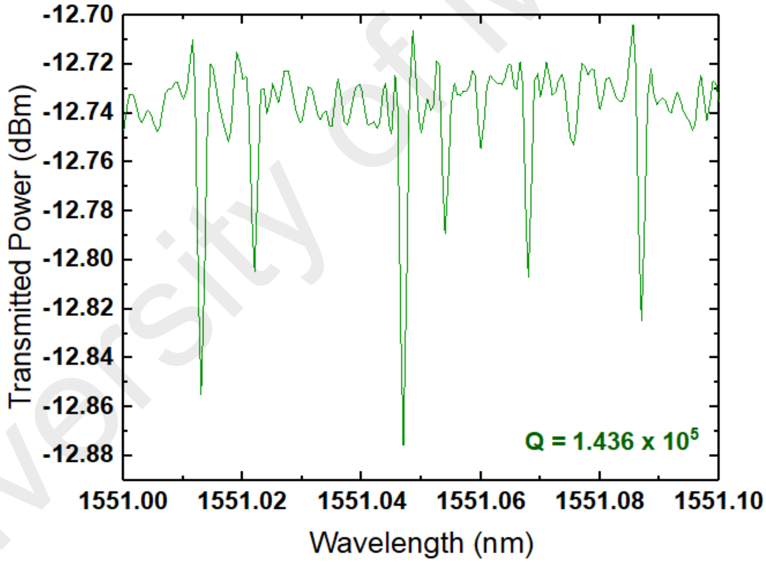
The tunable laser source (ANDO AQ4321D) used to supply wavelength range from 1551.0 nm to 1551.10 nm with 0.001 nm interval. The laser used to utilize the WGMs on resonator and experienced numbers of resonance depth. The optical power meter (THORLABS S145C) used to collect value of transmitted power. Through different diameter of tapered MF, pattern of resonance was defined inequivalent for each tapered size.



(a) Q = 1.411 × 10^5



(b) Q = 1.441 × 10^5



(c) Q= 1.436 × 10^5

Figure 3.2: The transmission power of the MBR coupled on (a) 2 µm, (b) 4 µm and (c) 8 µm at midriff diameter of tapered fiber

Fig 3.2 showed transmission power of three different tapered microfiber diameter. The MBR is coupled with tapered microfiber manage to developed some sharp peaks of resonant (Nasir, Murugan, & Zervas, 2016a) . The insertion loss for the MBR is roughly from -12 dBm to -18 dBm, which is differenced by different diameter size of tapered microfiber. The insertion loss could be control by managing the distance between the MBR with tapered microfiber and the angle position of the MBR while coupled with tapered microfiber(Cai, Painter, & Vahala, 2000). The calculation of quality factor is applied by defined the value of resonant wavelength ($\frac{\Delta\lambda}{\lambda}$) where is almost similar for different size of tapered fiber. The Q-factor of the MBR for all size of tapered MF is around 10^4 respectively.

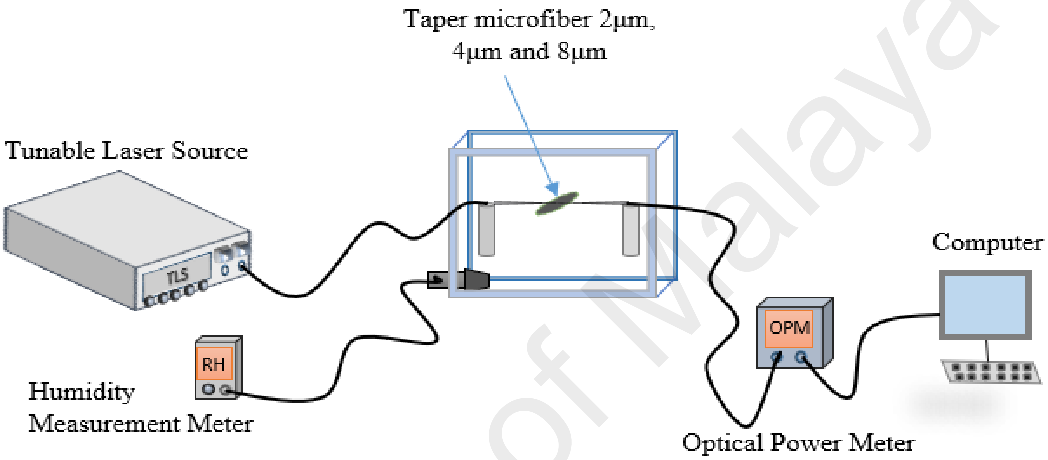


Figure 3.3: The MBR coupled with tapered microfiber in three different diameter size

As showed in Fig 3.3, the MBR coupled with three different diameters of tapered fiber. The experiment later continues to use as humidity sensing and conducted in sealed chamber. The chamber would use to stabilized percentage of humidity. It will reduce losses cause by external interferences during experiment. The wavelength used for sensing experiment is 1551.04 nm which the deepest resonant depth experienced. The wavelength supplied from the TLS and capture by optical power meter through the sensing part. The level of humidity is from 40% to 95% RH for all size of tapered microfiber respectively.

3.4 Results and Discussion

The results of the MBR coupled three diameter size of tapered MF recorded in linear trend line as Fig 3.4. Base on the line graph, the analysis has been recorded in Table 1 respectively. The graph showed the down trend for all condition while the humidity level increased. The result showed by 2 µm tapered MF while coupled with the MBR managed to have higher in sensitivity, linearity and standard deviation value, compare with other size of tapered MF.

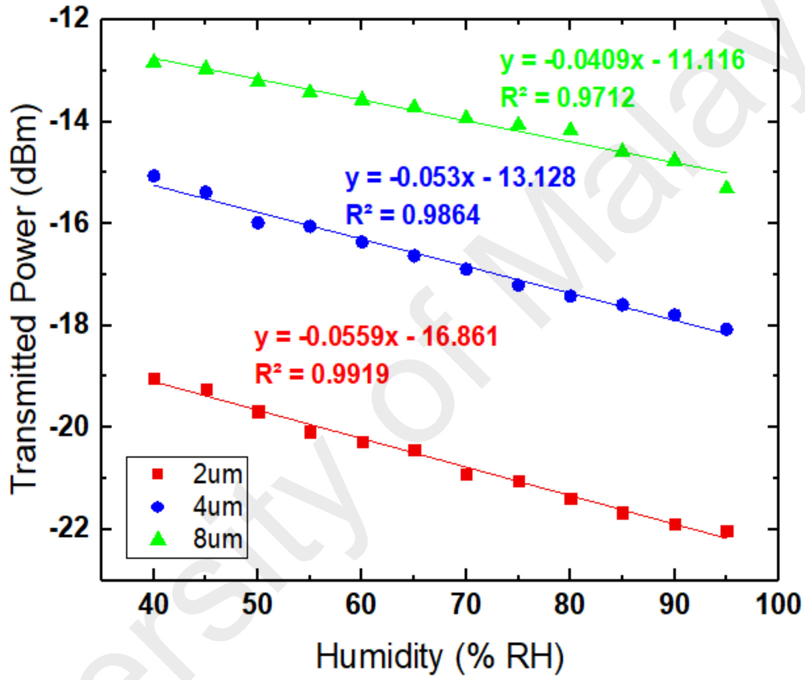


Figure 3.4: The linear trend line fitting for transmitted power of the MBR with three diameter size of tapered microfiber as humidity sensor

