

# Recent Progress in Microfiber-Optic Sensors

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**Abstract:** Recently, microfiber-optic sensors with high sensitivity, fast response times, and a compact size have become an area of interest that integrates fiber optics and nanotechnology. Distinct advantages of optical microfiber, such as large accessible evanescent fields and convenient configurability, provide attractive benefits for micro- and nano-scale optical sensing. Here, we review the basic principles of microfiber-optic sensors based on a broad range of microstructures, nanostructures, and functional materials. We also introduce the recent progress and state-of-the-art in this field and discuss the limitations and opportunities for future development.

**Keywords:** Optical microfiber; optical sensing; fiber-optic sensors; microstructures

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## 1. Introduction

Since the emergence of the optical fiber endoscope in the first half of the 20th century [1–3], fiber-optic sensors have enabled significant progress in the field of optical sensing [4]. A wide variety of sensor types and applications were demonstrated, which revolutionized optical sensing technology [4]. Current fiber-optic sensors are primarily based on extremely low-loss optical fibers, which were developed from the late 1960s [5, 6]. Optical fibers offer appealing characteristics for sensing applications, including lightweight, large operation bandwidth, immunity to electromagnetic interference, distributing and multiplexing capabilities, biocompatibility, and endurance in harsh environment [4]. Owing to these implementational advantages, fiber-optic sensors, such as fiber-optic gyroscopes [7], fiber-optic

hydrophones [8], fiber Fabry-Perot interferometers [9], and fiber gratings [10], have been widely employed in both commercial and military systems [4, 11].

Recently, emerging applications in nanotechnology and biology have imposed increasing demands for compact sensors with a smaller footprint, higher sensitivity, faster response, better resolution, and lower power consumption [12, 13]. To meet these imperative requirements, optical microfiber-based sensors have been exploited in the past decades [14–16]. Optical microfiber is a rapidly developing miniaturized waveguide with diameters ranging from tens of nanometers to several micrometers [14, 17]. Compared with standard optical fiber, it provides stronger confinement for guided light while maintaining a low insertion loss [18, 19]. When the diameter is as low as a subwavelength scale, a significant fraction of light

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can propagate in the evanescent field outside the physical boundary of the microfiber, which enables strong interactions between the microfiber and its surroundings [19]. These intriguing features make optical microfiber an ideal platform for optical sensing [14, 16, 20–22], near-field coupling [23, 24], atom/particle manipulation [25, 26], nonlinear interactions [27–34], and quantum optics [35, 36].

Thus far, a spate of microfiber-optic sensors have been demonstrated for various physical, chemical, and biological parameters (refractive index, temperature, humidity, magnetic field, etc.) [16, 22, 37–42]. This review intends to summarize the recent progress in this field. In Section 2, we review typical microfiber structures that can be utilized for optical sensing. Then, we describe the implementations of microfiber-optic sensors based on different operating mechanisms in Section 3. Finally, in Section 4, we discuss the remaining limitations in the field and conclude with perspectives for the further development of more practical microfiber-optic sensors.

## 2. Typical microfiber structures

### 2.1 Optical microfiber

Optical microfiber typically refers to fiber-optic microwires and nanowires with diameters close to, or below, the wavelength of guided light. The constituent materials of the microfiber can be silica, polymer, and other transparent dielectric media, such as chalcogenide glass [13, 14, 38, 43–48]. This review primarily focuses on silica-based microfiber and its sensing applications. A summary of polymer microfiber sensors can be found in other review articles [49, 50].

To fabricate low-loss silica microfibers with excellent uniformity and smoothness, a variety of fabrication methods have been proposed [18, 23, 44, 51–56]. Among the reported methods, the heat-and-pull technique is most frequently adopted because it can fabricate the longest and most uniform microfibers. The technique has been

previously used for the manufacture of fiber tapers and fiber couplers [14, 57, 58]. It typically employs a hydrogen flame, which heats and brushes the standard optical fiber that is being stretched. Owing to the pulling force applied by translation stages, the heated part of the fiber elongates, and the diameter gradually reduces. This forms a structure consisting of a stretched waist (the so-called microfiber), two unstretched standard fiber pigtailed, and biconical transition sections that link the waist to the pigtailed, as shown in Fig. 1. This structure provides ease of measurement because pigtailed ends enable ultralow-loss splicing to standard fiber components (insertion losses  $< 0.1$  dB), and the biconical transitions enable highly efficient coupling in and out of the microfiber waist [14]. The length and diameter of the waist and the shape of the transition regions can be precisely defined by controlling the flame movement and stretching parameters. Alternatively, the heating source in a heat-and-pull rig can be replaced by a microheater [44, 56] or a sapphire capillary tube heated by a CO<sub>2</sub> laser beam [52] to avoid random flame turbulence; this offers a safer fabrication solution without explosive gases. The typical optical loss of a silica microfiber manufactured by the heat-and-pull technique is as low as  $\sim 0.01$  dB/mm [51], owing to the low roughness and high homogeneity.

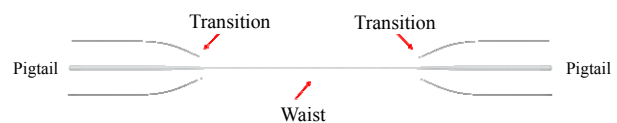


Fig. 1 Typical microfiber structure fabricated from standard optical fiber using the heat-and-pull technique.

Figure 2 shows the ratio of the power propagating in the air to that propagating in the fiber as a function of the microfiber diameter. The ratio increases with a decreasing diameter, indicating a larger fraction of power in the evanescent field for thinner microfibers. When the diameter reaches  $0.5 \mu\text{m}$ , nearly 94% of the total light energy is outside the microfiber, i.e., in the surrounding environment. Additional to the properties of large

evanescent fields, strong optical confinement, and tailorable waveguide dispersion, optical microfiber also provides excellent mechanical strength and flexibility [59]. Bending radii of a few micrometers have been achieved with low induced bending losses [60, 61]. The robustness and configurability of optical microfibers enable various compact microfiber structures, e.g., loops [52, 62, 63], knots [18, 64, 65], coils [66–70], couplers [71–76], and interferometers [77–86]. Moreover, gratings [21, 87–89] and functional materials [13, 38] can also be integrated with microfibers to enhance the functionalities of the platform. These structures will be discussed in the following sections.

