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Highly sensitive micro-hygrometer based on microfiber knot resonator

Qin Tian [a], Hangzhou Yang [a,*], Qiangzhou Rong [a], ZhongYao Feng [a], Ruohui Wang [a], Muhammad Khairol Annuar Bin Zaini [b], Kok-Sing Lim [b], Harith Ahmad [b], Pan Zhang [a], Xiangzi Ding [a], Kai Lu [a], Yudong He [a]

[a] School of Physics, Northwest University, TaibaiBeilu 229, Xi'an, Shaanxi 710069, China
[b] Photonics Research Centre, University of Malaya, 50603 Kuala Lumpur, Malaysia

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ABSTRACT

In this work, we experimentally demonstrated a microfiber knot resonator (MKR) for ambient relative humidity (RH) measurement. The microfiber device was manufactured by forming a ring from a low-loss microfiber, fabricated from a single-mode fiber (SMF) by using flame-heating technique. The resonator was successfully formed when a periodic output resonance spectrum was achieved. Without employing any coating hygroscopic material, the MKR was observed to highly sensitive to the variation of ambient RH ranging from of 30% RH to 94% RH. The proposed device is an extremely compact and fast response sensor, useful for a wide spectrum of industrial applications.

1. Introduction

Relative humidity (RH) is a key parameter of interest in the various sectors include medicine, bio-chemistry, pharmaceutical manufacturing, food processing industry and etc. So far, diverse methods have been employed for the measurement of RH in the ambient [1]. There are diverse types of hygrometers including chilled mirror hygrometer, mechanical hygrometer, infrared optical absorption hygrometer, wet and dry bulb psychrometer, electronic element and electrochemistry [2]. The electronic based humidity sensors have been the major player in the market for a long time due to their reliability, economy, low maintenance and long-term integrity. In comparison, the fiber-optic hygrometer, being as a bright younger generation, presents some advantages, such as multiplexing capability, low weight, small size, corrosion resistance and immunity to electromagnetic interference [3–9]. To date, there have been numerous reports on fiber hygrometer, in which most of them are based on hygroscopic materials, for example polymer coating on optical fiber transducers to improve the RH sensitivity of the fiber-optic sensing probe [10–13]. For example, moisture-sensitive materials HEC/PVDF has been used to form the hydrogel coating on the no-core fiber, the humidity induced RI changes surround the coating of no-core fiber, resulting in the reflected intensity change [14].

As a new type of humidity sensor, these optical fiber humidity sensors although have its unique advantages, they need the support of humidity-sensitive materials, and the coating process of humidity-sensitive materials increases manufacture complexity of the sensor, meanwhile the size and sensitivity of the sensor are limited by the material, coating technology [15,16]. Moreover, the light intensity interrogation technique is relatively simple and economy approach. However, this technique is vulnerable to the light transmission loss in the system due to external disturbances such as bending of fiber, vibration, stability of the light source. On the other hand, the wavelength interrogation technique is a more robust approach and less susceptible to the aforementioned external disturbances and it has a more dynamic measuring range. Therefore, the fiber-optic hygrometers based on the wavelength interrogation technique with high sensitive and non-coated humidity-sensitive materials has attracted a lot attention among many scholars and industrialists.

Recently, microfiber resonators have attracted much interest for their intriguing properties such as high sensitivity, high Q factor and low-loss coupling between the microfibers in the resonator [17,18]. Notably, MKR is an interesting microfiber structure made by forming an overhand knot with the microfiber. The fabrication does not require precise alignment, and it allows the formation of small resonator diameter [18]. Due to the small microfiber diameter, strong evanescent wave makes the MKR very sensitive to the variation of ambient medium, such as the refractive index [19]. This makes MKR a suitable optical sensor for small parameter change, for example micro-hygrometry. Measurement of RH can be achieved through the detection of change in refractive index. In the context of MKR sensor, the measurement is based on the shift of the resonance wavelength [20,21]. Apart from that, MKR has also been reported for temperature measurement [22,23].

In this paper, we proposed and experimentally demonstrated a humidity sensor based on a bare MKR without hygroscopic material

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[*] Corresponding author.
E-mail address: yanghz@nwu.edu.cn (H. Yang).

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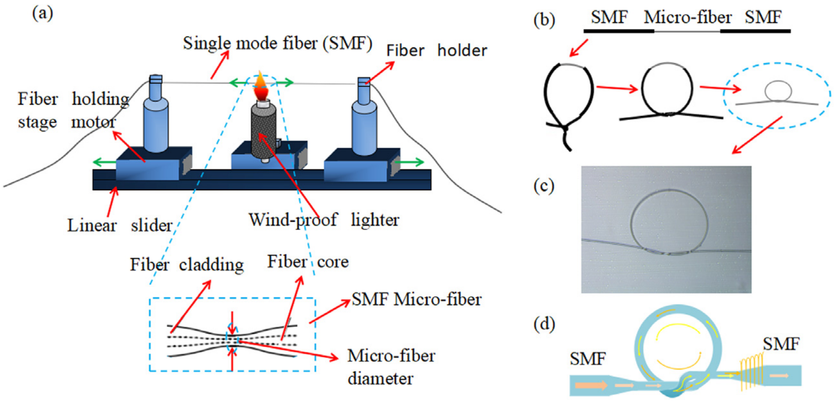

Fig. 1. (a) Experimental scheme for the fabrication of the microfiber, (b) the MKR, (c) microscopic image of the fabricated MKR, and (d) the schematic diagram of MKR.

coating. The MKR is formed by forming an overhand knot with the tapered fiber, producing a microfiber structure with low-loss integrability with standard fiber ports. The resonance peaks of the MKR are sensitive to the ambient RI change, and thus can be used for RH measurement. The wavelength of resonance peaks show high sensitivities to the RH change, making it as a preferable candidate for the RH detection in the micro-scale.

