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Review

Preparation and application of microfiber resonant ring sensors: A review

Liting Gai[a,b], Jin Li[a,*], Yong Zhao[a,b]

[a] College of Information Science and Engineering, Northeastern University, Shenyang 110819, China
[b] State Key Laboratory of Synthetical Automation for Process Industries, Northeastern University, Shenyang 110819, China

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ABSTRACT

Due to its advantages of strong evanescent field, optical limiting, easily integrating with common single-mode fiber, the micro-nano optical fiber has gotten a worldwide attention in recent years. The sensing technology based on microfiber resonant ring has the advantages of anti-interference, quick response, high resolution, small size and stable measurement, which enable its potential applications in the food industry, manufacturing and environment monitoring to determine the temperature, humidity, refractive index, and current. In this paper, the developments and applications of the microfiber resonant ring sensors were reviewed from three aspects: the manufacture methods for different types of microfiber resonance ring were summarized; the applications were described and analyzed in detail; the possible research content in future was prospected.

1. Introduction

Optical micro-nano fibers (MNFs) have the micro or nano-scale diameters, which is analogous to the wavelength of incident light [1,2]. Where, the whole stretched fiber and the surrounding environment are introduced as the core and cladding, respectively. Due to their extremely small diameters, this kind of MNFs are capable of offering large fractions of evanescent waves and high-intensity surface fields, enhancing significantly the interaction between guided light and surrounding specimens [3]. Furthermore, other advantages include the easy preparation, simple structure, low transmission loss, stable chemical properties and high mechanical strength have made MNF become a promise candidate for future optical device miniaturization and photonics devices [4–8]. Compared with other micro and nano machining process, the preparation of MNF is easier. Generally, it can be obtained by one step fabrication technique, such as melt-stretching and sol-dip-pulling method; the eigen structure of MNF is simple, which only require controlling its diameter and uniformity, instead of some complex nanofabrication on the surface or in the inside of fiber; its optical transmission loss is low, benefits from the smooth surface and strong optical confinement capacity; the stability of MNF devices can be promised by selecting the MNF materials with resistance to chemical corrosion or high temperature according to the application environment.

Tong and co-authors experimentally demonstrated low-loss optical waveguide in MNFs with diameters far below the wavelength of the guided light, which renewed the research interests in optical MNFs as potential building blocks for miniaturized optical components and devices [3]. Recently, various MNF-based photonic devices have been reported, among which MNF resonators and interferometer are particularly useful for sensing applications. In this paper, MNF resonators is mainly introduced in detail. In theory, due to the strong evanescent fields, MNFs is highly sensitive to the parameters change of external medium [9,10]. For MNF resonating ring, the circled light interferes with the light waves in the bus fiber. When external parameters changes, the effective refractive index (RI) and the length of the microfiber ring changes accordingly, resulting in the resonant wavelength shift in the output spectrum [11]. Namely, the MNF resonating ring can sense the changes of external parameters by observing the shift of resonant wavelength. Based on the theory, the MNF resonating ring sensors have attracted more and more attention and have been applied in many works recently. The MNF resonating ring sensors have many advantages, such as small size, anti-interference, quick response, high resolution, large detection limit and high sensitivity [12–16]. All these outstanding optical properties reveal the enormous potential value of MNF resonant ring sensors. Although the stability and selectivity need the further demonstration so far, the MNF resonant ring with various structures and parameters have been experimentally verified successfully in recent years. Meanwhile, different applications have been constantly explored as well. Therefore, the MNF resonating ring has a prominent performance in many parameters measurement, such as RI, humidity, current, temperature, concentration and magnetic field [17–26]. In the following sections, the preparation methods and applications for different types of MNF resonant ring will be introduced, compared and analyzed.

* Corresponding author.
E-mail addresses: lijin@ise.neu.edu.cn (J. Li), zhaoyong@ise.neu.edu.cn (Y. Zhao).

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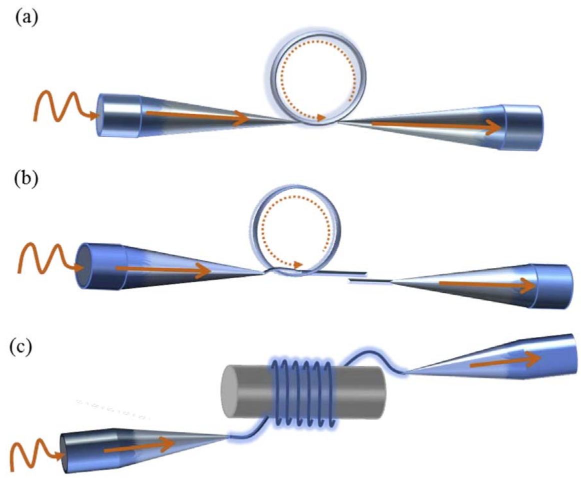

Fig. 1. Schematic of MNF homogeneous (a) MLR, (b) MKR, and (c) MCRs [27].