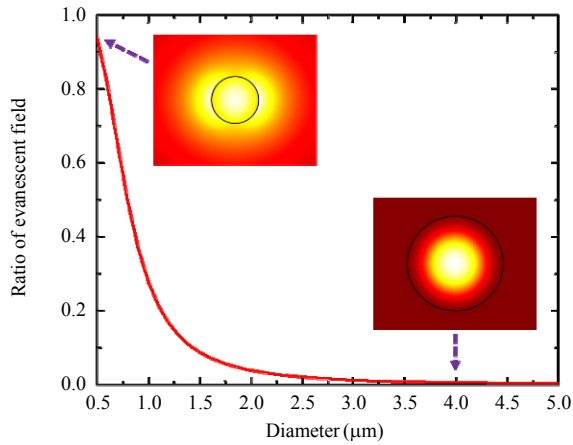


Fig. 2 Ratio of evanescent field penetrating into surrounding air to the field propagating in the fiber as a function of the fiber diameter at a wavelength of 1550 nm. The upper and lower insets are the power flow distributions of 0.5- $\mu\text{m}$ -diameter and 4- $\mu\text{m}$ -diameter silica microfibers, respectively. Dimensions of the insets are not to scale.

## 2.2 Microfiber coupler

A fiber coupler is a basic fiber optics device, which has been intensively studied [73, 90, 91]. Recently, it has attracted renewed attention, owing to the development of optical microfiber [74]. A microfiber coupler (MFC) is based on evanescent coupling between two adjacent microfibers. Its typical structure is shown in Fig. 3. For an MFC with a large index-contrast and two waveguides in physical contact, conventional perturbation theory cannot be applied. Thus, the supermode theory is employed to describe the MFC [92]. As shown in

Fig. 3, if light is launched into Port 1, the output powers from Ports 3 and 4 are given by

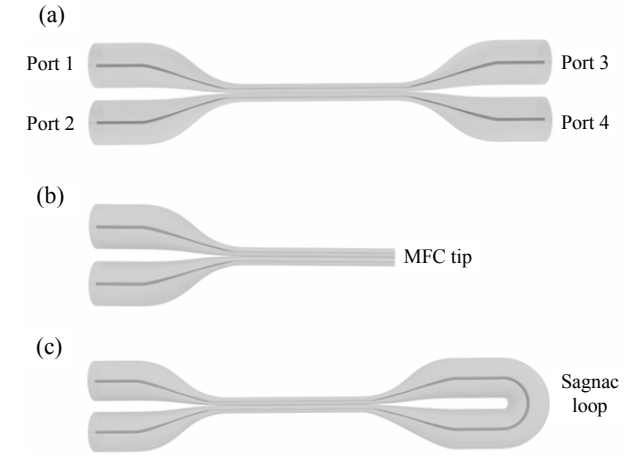


Fig. 3 Schematic of optical microfiber coupler (MFC) structures: (a) typical structure of MFC, (b) MFC probe, manufactured by cleaving the waist, and (c) Sagnac loop mirror, manufactured by fusing the MFC.

$$P_3^i = P_1^i \cos^2 \left( \frac{\pi L \Delta n_{\text{eff}}^i}{\lambda} \right) \quad (1)$$

$$P_4^i = P_1^i \sin^2 \left( \frac{\pi L \Delta n_{\text{eff}}^i}{\lambda} \right) \quad (2)$$

$$\Delta n_{\text{eff}}^i = n_{\text{eff}}^{i,\text{even}} - n_{\text{eff}}^{i,\text{odd}} \quad (3)$$

where  $i$  indicates transverse electric (transverse magnetic) polarization,  $P_1^i$  is the input power,  $L$  is the coupling length,  $\Delta n_{\text{eff}}^i$  is the effective refractive index (RI) difference between  $n_{\text{eff}}^{i,\text{even}}$  for the even supermode and  $n_{\text{eff}}^{i,\text{odd}}$  for the odd supermode, and  $\lambda$  is the optical wavelength. From the formulas, one can observe that the MFC outputs are strongly dependent on the variation of  $\Delta n_{\text{eff}}^i$ , which is caused by changes in the physical parameters of its surroundings, such as temperature and strain. Therefore, it is an attractive structure for highly sensitive optical sensing. The sensing parameters can be estimated by either monitoring the spectrum shift [71, 93] or the transmittance at selected wavelengths [94]. In addition, the MFC can operate as a microprobe [72, 75, 95], if its waist is cleaved, or a Sagnac loop [96–98], if output ports 3 and 4 are fused, as shown in Figs. 3(b) and 3(c), respectively.

The RI sensitivity ( $S$ ) of the MFC can be defined

as [99, 100]

$$S = \frac{\partial \lambda_s}{\partial n_a} = \frac{\lambda_s}{\Delta n_{\text{eff}}^i - \lambda_s \partial(\Delta n_{\text{eff}}^i) / \partial \lambda} \frac{\partial(\Delta n_{\text{eff}}^i)}{\partial n_a} \quad (4)$$

where  $\lambda_s$  is the wavelength of the dip in the MFC transmission spectrum,  $n_a$  is the RI of the surrounding medium, and  $g^i = \Delta n_{\text{eff}}^i - \lambda_s \partial(\Delta n_{\text{eff}}^i) / \partial \lambda$  is the group index difference between the even and odd supermodes. According to this equation, the RI sensitivity approaches infinity when  $g^i = 0$  at the turning point, which is an important characteristic that has been applied to enhance RI sensing [99, 100].

### 2.3 Microfiber interferometer

Interferometers are among the most broadly used structures for high-sensitivity optical sensing [101–103]. Microfiber interferometers (MFIs) have been demonstrated recently; these interferometers are based on evanescent coupling [77], birefringent interference [79, 80], and multimode interference [81–85]. Figure 4 shows the basic structures of a microfiber Mach-Zehnder interferometer (MZI) and modal interferometers. The operating principle of MFIs can be explained by dual-beam interference, and the transmission intensity is given by [38]

$$I = I_1 + I_2 + 2I_1 I_2 \cos \Delta \varphi \quad (5)$$

$$\Delta \varphi = \frac{2\pi}{\lambda} (n_{1,\text{eff}} L_1 - n_{2,\text{eff}} L_2) \quad (6)$$

where  $I_1$  and  $I_2$  are the intensities of the two light beams in respective arms, polarizations, or modes, and  $\Delta \varphi$  is the phase difference between them. The interference fringe in a transmission spectrum and the sensing parameters can be demodulated by a shift in the fringe. Compared with conventional waveguide MZIs, microfiber MZIs can provide a sensitivity that is one order of magnitude higher and a smaller footprint between tens and hundreds of micrometers [20]. The microfiber modal interferometers fabricated from single-mode fiber [81, 84–86, 99, 104, 105], microstructured fiber [83,

106–108], and multimode fiber [82, 109, 110] also provide the advantages of compactness, high sensitivity, and simple fabrication.