Table 3.1 showed sensitivity, linearity, standard deviation and p-value for three size of tapered microfiber as humidity sensor while couple with the MBR. The MBR couple with 2 µm tapered MF manages to have higher sensitivity value than other two diameter size of tapered MF which is 0.0559 dB% RH. The linearity for all coupled MBR were > 90% which is consider good performance. The standard deviation value by 2 µm tapered MF is 0.2 dBm lower than 4 µm and 0.3 dBm lower than 8 µm, which indicated that the best data collection by 2 µm. The P-value for all size of diameter tapered MF were $> 10^{-5}$, which is consider data collected in correct way. The small diameter of tapered fiber in directly capable to expose wide evanescent filed around the tapered fiber. This would increase potential of the WGMs to be inducted on resonator and maximize sensing performance. Additionally, the absorption of water particle by the MBR would be potentially increase the capability of the MBR couple with smallest tapered MF as humidity sensor (Arregui, Liu, Matias, & Claus, 1999; Batumalay, Harun, Irawati, Ahmad, & Arof, 2015).

Table 3.1: performance analysis of MBRs in humidity sensing activity

Parameters	2 µm	4 µm	8 µm
Sensitivity (dB/%RH)	0.0559	0.0530	0.0409
Linearity (%)	99.59%	99.32%	98.55%
Standard deviation (dBm)	0.7485	0.9613	1.0123
P-value	3.82×10^{-18}	3.82×10^{-16}	6.85×10^{-15}
Linear Range (%)	40 - 95	40 - 95	40 - 95

3.5 Summary

This chapter introduces the performance of sensor analyzed from toward different diameter of taper MF with the MBR coupled for diverse humidity level. The SMF-28 silica fiber tapered in three different sizes which are 2µm, 4µm and 8µm and the "soften-and-compress" technique used to form the MBR using manual splicing machine, were later coupled with the taper MF for sensing setup and midriff 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 splicing machine was set at 25 second heat time for every heat mode with common arc power at 111 respectively. TLS used to supply wavelength range from 1551.0 nm to 1551.10 nm with 0.001 nm interval. However, the Q-factor succeeds to have around 10^4 for all size of tapered microfiber of MBRs. The performance of the MBRs from investigate by comparing these three abilities to become a humidity sensor. The sensitivity, linearity, standard deviation and P-value were listed parameters used to evaluate sensing performance. In addition to, the P-value for all size of diameter tapered microfiber were $> 10^{-5}$, which is consider data collected in correct way. As conclusion, the result showed the best data collection by 2 µm tapered microfiber while coupled with the MBR managed to have higher in sensitivity, linearity and standard deviation value, compare with other size of tapered microfiber.

CHAPTER 4: MICRO-BOTTLE RESONATOR COATED WITH PMMA AND PVA FOR HUMIDITY SENSING

4.1 Introduction

Recently, OMRs captured attention in research field due to various promising performance in sensor purpose such in biological and chemical industries, where several structures mostly used such microsphere, micro-ring and micro-disc (Hanumegowda et al., 2005; Jali et al., 2018; Krioukov et al., 2003; Nadeau et al., 2002; Vollmer et al., 2003; Vollmer et al., 2002). The OMRs works by utilizing the WGMs inside the resonator also on the resonator outer shape. The WGMs on the surface of resonator were travel in nanometer length which contributed to the changed of the refractive index of resonator where also driven by potential artificial on the resonator surface. The high Q-factor and nature light involvement finally improved the WGMs quality as overall and it was defined by comparing the light suppression with the quality of modes in the resonator. The transmitted modes would experience high losses during traveled toward resonator where the Q-factor took part to be calculated for defining the valuable WGMs (Michelitsch et al., 2011). Additionally, the OMRs sensor able to perform in low test utilization, multiple capacities, high affectability with little impression.

Investigations on OMRs potential in sensing has been starched out especially on different structure and shape. Thus, each of OMR structure experienced different capability on WGMs supported which conducted to specific useable sensing application (Birks et al., 2000; Ilchenko et al., 2001). This was the root idea to used OMR micro-bottle shape structure as a sensor, where believed to be a strong contender among another OMR, based on several previous researched. The MBR has a structure of spheroid, allowed WGMs to performed expectedly incline which is make it strong resonator. Not same as other like microsphere (where mode-decline performed gradually), MBR could productively energized an assortment of modes, make it valued for sensing (Murugan et al., 2009). As specific, along the MBR hub which known as high quality, notable modes would display in spatial isolated areas. The mixing of WG-ball and WG-ring standard allowed MBRs to bolster in 3-D WGM genuine light confinement (Sumetsky, 2004).

Generally, Relative Humidity (RH) sensors use for many applications in medicine, architectural engineering fields, meteorology, and agriculture. The RH sensors can be described as a partial pressure of vapor ratio to the equivalence pressure of vapor water at the certain temperature. However, RH sensors have the disadvantage as an electromagnetic interference, long response time and corrosion. Optical fiber sensing methods with many benefits such as compact structure, electromagnetic resistant, low weight, high accuracy, fast response time and high stability. So optical fiber have been considered as applicants to overcome rh sensing weakness. Several techniques of the optical fiber RH sensing probes have been proposed, such as an OMR using a phase shift, coated MF, polymer single nanowire, and a quantum dot doped polymer.

In this chapter, we are introducing the comparison of different coated MBR for humidity sensing. The MBR formed with technique known as “soften-and-compress” on SMF-28 silica fiber using tapering machine. The MBR characteristic is firstly defined by employed with 2µm tapered bare fiber before being employed for humidity range of 40% - 95% with two different coated MBR. The MBR firstly coated with PMMA then followed with PVA coating, which purposely used for sensing characteristic. Analysis of the performance of MBR towards different coating material exposed the potential of MBR in humidity sensing.

4.2 Fabrication of PMMA

The MBR with mention diameter is coated with PMMA for use to utilize the WGMs by couple on 2µm taper bare MF. For the coating process of the MBR-PMMA coated, the PMMA which in crystal form is used for 1.0 mg and mixed with isopropanol liquid for 10 ml. This combination heated on the hot plate at 100°C and stirred at 700 RPM, for one hour, which is shown in figure 4.1. The complete solution liquid than placed on the top of the MBR and leave it to dry for one day. This is to ensure that the PMMA is finely coated on the surface of the MBR (Isa, Irawati, Harun, et al., 2018).