2. Sensor design and principle

The fabrication process of sensor comprises of two steps, namely micro-fiber fabrication and knot formation. As illustrated in Fig. 1(a), a standard single mode fiber (SMF) is tapered by flame-heating technique, the tapering of the fiber is achieved through elongation of the heated fiber by two translational stages. After that, the fabricated microfiber is carefully withdrew from the translational stages and transferred to a glass slide. As shown in Fig. 1(b), one SMF arm of the microfiber is broken to enable the formation of an overhand knot with the microfiber. The diameter of the knot can be decreased by pulling both SMF arms. The broken SMF arm of the microfiber knot is then spliced to a SMF pigtail and connected to a Static Optical Sensing Interrogator (SM125 by MICRON OPTICS, Scanning frequency of 2 Hz, Wavelength resolution of 1 pm) to enable in-situ monitoring of the transmission spectrum during the fabrication. Furthermore, the fabrication is aided with an optical microscope (Leica, DM2700M) to monitor the knot diameter. The pulling of the SMF arms stops when the desired comb spectrum of the MKR is attained. Fig. 1(c) shows the micrograph of the fabricated MKR.

The schematic diagram of MKR is shown in Fig. 1(d). In a typical MKR, the light entering from SMF will be split into two beams at the coupling region of the MKR, in which one of them will be guided into the knot whereas the other one will be transmitted to the other arm of the MKR and interfere with the output from the ring. This explains how resonance of light is achieved and the periodic output spectrum of the MKR is shown in Fig. 2. The resonance condition of the MKRs can be expressed as:

$$\lambda = \frac{2\pi n_{eff} R}{m} \tag{1}$$

where R is the radius of ring, n_{eff} is the effective refractive index of fiber, m is the resonance order. From Eq. (1), it is obvious that the resonance wavelength λ changes with the variation in n_{eff}. The contrast of the resonance spectrum depends on the balance between coupling and round-trip loss in the ring [24]. Meanwhile, the free spectral range (FSR) and the quality factor (Q) are important parameters for determining the performance of transmission spectrum of the MKR. The FSR of MKR is given by [25]

$$FSR = \frac{\lambda^2}{n_{eff} L} = \frac{\lambda^2}{\varphi} \tag{2}$$

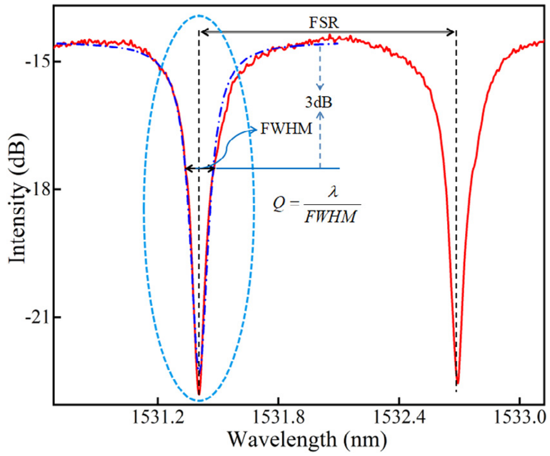

Fig. 2. The transmission spectrum of the MKR.

where L is the length of the microfiber ring, φ is the optical path length difference of the MKR. It is evident that the FSR of the MKR is inversely proportional to φ. The Q-factor of the resonator can be calculated as [15]:

$$Q = \frac{\lambda}{FWHM} \tag{3}$$

where FWHM is the full width half-maximum. Considering that the transmission dips of the notch in Fig. 2 are not symmetrically shaped, we acquire FWHM based on Lorentz fitting. As shown in Fig. 2, the FWHM of MKR is 0.13951 nm and hence the Q-factor of MKR is estimated to be 10 977 based on the calculation using Eq. (3). Once the resonator is achieved, the light propagation in tapered fiber is sensitive to the ambient refractive index [26].

In the experiment, we have further characterized how the optical transmission spectra of the MKR were influenced by the diameter of the different ring. Fig. 3 shows the transmission spectra of the proposed MKR at different ring diameters. For this configuration, they are fabricated with the same operation, including parameters of taper-drawing and ring formation. The decreasing ring diameter can increase the FSR of transmission spectrum, but reduces the Q-factor of MKR, as shown in Fig. 3(a)–(d). Among them, the spectra in Fig. 3(d) show the highest Q value.

Due the hydrophilic nature of the silica glass, the adhesion of water molecules on the surface of the microfiber changes the core effective refractive index of MKR. Consequently, the resonance wavelength shifts with humidity variation. The relationship between the change in resonance wavelength and the change in effective refractive index is given