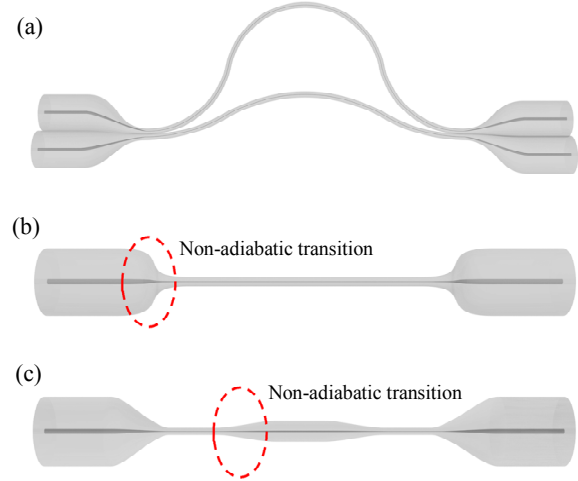


Fig. 4 Schematic of MFI structures: (a) microfiber Mach-Zehnder interferometer (MZI); (b-c) microfiber modal interferometers with non-adiabatic transitions.

### 2.4 Microfiber grating

A fiber grating is a periodic structure that modulates the effective RI along the optical fiber [111]. Since the first successful fabrication in 1978 [112], it has been widely utilized for optical filtering and sensing [10, 113]. A typical fiber Bragg grating (FBG) is several millimeters in length and has a diameter of approximately 100  $\mu\text{m}$ . Its relatively large size limits its applications in RI sensing and the detection of ultrasmall objects [21]. Owing to the large evanescent field induced by a small diameter and high RI contrast, microfiber gratings have become a powerful tool to overcome this limitation and have received increasing interest in recent years [21, 114]. Many microfiber gratings have been demonstrated using various techniques, including chemical etching [115, 116], laser irradiation/ablation [117–121], focused ion beam milling [122–128], lithography [129, 130], and external modulations [87, 131–133]. Compared with the conventional fiber, the high modulation of the effective RI ( $10^{-3} - 10^{-1}$ ) in microfibers enables ultra-compact gratings with lengths between

10  $\mu\text{m}$  and 100  $\mu\text{m}$  [21]. There are primarily two types of gratings in microfiber: the microfiber Bragg grating (MFBG) and the microfiber long period grating (MFLPG). For the MFBG, when the forward-propagating mode is coupled with the identical backward mode, the first-order diffraction can be described by the Bragg resonance condition [111]:

$$\lambda_B = 2n_{\text{eff}}A \quad (7)$$

where  $\lambda_B$  is the Bragg wavelength,  $n_{\text{eff}}$  is the effective RI of the guided mode, and  $A$  is the period of the MFBG. Any changes in the surrounding parameters that affect  $n_{\text{eff}}$  and  $A$  will finally result in a shift in the Bragg wavelength. For the MFLPG with a forward-propagating mode coupled into higher order modes in the same direction, a similar resonance condition can be obtained by considering the phase matching between coupled modes [111]:

$$\lambda_L = (n_{\text{eff},1} - n_{\text{eff},2})A = \Delta n_{\text{eff}}A \quad (8)$$

where  $\Delta n_{\text{eff}} = n_{\text{eff},1} - n_{\text{eff},2}$  is the modal effective RI difference. According to (8), the MFLPG has a significantly longer period than that of the MFBG; thus, its fabrication requirements are lower.

## 2.5 Microfiber resonator

As illustrated in Fig. 5, a variety of resonance structures can be implemented using optical microfibers, including a loop [52, 62, 63], a knot [18, 64, 65], coil [66–70], a photonic crystal (PhC) cavity [122, 125, 134–137], a ring [138, 139], a Fabry-Perot (FP) cavity [140–142], and their extended configurations [143–147]. A typical microfiber resonator has a quality ( $Q$ ) factor ranging from  $10^2$  to  $10^6$ , depending on the specific structures [13, 38]. The high  $Q$  factor enables its application in sensors, lasers, dynamic filters, optical delay lines, and quantum optics [38].

Considering a microfiber loop resonator as an example, the resonance condition is [148]

$$\lambda_c = \frac{n_{\text{eff}}L}{m} \quad (9)$$

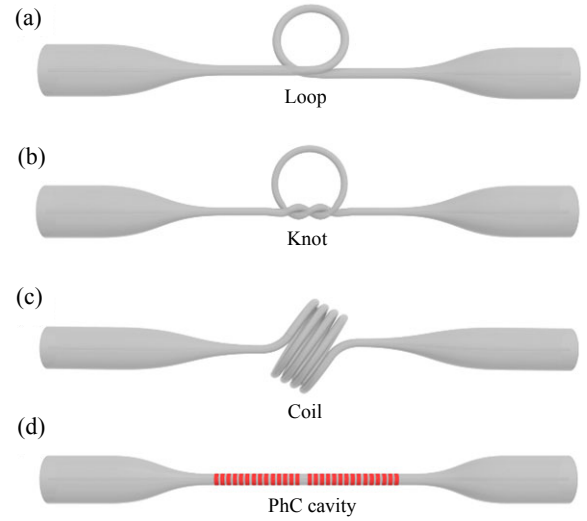


Fig. 5 Schematic of typical microfiber resonators: (a) microfiber loop resonator, (b) microfiber knot resonator, (c) microfiber coil resonator, and (d) microfiber PhC cavity.

where  $\lambda_c$  is the resonant wavelength,  $L$  is the circumference of the loop, and  $m$  is an integer representing the resonance order. According to (9), the RI sensitivity, obtained by monitoring the shift of the resonant wavelength, can be expressed as [148]

$$S = \frac{\partial \lambda_c}{\partial n_a} = \frac{\partial \lambda_c}{\partial n_{\text{eff}}} \frac{\partial n_{\text{eff}}}{\partial n_a} = \frac{\lambda_c}{n_{\text{eff}}} \frac{\partial n_{\text{eff}}}{\partial n_a} \quad (10)$$

which only depends on the change in the RI of the surrounding medium, regardless of the resonator's  $Q$  factor. However, the detection limit, which is an important figure of merit for optical sensors, may benefit from the high  $Q$  factor of microfiber resonators [68, 149].

## 2.6 Functional material-integrated microfiber devices

In addition to geometric structures, it is also an effective strategy to integrate functional materials into microfiber platforms to extend their functionalities. Owing to the large evanescent fields with high surface intensity, functional material-integrated microfiber devices offer strong light-matter interactions for sensing applications. Various aforementioned microfiber structures have been reported for integration with plasmonic materials [150–156], polymers [49, 157–160],

two-dimensional (2D) materials [161–173], sol-gels [174, 175], magnetic fluids [176–178], and biomaterials [41]. For example, Fig. 6 shows the typical configurations of hybrid graphene-fiber structures, including a free-standing microfiber, microfiber on a low-RI substrate, and a microfiber knot resonator on a low-RI substrate. These composite structures of 2D materials and microfibers are realized by the wet transfer method that is summarized in the review article [179]. The extremely high surface-volume ratio and ultrafast response of graphene provide useful characteristics for chemical molecular sensing and all-optical control [180, 181].