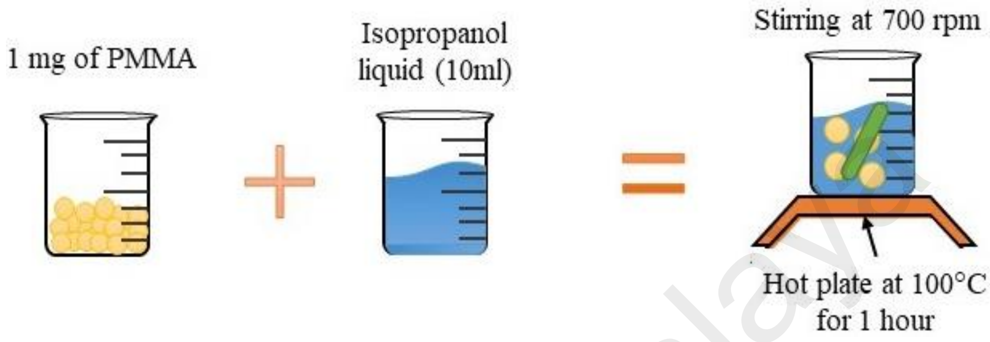


Figure 4.1: schematic diagram of process for fabrication of PMMA

4.3 Fabrication of PVA

The creation of PVA for this experiment has been done by using both the PVA and distilled water. Distilled water is a kind of water which boiled into the steam and evaporated back into the liquid in a distinct container. In industries, chemical & biological laboratories as well as for many other purposes, deionized water has been used which referred to as distilled water. Firstly, for fabrication of PVA solution, 5mg of PVA has been added with 12 ml of volume of distilled water. Next, the mixture is in ultrasonic bath for 6 hours with 20°C temperature, which is shown in figure 4.2. Eventually, dripping the PVA solution on MBR.

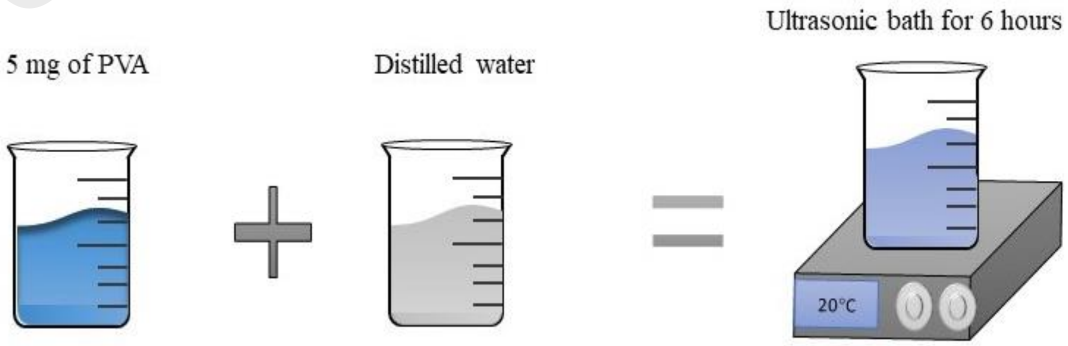


Figure 4.2: schematic diagram of process for fabrication of PVA

4.4 Experiment Setup

The experiment begins with the forming of the MBR using standard silica fiber SMF-28 by a technique known as "soften-and-compress" (G. Murugan, S et al., 2011). The manual splicing machine (Furukawa Electric Fitel S178A) is used for this technique, where several ARC numbers been applied in the middle of fiber until the bottle structure is formed. The size of bolster is totally depended on the numbers of ARC applied during the process, where create a different lump in the fiber focal point (Murugan et al., 2009). The bottle shape resonator would be utilizing the WGM after been employed with bare fiber 2µm diameter size which created by FBT (Lim et al., 2012). The bottle resonator would be formed in a specific parameter, which physically described as the bottle distance across D_b, the stem width D_s and the neck-to-neck length L_b, as in Fig 4.3 (Johari et al., 2018).

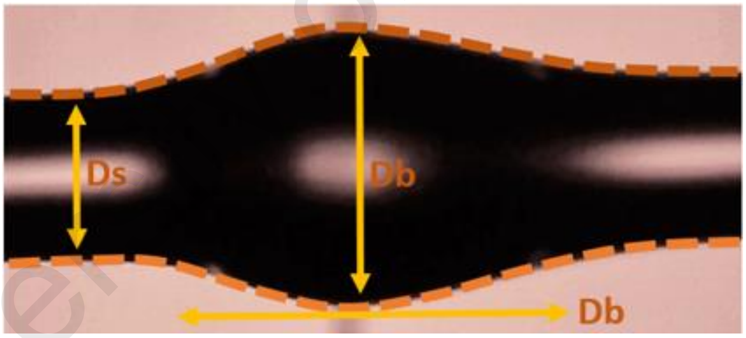
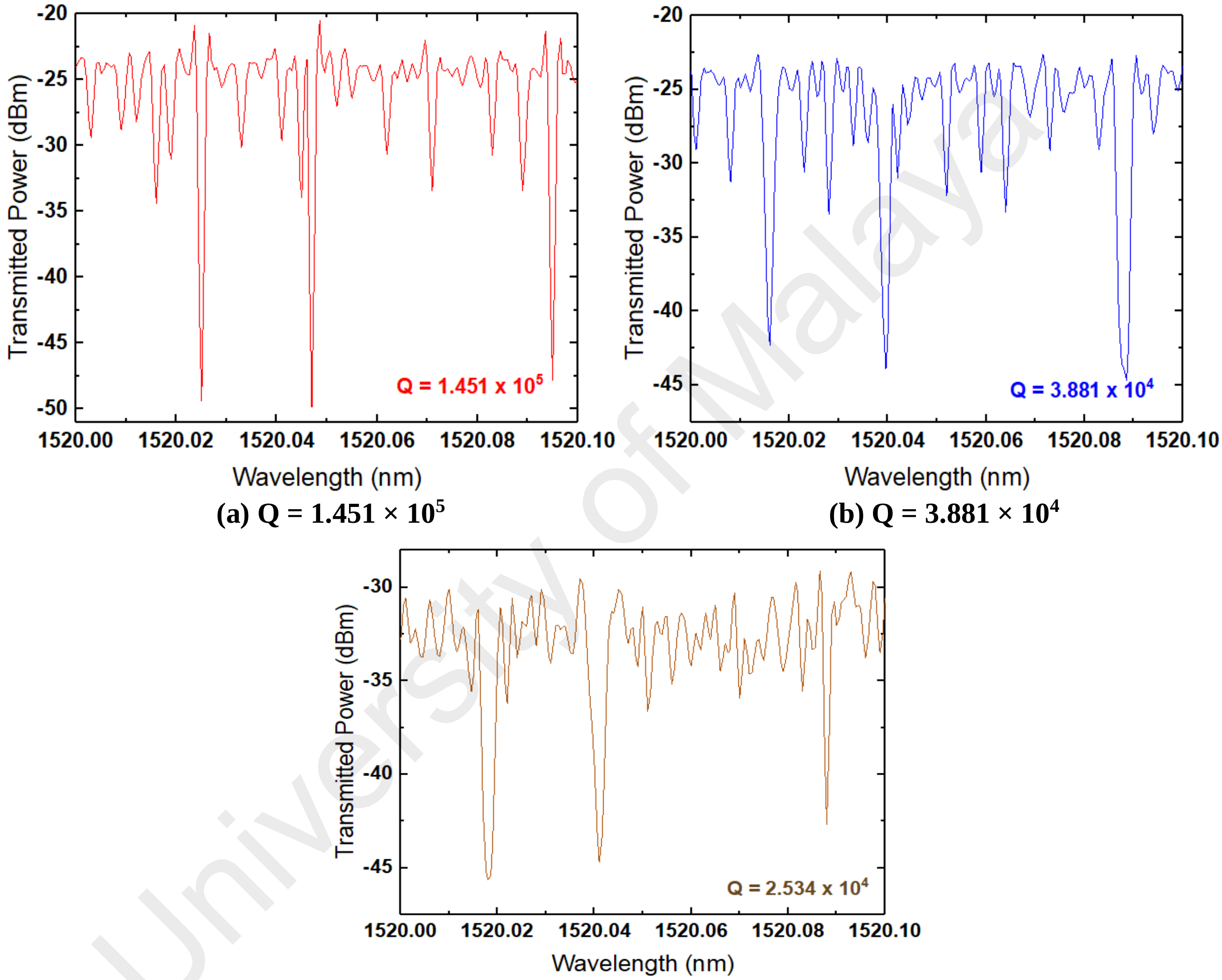


