Optical Microfiber Sensor : A Review

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Abstract. Due to numerous benefits such as geometrical simplicity, compact size, high sensitivity, broad detection range, low noise, and high accuracy, optical devices have attracted a lot of interest for sensing applications. It is critical in a variety of sectors, including cultural relic preservation, warehouse products maintenance, manufacturing process control, semiconductor, agriculture, food production storage, environmental control, health industries, chemical and home improvement. It outperforms its electronic equivalent owing to its capacity to function in tough and demanding situations such as combustible surroundings, greater pressure and temperature levels, and the ability to send signals over long distances without electromagnetic interference. Optical fiber sensors are classified based on their operating principles such as interferometers, fiber Bragg gratings (FBG), resonators and whispering galleries modes (WGM). This paper presents a comprehensive review related to the optical microfiber sensor such as its properties, fabrication techniques, evanescent wave, optical micro resonators and recent study on the application of microfiber towards humidity sensing. This review could be beneficial to help other researchers to gain greater view in the field of optical microfiber sensor.

Keywords: microfiber, optical sensor, evanescent wave

1. Introduction
During the last century, optical fibers were widely used in the field of telecommunications due to their special attributes such as low transmission loss, high bandwidth and multiplexing capability. Recently the optical fiber application has also shifted to other areas such as sensing to take advantage of the special features of it. Even though the price of the established electronic sensors counterpart is more competitive, optical sensors could find the target application by utilizing their unique features. Some of the unique features are low losses, remote sensing, immune to electromagnetic interference, no electrical
biasing is required to guide light and the viability to use in an environment which has explosion risk. Up to date, optical fiber sensor has gained tremendous interests for various bio-chemical sensing applications such as ethanol, sodium hypochlorite, formaldehyde and human chorionic gonadotropin [1-6]. It is driven by the rapid development of micro/nanotechnology and the need to reduce the size of the sensor while maintaining the key requirement of the sensor such as low power consumption, faster response, better spatial resolution and higher sensitivity [7, 8].

Microfibers have unique properties like large optical confinement, configurability, flexibility, strong optical confinement, and large evanescent field, making them ideal for physical sensing applications like ultra-sensitive surface absorption spectroscopy, hydrogen detection, chemical and refractive index sensors [9, 10]. Due to large evanescent wave propagates outward from the microfiber, it is extremely sensitive to changes in the ambient refractive index. When the proportion of power transmitted in the evanescent field increases, the refractive index of the surrounding material rises. It exhibits good evanescent coupling with other waveguides such as metal, semiconductor and substrate. Thus, high fractional evanescent field allow great responses towards humidity sensing [9].

The type and number of modes propagating through the fiber could be determined by the physical features of the fiber such as RI, core diameter and operating wavelength. Most portion of light energy resides inside the fiber while some portion infiltrates the clad. The small portion decays exponentially into the core-cladding edge. The low amplitude of the evanescent field in a normal single mode fiber (SMF) could be enhanced by tapering in order to increase interaction of analyte around the taper region with the transmitted light [11].

2. Properties
Microfiber offers several interesting optical properties such as strong evanescent field. Fractional power spreads in the evanescent field at the outer physical boundary of the small radii microfiber. This property is essential to fabricate high quality factor (Q) resonators and to launch light into high Q micro-resonators [12]. Microfiber also exhibits strong near-field interaction with its surrounding [13]. It has good evanescent coupling between the microfiber and the other waveguides such as substrates, semiconductor and planar waveguide. This lead to plenty of optical devices such as resonators, sensors and lasers [14].

Propagation loss also is an important property for microfiber. The propagation loss is due to several factors such as cracks, impurities connected to the micro/nano fiber surface and surface imperfections [12]. It increases as the microfiber radii decreases [15]. Theoretical studies on non-adiabatic intermodal transitions were established to examine the minimum microfiber waist diameter that can propagate signal. The transmission mode would disappear at a threshold rate approximately at a value lesser than the radiation wavelength [16]. It is also found that the small size microfiber degrades faster in air when there is a generation of cracks at the facet due to the water absorption [17].