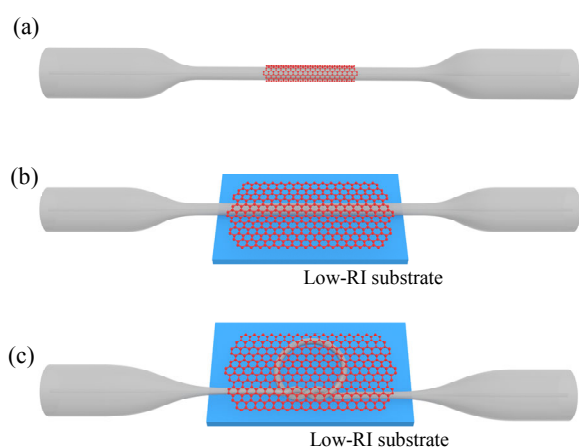


Fig. 6 Graphene functionalized optical fiber platform, presented as an example. Functional materials can be integrated with (a) a free-standing microfiber, (b) a microfiber on a low-RI substrate, and (c) a microfiber knot resonator on a low-RI substrate.

### 3. Microfiber-optic Sensors

Owing to favorable features, such as compact size and high sensitivity, a variety of microfiber-based optical sensors have been developed. Figure 7 summarizes the basic sensing principles of these sensors. According to these principles, most microfiber sensors can be classified into three categories. First, interference and resonance effects of microfiber structures lead to phase-based sensors. This type of sensor is extremely sensitive to phase changes resulting from

RI variation induced by surrounding medium alteration, thermal-optic or elasto-optic effects, and deformation caused by thermal expansion or externally applied forces. Information of miscellaneous measurands can be easily demodulated by monitoring the shift of the interference fringe and resonance dip or recording the intensity at specific wavelengths. Second, optical absorption, leaky radiation, and optical elastic scatterings enable loss-based microfiber sensors. Such sensors employ absorption spectroscopy, optical transmittance measurements, and optical microscopy in the analysis and characterization of gases, liquids, nanoparticles, and chemical or biological molecules. Selective sensing with enhanced performance can be realized by the integration of appropriate functional materials. Third, the newly generated frequency spectral components from optical inelastic scatterings, parametric and non-parametric nonlinear processes, and fluorescence contribute to frequency-based microfiber sensors. The strong optical confinement and large evanescent fields of the sensors enable ultra-sensitive scattering, nonlinear, and fluorescence spectroscopies for the investigation of various physical, chemical, and biological measurands. In the following sections, typical microfiber-optic sensors and their recent progress will be introduced in terms of the working principle classification.

#### 3.1 Phase-based sensors

Phase-based microfiber sensors that utilize interference and resonance effects have been widely studied because they exhibit simplicity and convenience in manufacturing and implementation. All the aforementioned microfiber structures, including couplers, MZIs, modal interferometers, gratings, and the various types of resonators, have been employed as sensing elements for a range of applications. In many cases, the variation in



interference and resonance conditions are caused by the effective RI change induced by the change of the surrounding RI. Thus, an effective sensitivity can be defined to describe the performance of phase-based

microfiber sensors [22]:

$$S_{\text{eff}} \propto \frac{\partial n_{\text{eff}}}{\partial n_a}. \quad (11)$$

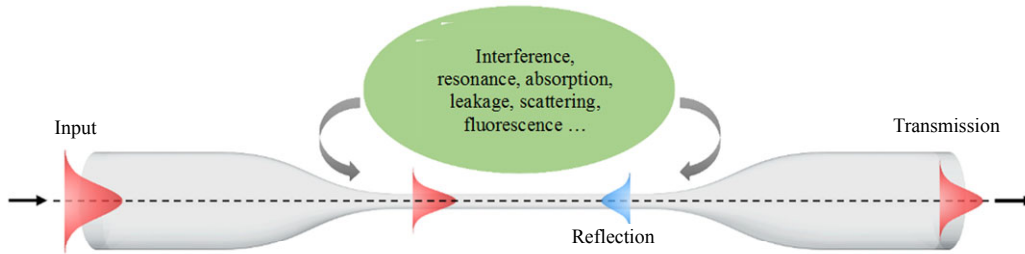


Fig. 7 Basic sensing processes of microfiber-optic sensors. By detecting and analyzing variations in optical phase, intensity, frequency, and polarization of the transmitted and reflected light signals from microfiber structures, the surrounding physical, chemical, and biological parameters can be demodulated regarding the detailed interaction processes. Diverse microfiber structures provide versatile platforms for various physical, chemical, and biological effects with favorable characteristics, such as a small footprint, strong optical confinement, and large evanescent fields. The green ellipse represents the typical physical effects that constitute the operating principles of microfiber-optic sensors.

The effective sensitivity is correlated to the microfiber diameter and the range of the surrounding RI. As illustrated in Fig. 8, a phase-based sensor exhibits a higher effective sensitivity with a decrease in the microfiber diameter or an increase in the surrounding RI. This feature is caused by the larger evanescent fields in smaller dimensions or reduced RI contrast, indicating that microfiber sensors with smaller diameters would benefit sensing applications.

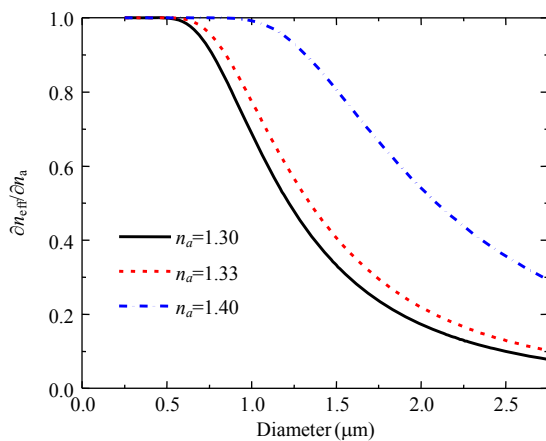


Fig. 8 Effective sensitivity of a phase-based silica microfiber sensor as a function of diameter for different surrounding refractive indices at a wavelength of 1 550 nm.

To date, MFCs have been widely demonstrated in the sensing of RIs [96, 100, 182], temperature [72, 75, 183, 184], strain/force [97], current [94], magnetic fields [94, 176], humidity [169, 185, 186], and other parameters. Most of the reported MFC RI sensors exhibited sensitivities in the range of 1 000 nm/RIU – 6 000 nm/RIU (RI unit) [93, 95, 96, 187, 188]. Ultrahigh sensitivity is possible when the MFC operates near the turning point [100] or relies on the birefringence-induced Vernier effect [182] (Fig. 9). Using a Sagnac loop mirror based on an MFC, Chen *et al.* implemented a highly sensitive reflective micro-force sensor with a maximum sensitivity of  $\sim 3754$  nm/N [97]. An MFC sensor was integrated with molybdenum disulfide ( $\text{MoS}_2$ ) nanosheets and implemented for the simultaneous measurement of relative humidity (RH) and temperature with an RH sensitivity of 115.3 pm/%RH in the range of 54.0 %RH–93.2 %RH and a temperature sensitivity of  $-104.8$  pm/ $^\circ\text{C}$  in the range of  $30$   $^\circ\text{C}$ – $90$   $^\circ\text{C}$  [169].