Figure 4.3: The fabricated of MBR with three physical parameters Optical MBR

The MBR with mention diameter is coated with PMMA and PVA for use to utilize the WGMs by couple on 2µm taper bare MF. The MBR used for WGM utilization would be bare MBR, MBR coated with PMMA and MBR coated with PVA.

The wavelength range between 1520.0 nm to 1520.10 nm is used to utilize the WGMs of bottle resonator by tapered bare MF with a 2 µm midriff diameter, where is supplied from the tuneable laser source (ANDO AQ4321D). The wavelength interval is 0.001 nm and it is supposed could discover the resonation depth through the transmission where is the optical power meter (THORLABS S145C) is used to collect transmitted power data.



(a) Q = 1.451 × 10^5

(b) Q = 3.881 × 10^4

(c) Q = 2.534 × 10^4

Figure 4.4: The transmission power of MBR coupled on 2 µm midriff diameter of tapered fiber (a)without coating, with (b)PMMA coated and (c)PVA coated

In Fig 4.4, the transmission modes if easily developed while its couple with the MBR whereas some of the sharp peaks which thought as resonant depth defined (Nasir et al., 2016a). The transmissions spectral utilized with the MBR non-coated for the first, followed by the MBR with PMMA coated and finished with the MBR-PVA coated.

The insertion loss showed by these three conditions is roughly from -19 dBm to -30 dBm, which differenced by the coated material used on the top surface of the MBR, which could finely be controlled by the distance between the MBR and the tapered bare MF while coupled (Cai et al., 2000). The taper bare MF formed in non-adiabaticity, whereas gave significant insertion loss. The Q-factor is to use to justify the quality of resonant depth for each MBR used, where can be defined as $\frac{\Delta\lambda}{\lambda}$ and probably not same for every MBRs. The Q-factor for the non-coated MBR is 1.451×10^5 which is higher than the MBR-PMMA coated is 3.881×10^4 and the MBR-PVA coated 2.534×10^4.

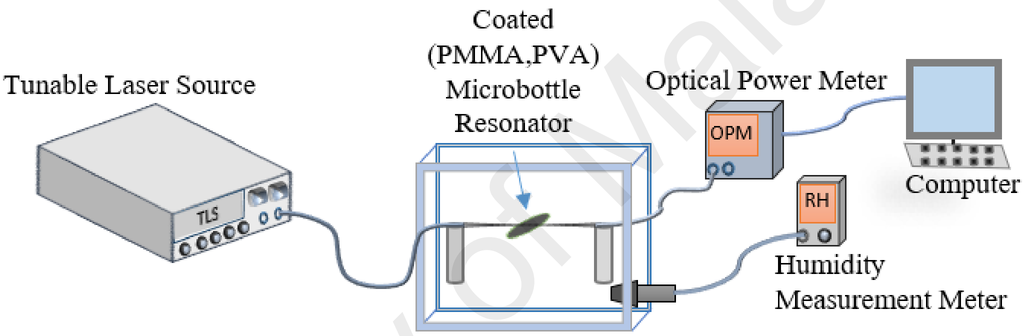


Figure 4.5: The setup of experimental of MBR (bare MBR, MBR coated PMMA and MBR coated PVA) with humidity sensing and a tapered microfiber of $2\mu m$ waist diameter

Fig 4.5 showed the setup of the experiment that has been used for humidity sensing. The MBRs placed in the humidity chamber where the humidity level tasted is controlled. The end of fiber setup related to TLS and another end related to computer through Optical Power Meter (OPM) for result collection. The humidity level was then varied from 40% to 95%. The transmitted power for humidity level recorded at 1520.04 nm on each org MBRs coupled. The experiment experienced three cycle repeatability for each MBR used, only to minimize random error. For one type of MBR, the level of humidity used is from 40% to 95% before another type of MBR (coated MBR) been used for the next experiment. The comparison then finally made after all MBR already used and experienced three-time repeatability. Finally, the transmitted power is recorded on 65% of humidity for 60 second period, purposely to investigate sensor stability.

4.5 Results and Discussion

The analysis of the MBRs performance showed in Fig 4.6 for different level of humidity. Three different linear graphs presented based on different MBR used during couple with taper MF. In general, decreasing trend presented by each MBRs with increasing level of humidity, which affected the performance of the sensor. As recorded in Table 1, the MBR coated with PVA notably better in sensitivity than other two type of MBR for humidity sensor which was 0.1215 dB % RH, two times higher than non-coated MBR. The standard deviation of the MBR-PVA coated also indicated highest than others by received the smallest number than others two, 0.2297 dBm. Even though the linearity and p-value of the MBR-PVA coated slightly lower, it only uses as an extra indicator to ensure the data is collected correctly, where is still acceptable (more than 90% with 0.2297 of p-value). As humidity sensing, the MBR coated with PVA indicated fine result than the MBR-PMMA coated and non-coated MBR. The losses increased while the transmission at high humidity levels happened due to a reduction on surface absorption experienced by the MBRs. Though, the losses are higher for the MBRs coated than non-coated MBR, due to multiple circulated of light experienced by non-coated MBR is better than coated MBRs. This help to increase the sensitivity of sensing for sensor (Arregui et al., 1999; Batumalay et al., 2015). However, the PVA used as coating medium on the MBR was lead to increase the sensitivity of sensor (Penza & Cassano, 2000).