2. Preparation of MNF resonators

2.1. Classification of MNF resonators

Typical MNF resonators can be divided into three categorys: micro-loop resonator(MLR), micro-knot (MKR) resonator and micro-coil resonator (MCR) [27–29]. As shown in Fig. 1, these three structures work based on the resonance effect. The strong evanescent field of MNF is used to sense the change of the surrounding medium parameter, which causes the change of the MNF effective RI and the shift of the resonance peak wavelength in output spectrum [11]. The structure of MLR is shown in Fig. 1(a). It is fabricated by circling the MNF, where the overlapping area maintains stability relying on the Van der Waals force and static electricity [30]. However, the structure is not stable because of the free overlap of coupling region. The glass with low RI is usually used to artificially fix its coupling region. Therefore, it’s hard to keep the same geometric parameter, whose small changes will exert a significant indeterminacy impact on the transmission characteristics. Fig. 1(b) indicates the schematic of MKR. The MKR is fabricated by knotting the MNF into a circle, whose structure is more stable than MLR. Moreover, the node structure promises a fixed circle; the loop length can be controlled easily to acquire the different free spectral range (FSR). Nevertheless, during the preparation of MKR, the coupling between the tail of the MNF node and the bus MNF will introduce a higher light loss and a more complex process. The MCR with muti-loops (MCRs) is shown in Fig. 1(c), where, a MNF is winded around on a dielectric rod with a smaller RI in comparison. The micro-coil resonator (MCR) is a 3D resonator consisting of self-coupled adjacent loops in a helix arrangement [29]. The MCRs structure was originally proposed in 2004 and first experimentally demonstrated in 2007. The quality factor (Q) of MCRs is higher than that of MLR, MKR and MCR (single loop). The highest Q factor was experimentally achieved by ~470,000 [31].

2.2. MNF preparation methods

The standard single-mode optical fiber (SMF) without coating layer is usually used to fabricateMNF by heating and directly stretching method. The SMF is firstly heated to softening state, which is then stretched into MNF by holding its both ends near the heating area. In the drawing process, the proportion of the fiber core and cladding reduce equally [32]. Because of the small RI difference between the fiber core and cladding (~0.004) and the small diameter of the fiber core of MNF (< 100 nm), the fiber core and cladding can be regarded as a whole part (fiber core), while the air as fiber cladding. Due to the large RI difference between fiber core and cladding, the MNF manifests a strong effect in optical limiting [33]. Generally, the preparation methods of MNF can be divided into two kinds, manual preparation method and mechanical preparation method.

2.2.1. Manual preparation methods

2.2.1.1. Two-step stretching method. The two-step stretching method includes two operations [34]. Firstly, the silica fiber is used as the MNF preform and heated by the alcohol burner to a molten state, which is then manually stretched into the microfiber with a few microns in diameter. Secondly, a sapphire rod taper is heated by the alcohol burner for several minutes, around which the prepared microfiber is convolved. The MNF will be obtained by further stretch the microfiber due to the good thermal conductivity and stability of the sapphire. Until recently, the silica MNF with a length of a few centimeters and a diameter of 50 nm has been fabricated.

2.2.1.2. Self-modulated drawing force method. For the method of self-modulated drawing force, a bending stress is introduced in the stretching process to improve the diameter uniformity of the MNF [35]. The tensile force along the optical fiber can be manipulated by the change of this bending stress. For the thick fiber, the bending stress exists near the thick diameter area and a larger tensile force is applied; as the optical fiber becoming thinner, the bending stress occurs in the smaller diameter area and the tensile force is reduced. Through this technique, the diameter of an as-fabricated MNF can reach down to 20 nm with the uniformity up to 0.1%. The stability and repeatability are difficult to guarantee for the manual preparation methods due to the random factor of human and the airflow disturbances of external environment in the drawing process.

2.2.2. Mechanical preparation methods

2.2.2.1. Flame-heated stretching method. A typical system of flame-heated stretching method is schematically illustrated in Fig. 2(a), where, B is the burner, in which the oxyhydrogen flame (high

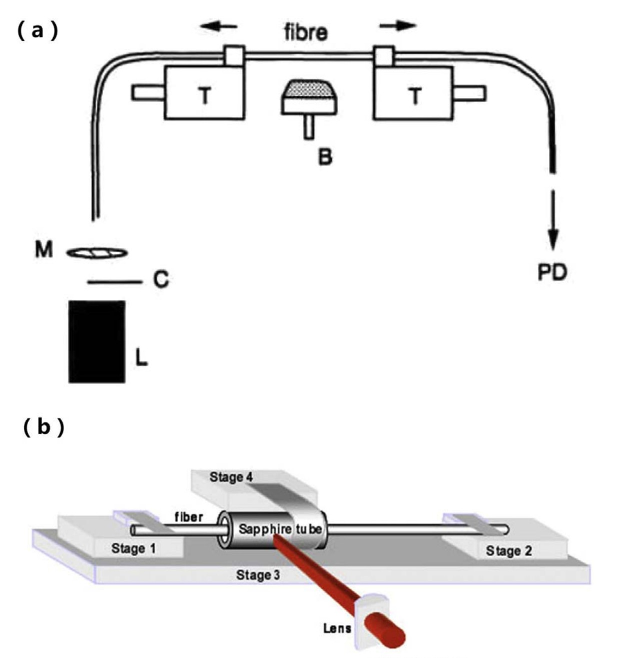

Fig. 2. Illustration of(a)flame-heated drawing method using oxy-hydrogen flame [36] and (b)laser-heated stretching method using a sapphire tube heated with a CO2 laser [37].