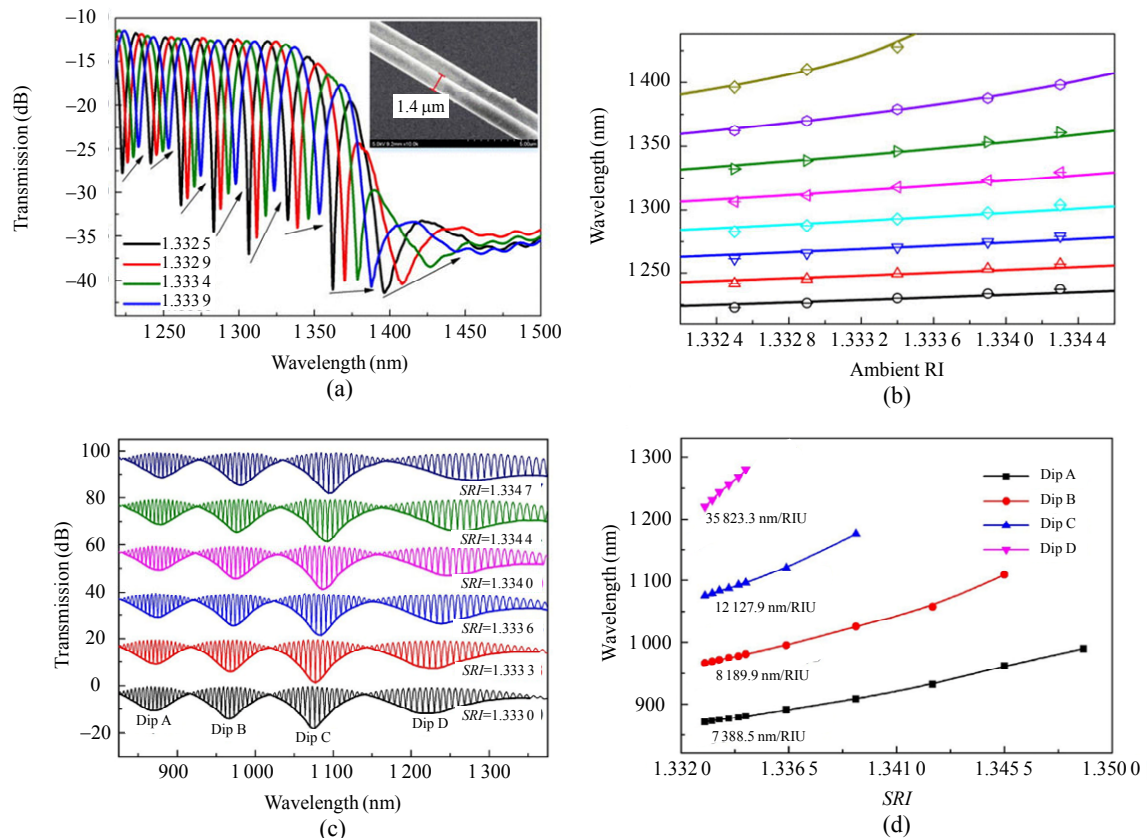


Fig. 9 Phase-based MFC sensors with ultrahigh sensitivities: (a) transmission spectral responses to different ambient RIs for an MFC sensor operating near the turning point of effective group index difference. Reproduced with permission [100]. Copyright 2016 AIP Publishing; (b) modeled (solid curves) and measured wavelengths (points) at transmission dips versus ambient RI for the MFC sensor operating near the turning point. Reproduced with permission [100]. Copyright 2016 AIP Publishing; (c) transmission spectra of an MFC sensor with the Vernier effect for different surrounding RIs (spectra are offset by 22 dB). Reproduced with permission [182]. Copyright 2018 Elsevier; (d) measured wavelengths at transmission dips versus surrounding RI for the MFC sensor with the Vernier effect. Reproduced with permission [182]. Copyright 2018 Elsevier.

MFI also exhibit excellent performance in phase-sensitive optical sensing. For example, Wo *et al.* [78] demonstrated an MZI using a 2- $\mu\text{m}$  silica microfiber as the sensing arm, with an RI sensitivity of 7 159  $\mu\text{m}/\text{RIU}$ . Excluding MZIs with different optical paths, modal interferometers comprising multimode microfiber [99] and non-adiabatic transition regions [189, 190] have been demonstrated for RI, gas, and liquid level sensing. Sun *et al.* [80] reported a highly birefringent microfiber loop interferometer with an RI sensitivity of approximately 24 373  $\text{nm}/\text{RIU}$  and a temperature stability above 0.005  $\text{nm}/^\circ\text{C}$ . Moreover, based on graphene-MFI hybrid structure, Yao *et al.* [191]

realized an all-optical  $\text{NH}_3$  gas sensor with a high sensitivity of  $\sim 6$   $\text{pm}/\text{ppm}$  and a resolution of  $\sim 0.3$   $\text{ppm}$  as shown in Figs. 10(a) and 10(b). A cascaded MFI structure is another interesting topic, owing to its ability to demodulate multiple sensing parameters [192–194]. A multimode microfiber-based dual MZI can achieve simultaneous measurements of RI and temperature with sensitivities of 2 576.584  $\text{nm}/\text{RIU}$  and 1 001.864  $\text{nm}/\text{RIU}$  and  $-0.193$   $\text{nm}/^\circ\text{C}$  and 0.239  $\text{nm}/^\circ\text{C}$ , respectively [192]. Recently, a microfiber modal interferometer was functionalized with glucose oxidase and proposed for bio-selective and high-sensitivity glucose detection with a



response coefficient of  $1.74 \text{ nm/mg}^{-1} \cdot \text{ml}^{-1}$ , as shown in Figs. 10(c) and 10(d) [195].