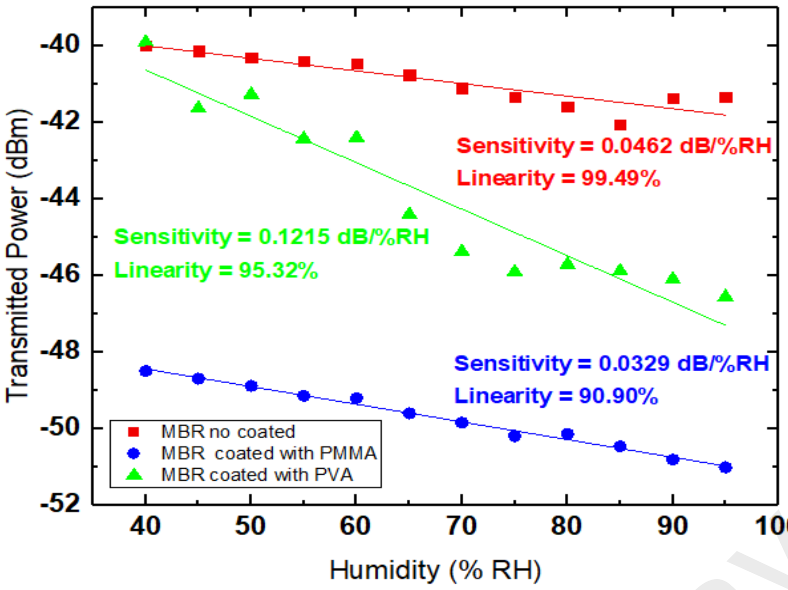
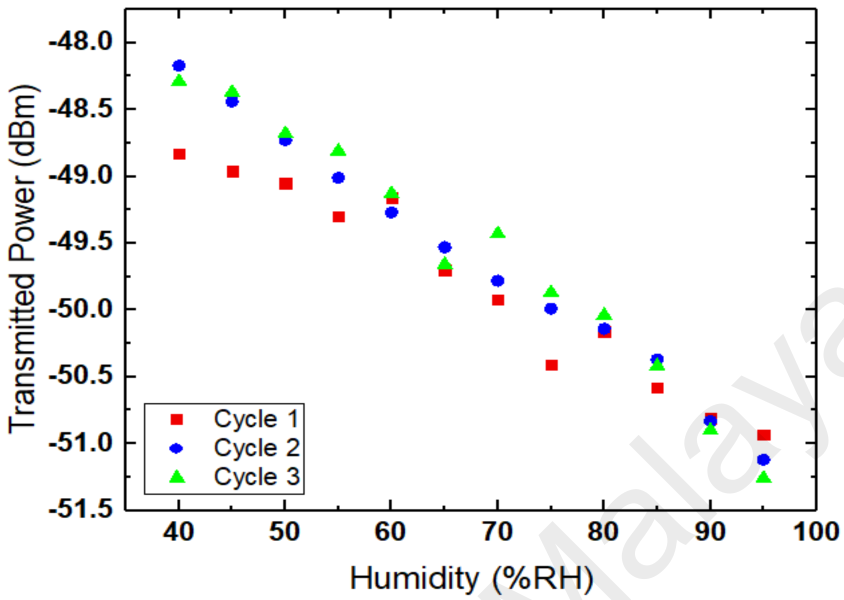


Figure 4.6: Transmitted power value with different concentration levels of formaldehyde for MBR and bare microfiber

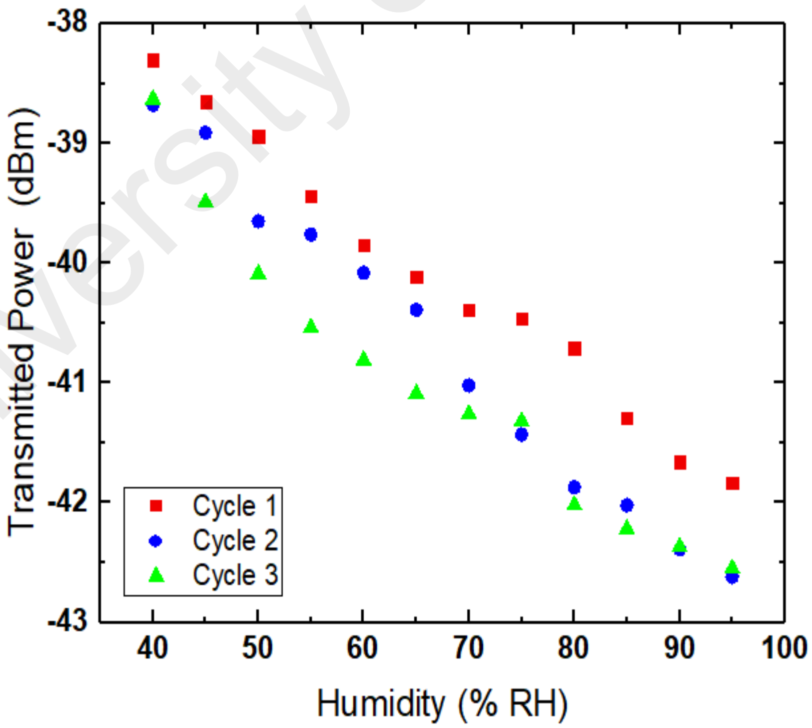
Table 4.1: Performance analysis of MBRs in humidity sensing activity

Parameters	**Non-coated MBR**	**MBR-PMMA coated**	**MBR-PVA coated**
Sensitivity (dBm/%RH)	0.0462	0.0329	0.1215
Linearity (%)	99.49%	90.90%	95.32%
Standard deviation (dBm)	0.8372	0.6528	0.2297
P-value	6.59×10^{-23}	5.42×10^{-17}	1.41×10^{-12}
Linear Range (%)	40 - 95	40 - 95	40 - 95