Besides that, microfiber is very sensitive to momentum change of photon guide through by mechanical displacement or vibration mass due to its small mass [13] This enable a development of compact opto-mechanical component/devices [18]. It also allows a low loss when light passing through sharp bends. Therefore microfiber could realize a compact devices with lower power consumption, faster response and smaller footprints [13, 19]. Microfiber is made-up by extending the optical fibers until reaching the desired waist diameter while keeping the original fiber sizes at their input and output ends. This eases a low loss splicing to interconnect with other standard size optical fibers. It also could be bent into a small bending radius to produce a compact devices [12]. The small waist fiber also has a large fraction of power transmitted outside the microfiber and overlaps with the external elements. Any changes in surrounding properties result in a change in output as shown in Figure 1 [20].
Figure 1. Sensitive area has a large fraction of power propagating to interact with the surrounding environment [20]

3. Fabrication techniques
Tapering of a SMF is a process of decreasing the diameter of the cladding (together with the core) by pulling the fiber's end while heating the waist of the fiber. During the tapering process, the light propagates inside the core infiltrates to the cladding. This cause them to acts as a new core and the external element as a new cladding [21]. In order to achieve high signal to noise ratio and low optical loss criteria, surface smoothness and geometric uniformity during fabrication procedure of the microfiber is crucially essential [13].

The tapered fiber adheres to adiabatic criteria if the main portion of power uncouples with higher order modes and sustain in the fundamental mode as the power propagate along the taper. It could be realized by demonstrating a tiny taper angle to the relative local change of the taper radius [21]. When the fiber was pulled during the tapering process, the radius of the fiber decreases and the light extrude from the core to the cladding and propagates throughout the taper region. Thus, the core, cladding and the air would influence the mode. The mode evolution inside the tapered fiber or microfiber is highly related to the shape of the taper. If the taper is too steep, a non-adiabaticity will occur that cause low transmission. The mode propagation become more adiabatic when the tapering angle reduced [22]. Figure 2 (i) shows the different shape between adiabatic and non-adiabatic tapered fiber.

There are several tapering methods to fabricate glass microfiber. The first technique is self-modulated taper drawing. It requires two-step process: first the waist diameter of the single mode fiber is reduced to a micro-meters using standard flame brushing technique. Then the microfiber is broken into two parts and one of the fiber pigtail is enfolded onto a small hot sapphire rod and the microfiber is further drawn into sub-micron diameter. Subsequently, the tip of the sapphire is heated using a flame at a distance from the fiber to stabilize the distribution of the temperature and trap the heat in a small volume [12]. Even though this technique has a quite complex fabrication process, it is capable to produce a tapered fiber with radius as small as 10 nm [23]. Second method is flame brushing technique as shown in Figure 2 (ii). This technique was initially invent to manufacture couplers [24]. It is conducted by applying small flame movement under a stretched optical fiber. The optical fiber extremities and burner are hold by stages and connected to the computer. An highly accurate microfiber could be fabricated by precisely controlled the flame movement [25]. It could produce micro/nanofibers with radius as small as 30 nm and longest nanowires with less measured loss [17]. Besides that this technique allow the microfiber with both ends pigtailed which is essential in practical applications that have issue on connectivity [12].

The flame brushing technique has been upgraded into modified flame brushing technique. This technique has set-up resembles similar as conventional flame brushing technique but the difference is the flame is changed with different heat source which are a micro-heater [26] or a sapphire capillary tube heated by a CO\textsubscript{2} laser beam [27]. Micro-heater is a resistive element which allows temperature to be adjusted by altering the current level. Whereas, temperature control using a sapphire/CO\textsubscript{2} can be
change by tuning the degree focusing of the laser beam onto the sapphire tube. This technique has superiority in terms of processing temperature to manufacture wide range of low softening microfibers [12]. Other method is direct drawing from the bulk technique. This technique required a small sapphire rod to be heated and placed in contact with bulk glass. This results in a localized softening to the bulk glass. As the sapphire rod is abruptly removed, micrometric glass filament is formed [12]. It has advantages in term of flexibility and low-cost equipment. However, the uniformity and the diameter of the microfiber are highly tough to retain. It has been widely used to fabricate microfiber from phosphate, tellurite and polymers [28].