MFBGs for RI [119, 121, 123, 128, 129], temperature [124, 127, 196], strain [196, 197], force [197, 198], and humidity [199] sensing have been reported; the large evanescent fields enable high RI sensitivities of  $10^2 \text{ nm/RIU} - 10^3 \text{ nm/RIU}$ . However, the temperature and strain sensitivities of MFBGs have not been improved compared with those of bulk FBGs. MFBGs exhibit an advantage over bulk FBGs for force sensing, particularly for detections of micro-force because their reduced thickness significantly enhances the sensitivity ( $10^2 \text{ nm/N} - 10^3 \text{ nm/N}$ ). For practical applications, it is beneficial to realize the simultaneous measurement of multiple parameters and avoid cross-sensitivity [196]. For

this purpose, Lee *et al.* [200] developed a multimode etched-core FBG sensor with an asymmetric non-adiabatic taper and demonstrated simultaneous demodulation of the RI, temperature, and strain with accuracies of  $1 \times 10^{-4} \text{ RIU}$ ,  $0.32 \text{ }^\circ\text{C}$ , and  $10 \text{ } \mu\text{e}$ , respectively. The functionality of an MFBG sensor can be enhanced by functional material coatings. For example, an MFBG coated with the graphene oxide (GO) film was implemented for relative humidity sensing with a sensitivity of  $17.361 \text{ pm/RH}\%$  and linear correlation coefficient of 99.89% [199]. In addition to MFBGs, MFLPGs were also implemented for optical sensing [87, 88, 201, 202], exhibiting a comparable performance with MFBGs, while requiring a simpler manufacturing process [87, 88, 117, 201–203].

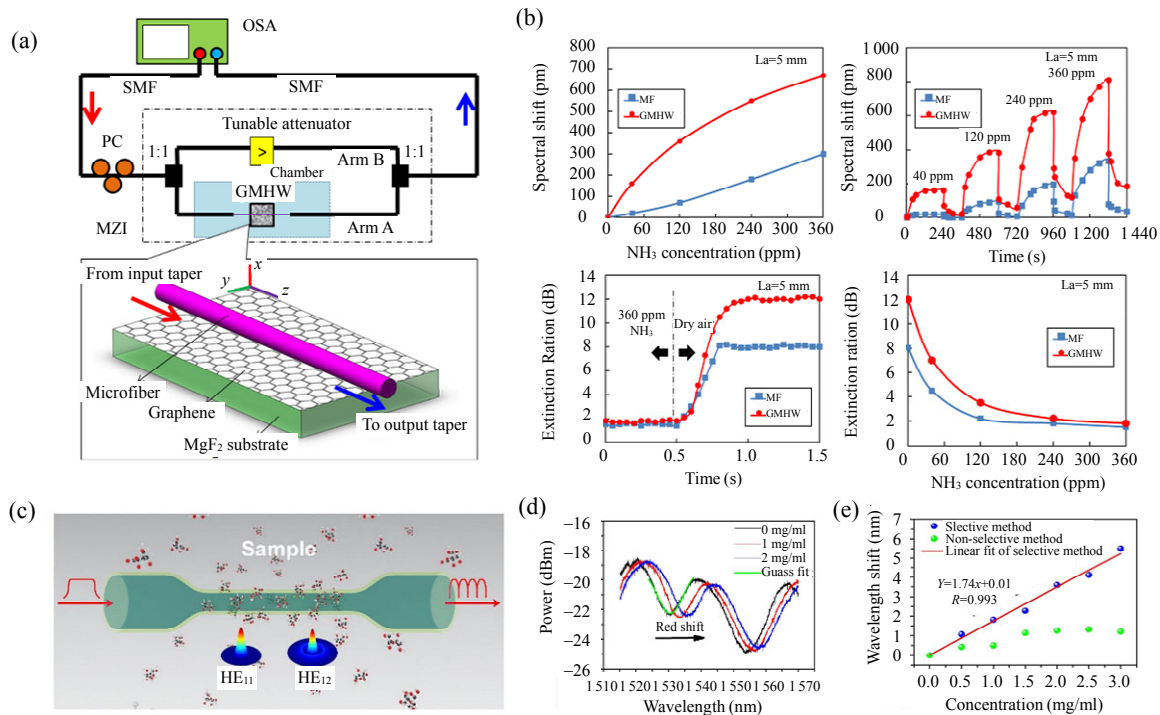


Fig. 10 Phase-based MFI sensors: (a) schematic diagram of a graphene/microfiber hybrid waveguide (GMHW) and setup of the GMHW-MZI for NH<sub>3</sub> sensing. Reproduced with permission [191]. Copyright 2014 Elsevier; (b) sensing performances of the GMHW (red) and the microfiber on MgF<sub>2</sub> without graphene attached (blue). Reproduced with permission [191]. Copyright 2014 Elsevier; (c) schematic diagram of a functionalized microfiber modal interferometer for selective and highly sensitive glucose detection. Reproduced with permission [195]. Copyright 2018 Elsevier; (d) spectra of the functionalized MFI in glucose solutions with different concentrations. Reproduced with permission [195]. Copyright 2018 Elsevier; (e) relationship between resonant wavelength shift and concentration for the functionalized MFI. Reproduced with permission [195]. Copyright 2018 Elsevier.

Owing to their compact size, high  $Q$  factor, and easy coupling strategy, microfiber-based resonant sensors have been widely applied in the

measurement of the RI [68, 69, 139, 140, 146, 147, 204], temperature [63, 141, 205–209], current [210, 211], electric field [212], magnetic field [178], and

humidity [213]. For example, as the simplest microfiber resonant structure, a microfiber loop resonator with a  $Q$  factor of  $\sim 10^5$  has been demonstrated for temperature sensing with  $\sim 0.1$  mK resolution [63]. However, the freestanding microfiber loop maintained by van der Waals and electrostatic forces is weak in mechanical stability. Alternatively, microfiber resonators based on more stable structures, such as a knot [178, 205, 208, 209, 212, 213], a coil [68, 69, 211, 214, 215], a ring [139], and an FP cavity [140, 141], have been proposed and implemented for sensing applications. An encapsulation process was also employed to stabilize the freestanding microfiber resonance structures [70, 216]; however, the packaging will influence the  $Q$  factor and field overlap between the structure and the analyte [217].

### 3.2 Loss-based sensors

Ultrasensitive microfiber absorption spectroscopy can be utilized for molecule detections [218, 219], owing to the large evanescent fields and strong light-matter interactions in subwavelength microfibers. For microfiber sensors based on absorption effects, the transmission loss depends on the fraction of the evanescent fields, molecular concentration, absorptivity, and effective interaction length [38]. To obtain high sensitivity, microfiber structures, such as optical resonators, can be introduced to enhance the overlap between guided light and the surroundings or increase the effective interaction length [220, 221]. Furthermore, functional material coatings, such as metal nanostructures [222–224], antibodies [224, 225], gelatin [226], doped sol-gel films [227], and graphene [228–230], have been adopted for the realization of selective sensing. Recently, an absorption-based strain sensor using a graphene-microfiber hybrid structure was reported [231]. The optical conductivity of graphene on a microfiber can be tuned using external strain applied on the microfiber, resulting in a change of transmission intensity in the spectrum [232, 233]. Sun *et al.* [234] showed that the absorption of the

graphene-assisted structure was also sensitive to the surrounding temperature. As illustrated in Figs. 11(a) and 11(b), Chen *et al.* [170] demonstrated that the absorption edge of the monolayer  $\text{WS}_2$  on a microfiber linearly shifted with the uniaxial strain, exhibiting a sensitivity of  $\sim 10$  nm/% strain.