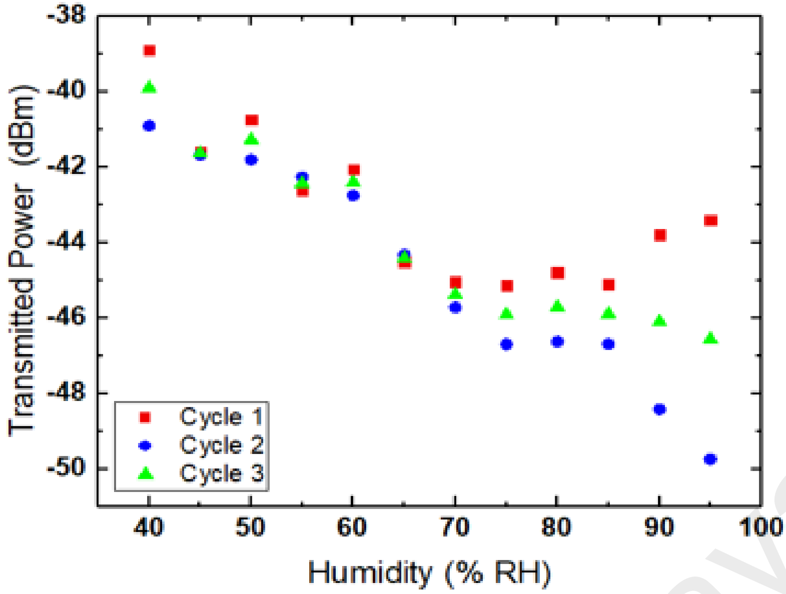
Three times repetition of experiment conducted for each type of the MBRs condition for different humidity level, purposely to investigate repeatability of the setup (Isa, Irawati, Rahman, Yusoff, & Harun, 2018). Fig 4.7 indicated the repetitions cycle done for humidity sensing for each type of the MBRs. The repeatability trend showed by the non-coated MBR is better than others two coated MBR. This is due to coated material which are PMMA and PVA allowed transmitted spectral to experienced unclear sequence compare with non-coated MBR. This procedure ensures that every MBRs coated or non-coated showed well-balanced as humidity sensing.



(a)



(b)



(C)

Figure 4.7: Transmitted power value of (a) non-coated MBR and (b) MBR-PMMA coated and (c) MBR-PVA coated for repeatability performance of varies with different humidity level

Fig 4.8 show the stability performance of the MBRs as humidity sensing within 60-second duration of testing. The humidity level used is 65% RH tasted on three different type of MBR on the same tapering size of 2 μm bare MF. By chance, non-coated MBR, MBR-PMMA, and MBR-PVA coated marked stable performance during this time duration. These MBRs showed below 3% of transmission variation, which is noticeable on this level of humidity.

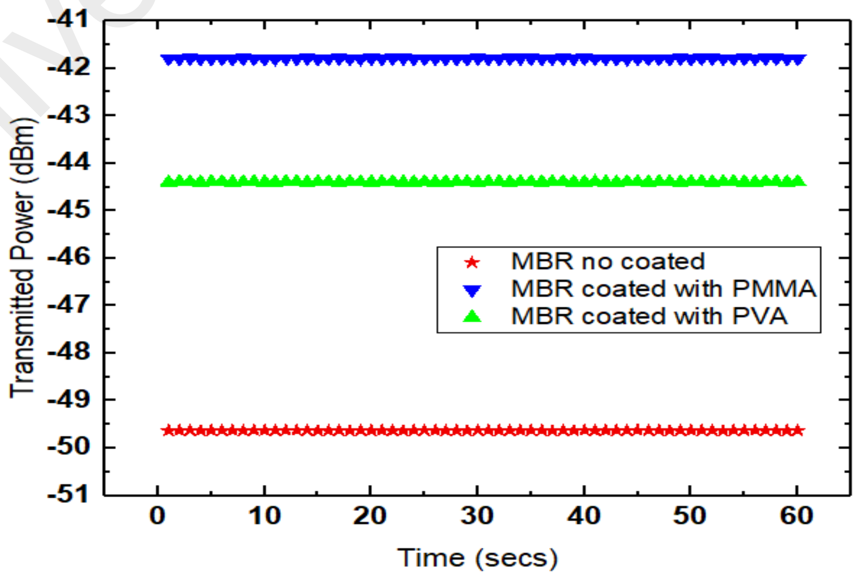


Figure 4.8: The performance of the non-coated MBR, MBR-PMMA coated and MBR-PVA coated varies with time for stability results

4.6 Summary

This chapter introduces the performance of non-coated MBR, MBR-PMMA coated and MBR-PVA coated as humidity sensing. A "soften-and-compress" technique used to form the MBR with midriff diameter of $D_b = 190\ \mu m$, stem diameter of $D_s = 125\ \mu m$ and bottle length of $L_b = 182\ \mu m$. For coating process with PMMA, isopropanol has been mixed with together before use for coating procedure. While PVA coating, distilled water were used to be mixed to foam a coating solution. These three different types of MBRs than used to utilize the WGMs via taper microfiber with waist diameter of 2 µm. TLS were supplied the wavelength with range from 1520.00 nm to 1520.10 nm with 0.001 nm interval. The quality factor succeeds to have $> 10^4$ for all type of MBRs with the non-coated MBR marked as highest in bunch. Via this performance, 1520.04 nm were chosen to be use as supply wavelength for sensing activity. The performance of the MBRs than investigate by comparing these three abilities to become a humidity sensor. The sensitivity, linearity, standard deviation and P-value were listed parameters used to evaluate sensing performance. The MBR-PVA coated than found success in most of parameter. The p-value which is $> 10^{-5}$ for all MBRs ensuring that these data collected correctly. The MBRs than undergoing 60 second of stability test for in 65% RH humidity level for stability procedure. As conclusion, the MBR-PVA coated performed well as humidity sensor than non-coated MBR and the MBR-PMMA coated.

CHAPTER 5: CONCLUSION

Nowadays, OMRs are contributing to the fundamental research through its discernible structures which followed the phenomena of WGMs. OMRs which tolerate WGMs can generate exceptionally high Q-factors on account of minimum scattering losses and leakage, and low material absorption. Through tailoring the size or diameter, material composition, and shape of the resonator, OMRs has shown great perspective based on the low power, compact size, and high speed. OMRs are widely demonstrated that it not only contributing the fundamental research but also broadly uses for device applications such as sensor and micro-laser with filter, small-scale etc.

Micro-bottle Resonator (MBR) is a new type of OMR, that has been given much consideration because of its distinct features rather than the other OMRs. MBR have several advantages over the other OMRs. This advantage is better control over the coupling by optical tapered MF, fast tunability by the strain application and the probability of attaining a great number of equally-spaced modes in the spectrum. The MBR was fabricated by a procedure which referred as "soften-and -compress" method. Then it was characterized based on the three specific diameters such as bottle diameter, stem diameter, and neck-to-neck length.

Firstly, the experiment has been done to evaluate the performance of sensor analyzed from toward different diameter of taper microfiber with the MBR coupled for diverse humidity level. The SMF-28 silica fiber tapered in three different sizes which are 2µm, 4µm and 8µm and the "soften-and-compress" technique used to form the MBR using manual splicing machine. TLS used to supply wavelength range from 1551.0 nm to 1551.10 nm with 0.001 nm interval. However, the Q-factor succeeds to have around 10^4 for all size of tapered MF of MBRs. The sensitivity, linearity, standard deviation and P-value were listed parameters used to evaluate sensing performance. In addition to, the P-value for all size of diameter tapered microfiber were $> 10^{-5}$, which is consider data collected in correct way. Eventually, the result showed the best data collection by 2 µm tapered microfiber while coupled with the MBR managed to have higher in sensitivity, linearity and standard deviation value, compare with other size of tapered microfiber.