Besides of the tapering method, heat sources also play essential role to produce a good quality microfiber. There are four heat sources have been commonly used during the tapering process such as flame [29], fusion splicer [30], CO₂ laser beam [31] and micro furnace [30]. There are two canonical segments in which the first one occurred relatively at long taper waist segment where the fiber is gradually decreases into a small and uniform diameter. While the second conical segment is the waist merging into the original SMF size [21]. The tapered fiber could be formed into different properties and shapes by controlling pulling settings such as pulling speed, length of the heated zone and pulling temperature. The most common heated source is flame-heated as shown in Fig. 6. The fiber is elongated and stretched slowly under a specific pulling force. A hydrogen flame is applied at the centre of the fiber. The process continues until the targeted diameter or length is achieved [13]. The waveguides of the microfiber could be monitored during the tapering process in term of propagation loss, group velocity delay and multimode interference [32].

Conventional flame-heated technique has disadvantages of random turbulence of the oxygen and flame during the burning process. Thus, CO₂ laser has been introduced to solve this issue [13]. Direct laser heating provide a self-regulating control which the stretching process would automatically stops when the diameter of the fiber reaching a desired value [33, 34]. Other technique is electrically heated taper drawing. This technique enables to shape the fiber into various geometries by precisely control the temperature distribution. It also offer an effective technique to draw microfiber with more flexibilities [13, 35].

![Microscopic image of (a) Adiabatic tapered fiber and (b) Non-adiabatic tapered fiber](image1)

**Figure 2.** (i) Microscopic image of; (a) Adiabatic tapered fiber and (b) Non-adiabatic tapered fiber [21], (ii) Fabrication technique of the microfiber using flame heated source [13]

### 4. Optical sensor using microfiber

Microfiber offers unique properties, such as visible surface field amplification, strong evanescent field, huge anomalous waveguide dispersion and configurability, intriguing possibilities for sensing applications. Microfiber also exhibits high evanescent coupling with other waveguides including metal, semiconductors, and substrates, as well as significant near-field interaction with its surroundings. Large evanescent field is an essential criteria for sensing application where significant power fraction is needed to interact with surrounding refractive index medium [13].
4.1. Evanescent Wave

A standard silica fiber comprises of two main parts which is core and cladding. The core commonly doped with higher refractive index (RI) to guarantee total internal reflection (TIR) under certain conditions according to Snell law. However, there is always small portion of energy transmission coupled into the cladding modes which is known as evanescent field. [36]. Evanescent wave is leakage/loss of electromagnetic field which represent by small portion of energy that penetrates the edge of core and cladding medium during the TIR. TIR occurred when incident angle ($\theta_i$) is greater than critical angle ($\theta_c$) which cause the light reflection back from core to cladding surface.

Studies show that the fraction of power in the evanescent field increases when normalise wavelength ($\frac{\lambda}{r}$) and surrounding refractive index increase [12]. Based on Figure 3, the fraction of power ($\eta_{EF}$) depend on the ratio of $\frac{\lambda}{r}$. $\eta_{EF}$ increase monotonically when $\frac{\lambda}{r}$ increase [37]. Hence, microfiber with smaller radius would produce larger evanescent wave fractional power. A fraction of power propagates in the evanescent field would exist when the diameter of the fiber is comparable to the wavelength. The evanescent field interact with any surrounding environmental change which makes it suitable for sensing application.

![Figure 3](image_url)

**Figure 3.** Relationship between fraction of power ($\eta_{EF}$) of the silica microfiber and the normalised wavelength ($\frac{\lambda}{r}$) ([37])

4.2. Optical microfiber resonators (OMRs)

Microfiber can be employed to manufacture various resonant structures such as micro-loop micro-knot and micro-coil as well as to excite resonant modes such as microspheres, micro-disks, microcapillaries and microbottle. This would produce modes propagating between two adjacent large evanescent field section that overlap and couple to produce a compact resonator [37, 38]. The most important parameter in resonator is quality factor $Q$. It can be calculated by dividing the wavelength $\lambda$ with the bandwidth (FWHM) of a resonance in the transmission spectrum as given in (1).

$$Q = \frac{\lambda}{\text{FWHM}}$$ (1)

Vienna et al. has used loop and knot resonator as refractometric sensors. The sensors operate by exploiting considerable fraction of the microfiber mode that transmitting in the fluidic channel [39]. Any variation in the analyte refractive index would results in a resonant wavelength shift as shown in Figure 4.
Figure 4. Resonant wavelength shift of loop and knot resonator as refractometric sensors [40]

Xu et al. developed a refractometric sensor using micro-coil resonator with an intrinsic channel for microfluidic applications as shown in Figure 5 (a) [41]. Its working principle is similar as the loop resonator refractometric sensor. It associates with the overlap between the evanescent wave and the analyte during the mode propagating in the microfiber. Resonant wavelength shift would occur if there is any refractive index change [42]. The microcoil resonator was embedded in Teflon and the sensor was exposed to isopropanol and methanol. The resonant wavelength shifts to longer wavelength as the analyte refractive index increases.