A microfiber sensor based on radiation modes was developed for conditions where the surrounding RI is larger than that of the microfiber. Gao *et al.* [236] demonstrated the possibility of employing leaky radiation to measure an environment RI that was higher than that of the microfiber material with a theoretically predicted sensitivity higher than  $400^\circ/\text{RIU}$ . Recently, Zhang *et al.* [237] reported a sensor that enabled multifunctional flow sensing in microfluidic chips, which utilized the transition from guided to radiation modes for a microfiber embedded in polydimethylsiloxane film.

Owing to the strong optical confinement and large evanescent fields, elastic light scatterings are significantly enhanced in a microfiber. For example, Polynkin *et al.* [238] reported a geometric scattering-based RI sensor by integrating a microfiber with a microfluidic channel; the sensor realized an estimated resolution of  $\sim 10^{-4}$  RIU. Liu *et al.* [239] proposed a Mie scattering-based microfiber RI sensor with an accuracy of  $1.8 \times 10^{-5}$  RIU. Rayleigh scattering is one of the most important elastic scattering effects and has been widely studied in microfibers because rapid detection and evaluation of nanoparticles are important in the fields of nanoscience and nanotechnology [235, 240–246]. Wang *et al.* [242] theoretically investigated nanoparticle-induced Rayleigh-Gans scattering in microfibers for optical sensing. By measuring the additional loss introduced by the scattering of microparticles, Wei *et al.* [246] implemented a microparticle sensor by simply using a microfiber. Chen *et al.* [244] demonstrated that the detection limit for a single nanoparticle can be enhanced by utilizing a hybrid plasmonic-photonic mode in a subwavelength microfiber. Yu *et al.* [245]

realized single-nanoparticle detection and sizing by a microfiber pair in an aqueous environment. Recently, they have further demonstrated an

accurate evaluation of the distribution of ultrafine particulate matter in air using a microfiber array as shown in Figs. 11(c) and 11(d) [235].

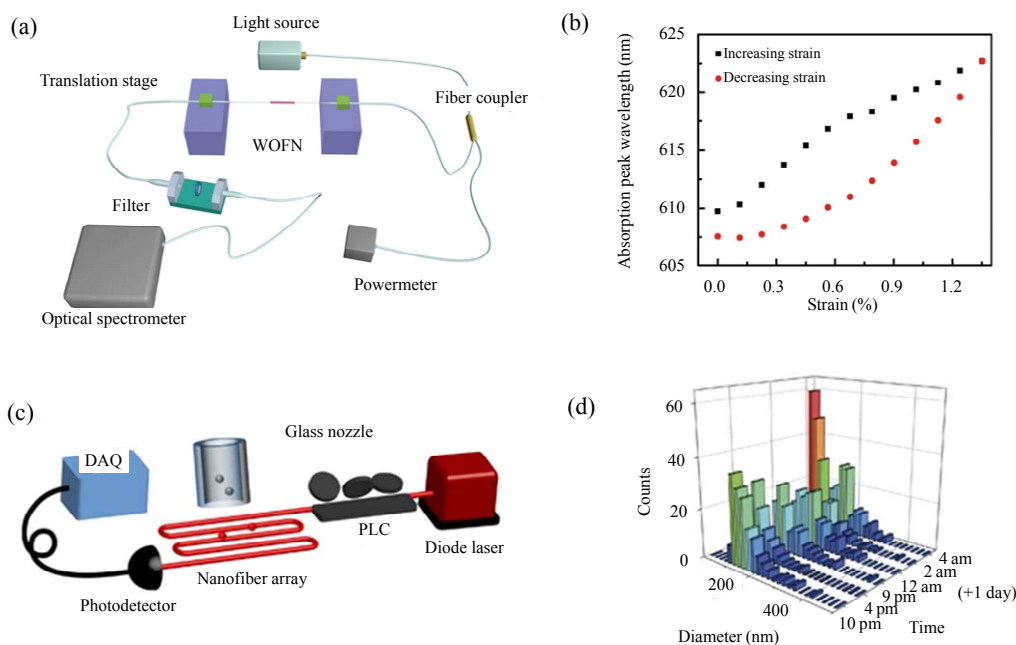


Fig. 11 Loss-based microfiber sensors: (a) experimental setup for in-line strain manipulation of absorption spectra of monolayer WS<sub>2</sub> to an optical fiber nanowire (WOFN). Reproduced with permission [170]. Copyright 2019 Springer Nature; (b) absorption peak wavelength of the WOFN with the increase and decrease in the strain. Reproduced with permission [170]. Copyright 2019 Springer Nature; (c) schematic setup of a Rayleigh-Gans-scattering-based nanofiber array size spectrometry. DAQ, data acquisition system; PLC, polarization controller. Reproduced with permission [235]. Copyright 2018 Springer Nature; (d) size histogram of nanoparticles in six air samples collected from different moments, evaluated by the nanofiber array size spectrometer. Reproduced with permission [235]. Copyright 2018 Springer Nature.

### 3.3 Frequency-based sensors

In addition to elastic light scattering, the abundant inelastic scattering effects in microfibers also provide useful tools for sensing applications. Recently, Brillouin scattering in microfiber has attracted increasing interest because the microfiber can strongly confine both optical and acoustic modes at a nanoscale and provide a unique platform to investigate photon-phonon interactions [247–253]. For optical sensing, Brillouin scattering may benefit the sensitivity and compactness of microfiber sensors, owing to the rise of surface acoustic waves. Godet *et al.* [254] characterized subwavelength microfibers with a resolution of a few nanometers using Brillouin spectroscopy. Huang *et al.* [255] demonstrated a microfiber Brillouin sensor with a maximum pressure sensitivity of 0.066 MHz/kPa and a temperature sensitivity two times higher than

that of a standard fiber-based Brillouin sensor. Luo *et al.* [256] revealed strain sensitivities of 0.0086 MHz/ $\mu\epsilon$  and 0.020 MHz/ $\mu\epsilon$  for the axially symmetric R<sub>01</sub> and R<sub>02</sub> acoustic modes in a microfiber, respectively. Recently, Huang *et al.* [257] demonstrated an RI sensor utilizing Brillouin scattering in a microfiber with a 2- $\mu\text{m}$  diameter with an RI sensitivity of  $\sim 1.6$  GHz/RIU.