Secondly, the experiment has been done to evaluate the performance of non-coated MBR, MBR-PMMA coated and MBR-PVA coated as humidity sensing. These three different types of MBRs than used to utilize the WGMs through taper MF with waist diameter of 2 µm. TLS were supplied the wavelength with range from 1520.00 nm to 1520.10 nm with 0.001 nm interval. Through this performance, 1520.04 nm were chosen to be use as supply wavelength for sensing activity. However, the performance of the MBRs than investigate by comparing these three abilities to become a humidity sensor. The sensitivity, linearity, standard deviation and P-value were listed parameters used to evaluate sensing performance. Eventually, the MBR-PVA coated than found success in most of parameter. The P-value which is $> 10^{-5}$ for all MBRs ensuring that these data collected correctly. The result shown, the MBR-PVA coated performed well as humidity sensor than non-coated MBR and the MBR-PMMA coated.

As a future work, this work could be tested for humidity sensing although there are some other challenges to produce a sensor.

REFERENCES

Allwood, G., Wild, G., & Hinckley, S. (2017). *Fiber bragg grating sensors for mainstream industrial processes*: Electronics, 6(4), 92. doi:10.3390/electronics 6040092.

Armani, A., M, & Vahala, K., J. (2007). *Biological and chemical detection using ultra-high-Q toroidal microresonators*: Biophys. J, 94, 29a-29a.

Arregui, F., J, Liu, Y., Matias, I., R, & Claus, R., O. (1999). *Optical fiber humidity sensor using a nano Fabry–Perot cavity formed by the ionic self-assembly method*: Sensors and Actuators B: Chemical, 59(1), 54-59.

Baker, M. I., Walsh, S. P., Schwartz, Z., & Boyan, B. D. J. J. o. B. M. R. P. B. A. B. (2012). *A review of polyvinyl alcohol and its uses in cartilage and orthopedic applications*. *100*(5), 1451-1457.

Barrios, C., A, Gylfason, K., B, Sanchez, B., Griol, A., Sohlstrom, H., Holgado, M., & Casquel, R. (2007). *Slot-waveguide biochemical sensor*: Optics Letters, 32(21), 3080-3082.

Batumalay, M., Harun, S., W, Irawati, N., Ahmad, H., & Arof, H. (2015). *A study of relative humidity fiber-optic sensors*: IEEE Sensors Journal, 15(3), 1945-1950.

Bianucci, P. (2016). Optical microbottle resonators for sensing. *sensor*, *16*(11), 1841.

Birks, T., Knight, J., & Dimmick, T. J. I. P. T. L. (2000). High-resolution measurement of the fiber diameter variations using whispering gallery modes and no optical alignment. *12*(2), 182-183.

Cai, M., Painter, O., & Vahala, K., J. (2000). *Observation of critical coupling in a fiber taper to a silica-microsphere whispering-gallery mode system*: Physical review letters, 85(1), 74.

Chen, Y., Xu, F., & Lu, Y. Q. (2011). *Teflon-coated microfiber resonator with weak temperature dependence*. Optics express, 19(23), 22923-22928.

Feron, P. (2004). *Whispering gallery mode lasers in erbium doped fluoride glasses*: Paper presented at the Annales de la Fondation Louis de Broglie.

Gomilsek, M. (2011). *Whispering gallery modes*: Univ. Ljubl. Ljubl. Semin.

Guo, X., Ying, Y., & Tong, L. (2013). *Photonic nanowire: from subwavelength waveguides to optical sensors*. Accounts of chemical research, 47(2), 656-666.

Hanumegowda, N., M, White, I., M, Oveys, H., & Fan, X. (2005). *Label-free protease sensors based on optical microsphere resonators.*: Sensor Letters, 3(4), 315-319.

Hoss, R., J, & Lacy, E., A. (1993). *Fiber Optics*: Pearson Education.

Humar, M., Ravnik, M., Pajk, S., & Muševič, I. (2009). *Electrically tunable liquid crystal optical microresonators*: Nature Photonics, 3(10), 595.

Ilchenko, V., S, Gorodetsky, M., L, Yao, X., S, & Maleki, L. (2001). *Microtorus: a high-finesse microcavity with whispering-gallery modes*: Optics Letters, 26(5), 256-258.

Isa, N., M, Irawati, N., Harun, S., W, Ahmad, F., Rahman, H., A, & Yusoff, M., H, M. (2018). *Multi-walled carbon nanotubes doped Poly (Methyl MethAcrylate) microfiber for relative humidity sensing*: Sensors and Actuators A: Physical, 272, 274-280.

Isa, N., M, Irawati, N., Rahman, H., A, Yusoff, M., H, & Harun, S., W. (2018). *Polyaniline Doped Poly (Methyl Methacrylate) Microfiber for Methanol Sensing*: IEEE Sensors Journal.

Jali, M., H, Rahim, H., R, A, Ashhadi, M., J, M, Thokchom, S., & Harun, S., W. (2018). *Applied microfiber evanescent wave on ZnO nanorods coated glass surface towards temperature sensing*: Sensors and Actuators A: Physical, 277, 103-111.

Jeunhomme, L., B. (1983). *Single-mode fiber optics. Principles and applications.*: Optical Engineering, New York: Dekker, 1983.

Jiang, X., Chen, Y., Vienne, G., & Tong, L. J. O. l. (2007). All-fiber add-drop filters based on microfiber knot resonators. *32*(12), 1710-1712.

Jin, N. J., Yeon, J., Min, S.-H., Yeon, K.-S. J. I. J. o. C. S., & Materials. (2018). *Strength Developments and Deformation Characteristics of MMA-Modified Vinyl Ester Polymer Concrete*. *12*(1), 4.

Johari, Md, M. A., Khudus, M. I. M. A., Jali, M. H. B., Al Noman, A., & Harun, S. W. (2018). *Effect of size on single and double optical microbottle resonator humidity sensors*: Sensors and Actuators A: Physical.

Jung, Y., Brambilla, G., & Richardson, D. J. J. O. l. (2010). Polarization-maintaining optical microfiber. *35*(12), 2034-2036.

Kippenberg, T., J, A. (2004). *Nonlinear optics in ultra-high Q whispering-gallery optical microcavities*: California Institute of Technology.

Kringlebotn, J., Archambault, J., L, Reekie, L., & Payne, D. (1994). *Er 3+: Yb 3+-codoped fiber distributed-feedback laser*: Optics Letters, 19(24), 2101-2103.

Krioukov, E., Greve, J., & Otto, C. (2003). *Performance of integrated optical microcavities for refractive index and fluorescence sensing*: Sensors and Actuators B: Chemical, 90(1-3), 58-67.