The most dominant resonant sensors is based on heterogeneous sensors which exploit microfiber to extract light from high-Q resonators such as microcapillaries, microtoroids, microspheres and microbottle resonator [43]. Coupling efficiencies could achieve up to 90% by properly matching the propagation constant of the mode in the resonator and the microfiber [44]. These high-Q resonators are suitable for evanescent sensing for biological and chemical detection due to its large resonator surface [42, 45]. For instance, microspheres with Q-factor of $2 \times 10^7$ has been used to detect protein streptavidin [46]. While Noto et al. [47] uses multiple spheres coated with dextran-biotin hydrogel for DNA strands detection. Another work by [48] implement microsphere with radius of 39 um at wavelength of 763 nm to identify influenza A virus as shown Figure 5 (b).

Figure 5. (a) Microcoil resonator for refractometric sensors using an intrinsic channel for microfluidic applications [41], (b) Heterogeneous sensors which exploit microsphere to detect influenza A virus [48]
5. Recent works on optical microfiber humidity sensing

Humidity is defined as the content of water vapor in the gases. It has been commonly expressed in terms of relative humidity (%RH). It is the ratio of actual vapor pressure at a particular temperature \(P_w\) divide by the saturation vapor pressure at the same temperature \(P_{ws}\) as described on formula 
\[
\%RH = \frac{P_w}{P_{ws}} \times 100\%
\]

Agriculture, meteorology, sterilisers, incubators, textile manufacturing, air conditioning, and chemical gas purification are just a few of the applications. Despite the fact that optical fiber humidity sensors are more expensive than typical electronics sensors, they have advantages such as compact size, the ability to multiplex data from numerous sensors, and insensitivity to electronic magnetic fields [30]. Due to its poor sensitivity and long reaction time, existing percent %RH sensors such as wet and dry bulb psychrometers were not feasible, whilst electronic-based percent %RH sensors suffer from electromagnetic interference [50].

In wet atmosphere, H\(_2\)O molecules will compete with the oxygen molecules for the surface reaction sites. As the %RH level increase, the number of oxygen species would continually decrease causing reduction of baseline resistance which translate into lower sensor response [51]. Therefore, the charge carrier transport due to chemisorbed mechanism occur at lower %RH while physisorption based on Grotthuss mechanism takes place at a higher %RH level as depicted in Figure 6 [52, 53].

![Absorption phenomenon on ZnO](image)

Microfiber bottle resonator, long-period grating coated with gelatin, electrostatic self-assembly of tapered optical fibre, polymethyl methacrylate (PMMA) microfiber doped with agarose gel, silica fiber interferometer, and side polish fibre coated with tungsten disulphide are some of the optical humidity sensing mechanisms that have been proposed [30, 54]. Nanostructure material has attracted attention for use in humidity sensing as compared to the traditional pores ceramic structure because it has hollow structures, ultra-high surface-to-volume ratio, large grain boundary areas and small grain size [55].

The optical humidity sensor working principle could be categorized into several major groups which are based on optical absorption, fiber Bragg gratings (FBG), interferometers and micro-resonators [56]. For optical absorption method, it is based on the reaction between the sensitive material and the evanescent field. This leads to change of transmitted output power. It has advantages on low fabrication cost [57], high reliability and simple setup [58]. However, the drawback of this method is the changes of the transmitted output power could be effected by the undesired factors such as fluctuations of the light source. Several sensitive material have been studied such as zinc oxide [59], tungsten disulfide [60] and reduced graphe oxide (rGO) [61]. For instance, a D-shape optical fiber coated with tungsten disulfide (WS\(_2\)) has shown a quite good sensitivity with 0.1213dB/%RH and resolution of 0.475%RH as shown in Figure 7 (a).

