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High sensitivity balloon-like refractometric sensor based on singlemode-tapered multimode-singlemode fiber

Biyao Yang, Yanxiong Niu, Bowen Yang, Yanhui Hu, Lingling Dai, Yiheng Yin, Ming Ding*

School of Instrumentation Science and Opto-Electronics Engineering, Beihang University, Beijing 100191, China

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ABSTRACT

A high sensitivity refractive index (RI) sensor based on balloon-like singlemode-tapered multimode-singlemode (STMS) fiber structure is proposed. The configuration is formed by bending the tapered multimode fiber (MMF) like a balloon shape, which is sandwiched between two singlemode fibers (SMFs). Taking the advantage of tapering and bending, the sensitivity is dramatically improved. The maximum sensitivity of 6909 nm/RIU at RI = 1.42 is experimentally achieved. The proposed refractometer is promising and attractive in chemical and biological applications for its superior properties, such as high sensitivity, compact size, easy fabrication, and low cost.

1. Introduction

Optical fiber based refractive index (RI) sensors have been widely studied over the past decades. There are a number of approaches to implement optical RI sensing, including Mach–Zehnder interferometers (MZI) [1], Fabry–Perot interferometers (FPI) [2], fiber Bragg gratings (FBGs) [3], surface plasmon resonance [4], and long period fiber gratings (LPFGs) [5]. In recent years, optical fiber refractometers based on singlemode-multimode-singlemode (SMS) have attracted a lot of interest with the advantages of high sensitivity, compact size, and simple fabrication [6]. For RI sensing, a large overlap needs to take place between the propagation modes and the surrounding medium, therefore the cladding of the multimode fiber (MMF) has to be removed. The common method is to use hydrofluoric acid to etch off the cladding [7]. However, chemical corrosion is not only dangerous but also difficult to control, which increases the complexity of fabrication and makes the surface rough. To facilitate the fabrication process, the singlemode-coreless MMF-singlemode fiber (SCMS) structure which replaces the conventional MMF with coreless MMF has been reported [8,9]. But the sensitivity is relatively low compared with other all-fiber refractometers. Y. Cardona-Maya et al. achieved the enhancement of the sensitivity by reducing the diameter and depositing high refractive index thin-film on the coreless fiber. A high sensitivity of 1442 nm/RIU in the range of 1.32–1.35 has been attained [10]. However, in this work, HF etching was also used to reduce the diameter of coreless fiber. In order to overcome the limitation of chemical corrosion and improve the sensitivity, Wang et al. proposed an evanescent field fiber refractometer relying on the singlemode-tapered multimode-singlemode (STMS) structure [11]. Due to the increase of power propagating in evanescent field at small taper diameters, the STMS achieves high sensitivity better than 1900 nm/RIU at RI of 1.44 [12]. A higher sensitivity of 2946 nm/RIU can be attained by tapering the coreless MMF sliced between two singlemode fibers (SMFs) [13]. Therefore, tapered SMS fiber structure has an ability to improve the performance of the SMS-based RI sensors with the advantages of large evanescent field, compact physical size, low cost and easy fabrication [11–15].

Meanwhile, on the basis of the increase of evanescent field due to fiber bending, bent optical fiber structures exhibit great potential in RI sensing [16]. Zhang et al. demonstrated a refractometer based on MZI which was generated from two fiber bending sections in a SMF. A maximum RI sensitivity of −204 nm/RIU was achieved in the RI range of 1.3288–1.3696 [17]. Bent SMS-based optical devices were also successfully used in RI sensing applications and achieved a sensitivity of 258 nm/RIU for a curvature of 0.36 cm^{-1} [18]. Recently, the tapering technology combining with bending has been implemented in many fiber structures for high sensitivity [19–21]. The sensor based on tapered and bent Ge-doped fiber achieved a maximum sensitivity of 11006.0 nm/RIU at RI of 1.430 [19]. In order to reduce the physical size and cost of the RI sensor, the tapered SMF was designed into a balloon-like shape however the sensitivity dropped down to 404.9 nm/RIU [22].

* Corresponding author.
E-mail address: mingding@buaa.edu.cn (M. Ding).

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In this paper, a compact and high sensitivity refractometer based on balloon-like STMS fiber structure is proposed. Different from the refractometer utilizing a tapered-fiber-based balloon-like interferometer, this configuration composites MZI and multimode interference (MMI) in the MMF section and achieves a high sensitivity. The theoretical analysis and simulation results predict that the evanescent field would be enhanced after the MMF is tapered and bent. To optimize the refractometer, the influence of the bending radius on the sensitivity of the sensor has also been investigated. The RI response is demonstrated experimentally and achieves a maximum sensitivity of 6909 nm/RIU at RI = 1.42. The proposed sensor takes advantage of tapering and bending, achieving a significant improvement of sensitivity and preserving the characteristic of compact size, easy fabrication and low cost.

2. Principle and simulation

The schematic of the sensor structure is shown in Fig. 1(a). The configuration is simply formed by bending the STMS fiber structure like a balloon shape.