Lim, K., Harun, S., Arof, H., & Ahmad, H. (2012). *Fabrication and applications of microfiber*: InTech.

Little, B., E, Laine, J., P, & Haus, H., A. (1999). *Analytic theory of coupling from tapered fibers and half-blocks into microsphere resonators*: Journal of lightwave technology, 17(4), 704.

Lott, J., Ledentsov, N., Ustinov, V., Maleev, N., Zhukov, A., Kovsh, A., & Bimberg, D. (2000). *InAs-InGaAs quantum dot VCSELs on GaAs substrates emitting at 1.3 μm*: Electronics Letters, 36(16), 1384-1385.

Lou, J., Wang, Y., & Tong, L. (2014). *Microfiber optical sensors: a review. Sensors (Basel)*: 14(4), 5823-5844. doi: 10.3390/s140405823.

Matsko, A., B, & Ilchenko, V., S. (2006). *Optical resonators with whispering-gallery modes-part II: applications*: IEEE Journal of selected topics in quantum electronics, 12(1), 15-32.

Matthew, R., & Foreman, J., D, S. (2015). *Whispering gallery mode sensors. Advances in Optics and Photonics,* : 17(2), 168-240.

Michelitsch, T., Maugin, G., A, Mujibur, R., Derogar, S., Nowakowski, A., F, & Nicolleau, F., C. (2011). *A self-similar field theory for 1D linear elastic continua and self-similar diffusion problem*: arXiv preprint arXiv:1105.5322.

Murugan, G., S, Petrovich, M., Jung, Y., Wilkinson, J., & Zervas, M. (2011). *Hollow-bottle optical microresonators*: Optics Express, 19(21), 20773-20784.

Murugan, G., S, Wilkinson, J., S, & Zervas, M., N. (2009). *Selective excitation of whispering gallery modes in a novel bottle microresonator*: Optics express, 17(14), 11916-11925.

Murugan, G. S., Petrovich, M., Jung, Y., Wilkinson, J., & Zervas, M. (2011). Hollow-bottle optical microresonators. *Optics express, 19*(21), 20773-20784.

Nadeau, J., L, Illchenko, V., S, Kossakovski, D., Bearman, G., H, & Malkei, L. (2002). *High-Q whispering-gallery mode sensor in liquids*: Paper presented at the Laser Resonators and Beam Control V.

Naqshbandi, A., Khan, W., Rizwan, S., & Khan, F. (2012). *Studies on the protective effect of flaxseed oil on cisplatin-induced hepatotoxicity.*: Human & Experimental Toxicology, 31(4), 364-375. doi: 10.1177/0960327111432502.

Nasir, M., N, M, Murugan, G., S, & Zervas, M., N. (2016a). *Broadly tunable solid microbottle resonator* In Photonics Conference (IPC), 2016 IEEE (pp. 759-760). IEEE.

Nasir, M., N, M, Murugan, G., S, & Zervas, M., N. (2016b). *Spectral cleaning and output modal transformations in whispering-gallery-mode microresonators*: JOSA B, 33(9), 1963-1970.

Nasir, M., N, M, Yusoff, Z., Al-mansoori, M., H, Rashid, H., A, A, & Choudhury, P., K. (2009). *Widely tunable multi-wavelength Brillouin-erbium fiber laser utilizing low SBS threshold photonic crystal fiber*: Optics express, 17(15), 12829-12834.

O'Shea, D., Junge, C., Nickel, S., Pöllinger, M., & Rauschenbeutel, A. (2011). *Ultra-high Q whispering-gallery-mode bottle microresonators: properties and applications*: Paper presented at the Laser Resonators and Beam Control XIII.

Penza, M., & Cassano, G. (2000). *Relative humidity sensing by PVA-coated dual resonator SAW oscillator*: Sensors and Actuators B: Chemical. 68(1-3): p. 300-306.

Richtmyer, R. (1939). *Dielectric resonators*: Journal of Applied Physics, 10(6), 391-398.

Righini, G., C, Dumeige, Y., Féron, P., Ferrari, M., Nunzi Conti, G., Ristic, D., & Soria, S. (2011). *Whispering gallery mode microresonators: fundamentals and applications*: Rivista del Nuovo Cimento, 34(7), 435-488.

Savchenkov, A., A, Matsko, A., B, Ilchenko, V., S, & Maleki, L. (2007). *Optical resonators with ten million finesse*: Optics express, 15(11), 6768-6773.

Sumetsky, M. (2004). *Whispering-gallery-bottle microcavities: the three-dimensional etalon*: Optics Letters, 29(1), 8-10.

Tobin, L., Y, & Dumon, P. (2010). *Fundamental principles of operation and notes on fabrication of photonic microresonators Photonic Microresonator Research and Applications*: (pp. 1-27): Springer.

Tong, L. (2018). *Micro/Nanofibre Optical Sensors*: Challenges and Prospects. Sensors, 18(3), 903.

Tong, L., Hu, L., Zhang, J., Qiu, J., Yang, Q., Lou, J., & Ye, Z. (2006). *Photonic nanowire directly drawn from bulk glasses* Optics Express, 14(1), 82-87.

Tong, L., & Sumetsky, M. (2011). *Subwavelength and Nanometer Diameter Optical Fibers*. Springer Science & Business Media.

Umar , A., Khairil , J., Abd, K., & Nor Aziah, B. (2015). *A review of the properties and applications of poly (Methyl Methacrylate) (PMMA)*. Faculty of Science, Universiti Teknologi Malaysia, Johor Bahru: Malaysia Published online.

Vahala, K., J. (2003). *Optical microcavities*: Nature, 424(6950), 839.

Vollmer, F., Arnold, S., Braun , D., Teraoka, I., & Libchaber, A. (2003). *Multiplexed DNA quantification by spectroscopic shift of two microsphere cavities*: Biophysical journal, 85(3), 1974-1979.

Vollmer, F., Braun, D., Libchaber, A., Khoshsima, M., Teraoka, I., & Arnold, S. (2002). *Protein detection by optical shift of a resonant microcavity*: Applied Physics Letters, 80(21), 4057-4059.

Wu, X., T, L. (2013). *Optical microfibers and nanofibers*: Nanophotonics.

Yoon, M.-S., Kim, H.-J., Brambilla, G., & Han, Y.-G. J. J. o. t. K. P. S. (2012). Development of a small-size embedded optical microfiber coil resonator with high Q. *61*(9), 1381-1385.

Zeng, X., Wu, Y., Hou, C., Bai, J., & Yang, G. J. O. C. (2009). A temperature sensor based on optical microfiber knot resonator. *282*(18), 3817-3819.

Zhang, L., Lou, J., & Tong, L. (2011). *Micro/nanofiber optical sensors*. Photonic Sensors, 1(1), 31-42.

Zhe Chen, V., K, S, H, & Xiaoqing, L. (2011). *Optically tunable microfiber-knot resonator*: Optical Society of America, 19.