Second method is based on FBG which comprises of a periodic perturbation of the refractive index. FBG operated when small amount of light transmitted inside the fiber is reflected at each periodic refraction change [58]. All the reflected signal combine coherently into a al large reflection at specific
wavelength when the grating period reaching half of the input’s wavelength [62]. The grating phenomenon is described in (2).

$$\lambda_B = 2n\Lambda$$  \hspace{1cm} (2)

where $\lambda_B$ is the Bragg wavelength, $n$ is the effective index of the grating and $\Lambda$ is the grating period.

Several sensitive layers such as carbon nanotubes (CNT) and graphene oxide [63] have been coated onto FBG to improve the sensor sensitivity. For instance, the CNTs coated produced higher sensitivity as compared to conventional FBG with 31 pm/\%RH [64]. The device is depicted in Figure 7 (b).

![Figure 7](image1)

**Figure 7.** (a) D-shape coated by tungsten disulfide coating and (b) the SEM image of the coating layer [60], (b) Optical fiber humidity sensor based on fiber Bragg gratings [63]

Modal interferometer can be formed when difference effective refractive indices of different fiber modes produce interferometric phase difference [65]. Numerous topological structures such as Mach-Zehnder interferometers (MZI) could be realized by splicing different types of fibers in a hybrid structure [66]. It requires two different optical paths to generate the interference. One is the core of the optical fiber and the other path is the cladding. The cladding modes would guide propagate signal through the cladding to generate a modal interferometer based on MZI [58]. One of the structure is double in-line adiabatically tapered fibers as shown in Figure 8 [67]. The first tapered region causes fundamental mode to diffract and excited the cladding modes. The effective refractive indices differences between the core and cladding modes produce phase shift. As the structure exposed to higher \%RH, the effective RI of the cladding modes increase while the RI of the core mode maintain and lead to a greater phase shift. Performance comparison of some of microfiber based humidity sensors are listed in Table 1.

![Figure 8](image2)

**Figure 8.** Double in-line adiabatically tapered fibers structures to form Mach-Zehnder interferometer [67]
### Table 1. Comparative table of several microfibers based humidity sensor

| No | Type                        | Principle/Method                                 | Performances          | References |
|----|-----------------------------|--------------------------------------------------|-----------------------|------------|
| 1  | Microfiber bottle resonator | Single & double bottle                            | Sensitivity of 0.061 dBm/%RH | [54]       |
| 2  | Strain induced Bragg wavelength | Coated with polyimide                           | Sensitivity of 2.1 pm/%RH | [68]       |
| 3  | Microbottle                | Integrate with microfiber                        | Sensitivity of 0.0487 dBm/%RH | [56]       |
| 4  | PMMA microfiber            | Doped with agarose gel                           | Sensitivity of 0.1 μw/%RH | [69]       |
| 5  | Microbottle resonator      | Coated with PVA                                 | Sensitivity of 0.1311 dBm/%RH | [70]       |
| 6  | Microfiber with glass substrate | Coated with ZnO nanorods                      | Sensitivity of 0.0527 dBm/%RH | [71]       |
| 7  | Hybrid SMF                 | Coated with PVA                                 | Sensitivity of 1.994 μW/%RH | [72]       |
| 8  | Strain induced FBG         | Coated with polyimide                           | Sensitivity of 13.6 pm/%RH | [73]       |
| 9  | SMF microfiber             | Laid on glass substrate                         | Sensitivity of 14.2 pm/%RH | [74]       |
| 10 | Etched FBG                 | Coated with CNT                                 | Sensitivity of 31 pm/%RH | [64]       |
| 11 | Microloop                  | Coated with ZnO nanorods                        | Sensitivity of 0.2774 dBm/%RH | [75]       |
| 12 | Microknot                  | PMMA microfiber interferometric                 | Sensitivity of 8.8 pm/%RH | [76]       |
| 13 | Microtoroid+tapes          | Poly (N isopropylacrylamide)                    | Sensitivity of 13 pm/%RH | [77]       |
| 14 | Microsphere resonator      | Integrated with ZnO coated glass                 | Sensitivity of 0.0748 dBm/%RH | [78]       |

6. Conclusion
This paper has summarized most of the related research works pertaining to optical microfiber sensor. It could bring a new glance on the potential research ideas in this field. Since the optical sensor has superiority as compared to electronic sensor such as immunity to the electromagnetic interference, advancement in this field is highly encourage. It expected that this paper could motivate researchers to improvise current optical microfiber sensor towards more sensitive, simple and low cost sensing device.

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