When the lights propagating along the input SMF inject into MMF section, the multiple modes would be excited and MMI occurs between different excited modes. The input light field can be expressed as [23]:

$$E(r,0)=\sum_{m=1}^{M} b_m\Psi_m(r) \tag{1}$$

where $\Psi_m(r)$ presents the mth eigenmode excited in MMF section, b_m is the excitation coefficient of each mode and can be expressed by the overlap integral between the $E(r,0)$ and $\Psi_m(r)$:

$$b_m=\frac{\int_0^{\infty}E(r,0)\Psi_m(r)r\,dr}{\int_0^{\infty}\Psi_m(r)\Psi_m(0)r\,dr} \tag{2}$$

The light field at the propagating distance z in MMF can be calculated by overlaying all modes:

$$E(r,z)=\sum_{m=1}^{\infty} b_m\Psi_m(r)\exp(j\beta_m z) \tag{3}$$

where β_m is the propagation constant of the mth eigenmode. The transmission power can be determined by overlap integrating between the $E(r,z)$ and the SMF output field of fundamental mode $E_0(r)$ as:

$$L_s(z)=10\cdot\log_{10}\left\{\frac{\left|\int_0^{\infty}E(r,z)E_0(r)r\,dr\right|^2}{\left|\int_0^{\infty}|E(r,z)|^2 r dr\int_0^{\infty}|E_0(r)|^2 r\,dr\right|^2}\right\} \tag{4}$$

On account of the MMF tapering, the power of the multiple modes in taper region is easy to leak out to generate a large evanescent field, which can interact with the surrounding medium. Furthermore, due to stress-optic effects, bending induces that the inner half of the fiber suffers compression toward to the center of the bending whereas tension is along the outer half of the fiber. As a result, RI distribution is no longer symmetrical within the cross-section of the balloon-like STMS. The bent MMF can be represented by an equivalent straight MMF after the conformal mapping. The modified RI distribution is illustrated in Fig. 1(b) and can be defined as [24]:

$$n=n_0\left(1+\frac{x}{R_{eff}}\right) \tag{5}$$

where n_0 is the RI distribution of the straight tapered MMF, x is a coordinate which is perpendicular to the bent fiber axis with the positive x-axis pointing the outer half of the fiber, and R_{eff} is the equivalent bending radius, which can be expressed as:

$$R_{eff}\equiv\frac{R}{1-\frac{n_0{}^2}{2}[P_{12}-\nu(P_{11}+P_{12})]} \tag{6}$$

where R represents the actual bending radius, P_{11} and P_{12} are components of the photo-elastic tensor, and ν is the Poisson's ratio. As for silica fiber, $R_{eff}/R\approx 1.28$ [24], thus the equivalent RI distribution is simply written as:

$$n=n_0\left(1+\frac{x}{1.28R}\right) \tag{7}$$

Considering only mth and nth modes excited in the balloon-like structure, the two modes would form MMI in the core of MMF firstly. When they propagate to the tapered and bending region, the mth mode would break free from the constraint of core and become the cladding mode as the result of the asymmetric RI distribution. After passing through the tapered and bending region, the mth mode would recouple to the core, forming MZI with the nth mode. Then as an optical path difference existing between the two modes, MMI occurs again in the core of MMF. Here the tapered and bending region is working more like a phase modulator for mth mode. The phase difference can be expressed as:

$$\Delta\phi=\Delta\phi_{MZI}+\Delta\phi_{MMI} \tag{8}$$

where $\Delta\phi_{MZI}=2\pi\Delta n_{eff1}L_1/\lambda$ is the phase difference caused by MZI in the tapered and bending region, related to the tapered and bending length L_1 and Δn_{eff1} which represents the effective index difference between the cladding mode (mth mode) and the core mode (nth mode). $\Delta\phi_{MMI}=2\pi\Delta n_{eff2}(L-L_1)/\lambda$ is the phase difference induced by MMI, where Δn_{eff2} is the effective index difference between mth and nth modes propagating in the core of MMF, and L is the total length of MMF. When $\Delta\phi=(2k+1)\pi$, the wavelength of the interference minimum is deduced as:

$$\lambda=\frac{2[\Delta n_{eff1}L_1+\Delta n_{eff2}(L-L_1)]}{2k+1} \tag{9}$$

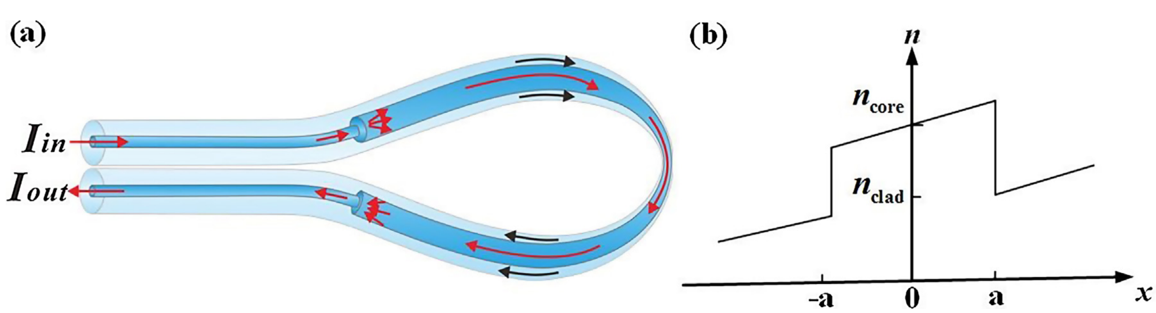

Fig. 1. (a) Schematic of the balloon-like STMS structure. The red arrows represent the core modes and the black arrows are the cladding modes. (b) The equivalent RI distribution after conformal mapping. n_{core} and n_{clad} are the RI of the core and cladding, a is the radius of fiber, and x-axis is perpendicular to the bent fiber axis with the positive x-axis pointing the outer half of the fiber toward to the center of the bending, respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)