Intrinsic Raman scattering in bulk optical fiber was employed for distributed temperature sensing [258, 259]; however, most of the reported microfiber sensors are based on external Raman scattering induced by surrounding media [260, 261]. In these studies, the microfiber's large evanescent field was typically employed as the probe to interact with the surroundings. However, the efficiency of Raman scattering is extremely low. Thus, it typically requires a high-powered pump source and a highly

sensitive spectrometer or a long microfiber to generate Raman signals with sufficient intensity. With the emergence of surface-enhanced Raman scattering, microfibers and microfiber tips decorated with plasmonic structures have been employed for ultra-sensitive molecular sensing [262–266].

The strong optical confinement and significant evanescent fields in microfiber are beneficial for ultra-sensitive molecular fluorescence spectroscopy [267–269]. In comparison with the absorption spectroscopy, the fluorescence spectroscopy contains two physical processes: fluorescence excitation and collection [270, 271]. Both processes can be implemented via evanescent coupling of the microfiber guided modes. Li *et al.* [269] reported a hybrid microfiber-microfluidic device for fluorescence measurements with a detection limit as low as 100 pM and excellent reversibility in a concentration range between 0 nM and 10 nM. In addition to embedding microfibers in the microchannels of microfluidic chips, hollow core microfiber has been employed for optofluidic manipulation and fluorescence detection in fluidics with an effective detection volume at the femtoliter scale [267] (Fig. 12). There is a growing interest in interfacing atoms with optical microfiber to manipulate and probe the atomic fluorescence [36, 272–274]. For example, spontaneous emission rates of excited atoms/molecules were investigated when positioned around a subwavelength microfiber, which opened a promising field in quantum electrodynamics [272, 274].

Moreover, microfiber tips have been used as fluorescence probes for bio/chemical detection. The nanoscale fiber tip is typically fabricated by cleaving a tapered fiber and functionalized using metal layer coated on the end face or functional materials (e.g., bioreceptors [275], dyes [276, 277], semiconductor/doped-polymer nanowires [278], and plasmonic structures [279]) attached to the tip. The micro-tip sensors exhibited excellent capabilities of

single-cell-level investigations into chemical reactions in biosystems. Moreover, they provided minimally invasive tools to probe subcellular compartments inside individual living cells for health effect studies and medical applications [279].

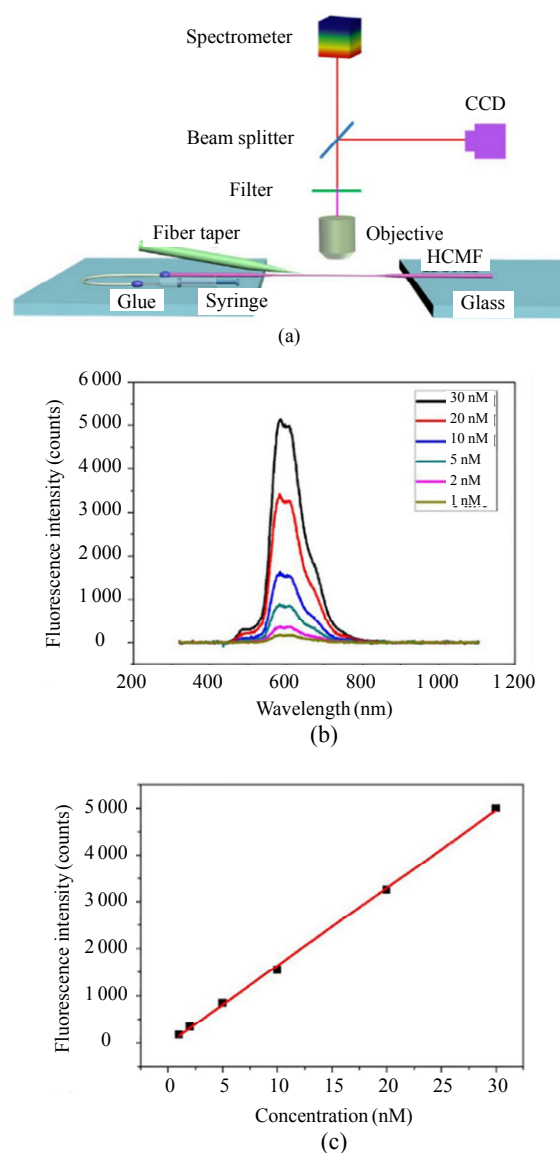


Fig. 12 Frequency-based microfiber fluorescence sensor: (a) scheme of the experimental setup for a hollow-core-microfiber-based fluorescence detector. Reproduced with permission [267]. Copyright 2018 Elsevier; (b) fluorescence spectra of fluorescent microsphere suspensions at different concentrations for the hollow-core-microfiber-based fluorescence detector. Reproduced with permission [267]. Copyright 2018 Elsevier; (c) fluorescence peak intensity as a function of concentration of fluorescent microsphere suspensions for the hollow-core-microfiber-based fluorescence detector. Reproduced with permission [267]. Copyright 2018 Elsevier.

#### 4. Challenges and prospects

Although significant progress has been made for microfiber-optic sensors in the past decades, we notice that several limitations must be resolved to enable wider applications. The first challenge is the fabrication of microfiber-based sensors with high repeatability, good scalability, and long-term stability. This is crucial for practical applications, especially for migrating microfiber sensors from laboratories to commercialized products. Thus far, a technique has been proposed to precisely manufacture microfibers with *in-situ* control of the waist diameter [280]. Packaging methods, including embedding the microfibers in low-RI materials [69, 70, 217, 281–283], integrating them with microfluidic chips [219, 269], and sealing them in glass tubes [284], were also demonstrated for better protection of sensitive microfiber sensing elements. However, the limitation regarding the efficient manipulation of fragile microfibers and performance maintenance after packaging still remains. The second challenge is the competition from other platforms, such as micro-electro-mechanical system sensors [285] and silicon photonic sensors [286, 287]. These integrated sensing devices rely on mature semiconductor fabrication techniques and offer the same advantages of a small footprint, high sensitivity, and fast response. Thus, it is critical to find the unique superiorities of microfiber sensors in some specific applications. Recently, with the emergence of the wearable technology, highly flexible microfiber-optic sensors may be utilized for human health monitoring and human-machine interaction [13, 288, 289].

#### 5. Conclusions

We have reviewed the typical microfiber structures that can be harnessed for optical sensing. We have also summarized the implementations of microfiber-optic sensors based on different operating mechanisms, including interference,

resonance, absorption, leakage, scattering, and fluorescence effects. We discussed the remaining challenges and concluded with prospects for future development of more practical microfiber-optic sensors. The microfiber platform will continue to offer increasing opportunities for sensing applications in combination with new structures and functional materials. It seems promising that the limitations of existing microfiber-optic sensors may be solved in the near future, and we expect that the sensors will be finally implemented in commercialized applications.

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