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A Mach-Zehnder interferometer based on tapered dual side hole fiber for refractive index sensing

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ABSTRACT

An in-line fiber Mach-Zehnder interferometer (MZI) based on tapered dual side hole fiber (DSHF) is proposed and fabricated for refractive index measurement. The MZI is composed of a short piece of tapered DSHF which is sandwiched between two single mode fibers (SMFs). The DSHF is heated and tapered by using an oxy-hydrogen flame. At the taper zone, the core mode of the lead-in SMF is coupled to several cladding modes of the DSHF, and interference happened between the core and cladding modes of the DSHF. Due to the existence of the air hole at the tapered DSHF zone, the cladding modes can be much more easily stimulated than general SMF. The experiments indicated that the proposed sensor has a high refractive index sensitivity of 816.1 nm/RIU in the refractive index range of 1.333–1.379 with the tapered DSHF diameter of 33 µm. In addition, the sensor had a low temperature response of 19.9 pm/°C in the range from 30 to 110 °C. The proposed sensor is attractive for its high refractive index sensitivity, and easy fabrication, making it of potential value for refractive index measurements for chemical and biological sensing.

1. Introduction

Refractive index (RI) measurement is important in many fields such as chemical, biological and medicine. Optical fiber sensors are ideally suited for RI sensing due to their advantages of high sensitivity, compact size and in situ measurement. Various optical fiber RI sensors based on different structures have been developed and in-fiber interferometers are widely employed because of the low cost and high sensitivity [1–17]. Among the interferometric configurations, interferometers based on tapered structures attract great attentions due to their easy fabrication process. In-fiber Mach-Zehnder or Michelson interferometers based on abrupt tapers have been realized through a fiber-taper machine or a fusion splicer, and sensors based on tapered single mode fibers (SMF) [8–10], tapered multimode fibers [11,12], tapered microfiber [13], tapered thin core SMF [14] have been developed. These interferometric sensors have many advantages such as simple structure, ease of fabrication and cost effectiveness. However, for the RI sensors based on tapered SMF, the RI sensitivities are relatively low and the total length of the structure is generally tens of millimeters, which is not compact for integrated applications [9], and for the RI sensor based on the tapered multimode fiber, the length of the multimode fiber is tens of millimeters, which is not suitable for the small-scale situation [11]. For the interferometer based on the tapered microfiber, the fabrication of the microfiber is complex [13], and for the RI sensor based on tapered small core SMF, the fabrication is relatively complex and the RI sensitivity is relatively low [14]. In-fiber interferometers based on SMF-tapered hollow core fiber (HCF)-SMF [15] and SMF-tapered photonic crystal fiber-SMF [16] structure were also developed for RI sensing. Such interferometer-based RI sensors are have relative high sensitivity, and easy fabrication.

In this paper, we present a sensitivity-enhanced SMF-tapered dual side hole fiber (DSHF)-SMF sensor based on the principles of the Mach–Zehnder interferometer for RI measurements. The sensor was fabricated by splicing a short section of DSHF between two SMFs and the DSHF was tapered using a fiber-tapering machine. The DSHF was drawn into a taper to enhance the intensity of evanescent wave and coupling degree between cladding modes and external RI solutions. Such a feature has two significant advantages: First, compared with sensors based on tapered SMF [9], due to the existence of the two large holes of the DSHF, the sensor based on the tapered DSHF can easily excite the cladding modes in the condition of the short taper length and thick taper diameter, and the structure was stronger as well as it has high sensitivity. Secondly, compared with the sensor based on tapered photonic crystal fiber [16], the two holes of the DSHF still exist after tapering, and there is no collapse in the taper region. The experimental results showed that the proposed sensor has a high RI sensitivity of

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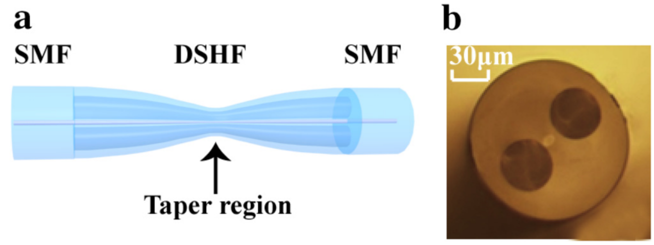

Fig. 1. (a) The schematic diagram of the SMF-tapered DSHF-SMF interferometer, (b) The cross-section image of the DSHF.

816.1 nm/RIU in the RI range of 1.333–1.379 with a tapered DSHF diameter of 33 μm. Even if the diameter of the tapered DSHF increases to 45 μm, the RI sensitivity can still be maintained as high as 535.5 nm/RIU. In addition, the sensor has a low temperature response of 19.9 pm/°C in the range from 30 to 110 °C corresponding to general tapered SMF structures. The described device has the advantages of high RI sensitivity, robustness, compact size, and an easy fabrication process.

2. Sensor fabrication and working principle

2.1. Fabrication of the MZI interferometer

The schematic diagram of the SMF-tapered DSHF-SMF interferometer is illustrated in Fig. 1(a). It composed of a section of tapered DSHF which is fusion spliced between a short segment of the lead-in SMF and a short segment of the lead-out SMF. The cross-section image of the DSHF is shown in Fig. 1(b). The DSHF is composed of an elliptical core and two large air holes beside the core. The lengths of the major and minor axes of the core are about 11.4 μm and 8.7 μm, respectively, and the diameters of the circular air holes and the cladding are 40 μm and 125 μm, respectively. The core diameter and cladding diameter of the used SMF (SMF-28e, Corning) are 8.2 μm and 125 μm, respectively.

The fabrication process of the SMF-tapered DSHF-SMF interferometer is as follows. Firstly, a segment of lead-in SMF and a segment of DSHF were cleaved, and then spliced together through aligning the core of the SMF to the core of the DSHF by a fusion splicer (Fujikura FSM-100P) with the manual program. In the SMF-DSHF splicing process, the arc discharge current and discharge time were respectively set to be 199 bit and 1 s, to make sure that the SMF and the DSHF not only were solidly spliced together, but also the air holes of the DSHF were not collapsed. Secondly, the DSHF was cleaved by a high precision fiber cleaver with a distance of about 2.5 mm away from the SMF-DSHF fusion spliced joint. It was then spliced with another segment of lead-out SMF. After the splicing, the lead-in SMF and the lead-out SMF of the fabricated device were connected to a Super luminescent Light Emitting Diode (SLED) and an optical spectrum analyzer (OSA) (AQ6370, Yokogawa), respectively. The SLED has a bandwidth of 200 nm ranging from 1450 nm to 1650 nm, and the OSA has a maximum wavelength resolution of 0.02 nm. Finally, the fabricated device was tapered in the middle of the DSHF by the oxy-hydrogen flame of a fiber-tapering machine (Kaipule Co. Ltd. AFBT-8000MX-H). The flow of H_2 and the tapering velocity which could affect the extinction ratio of the interference peaks in the transmission spectrum were set to be 150 ml/s and 120 μm/s, respectively. During the tapering process, the transmission spectrum was monitored by the OSA.

Fig. 2(a) presents the microscope image of the fabricated SMF-tapered DSHF-SMF interferometer, where the SMF-DSHF fusion splice junction are not fully displayed. The amplified image of the tapered region is shown in the inset of the Fig. 2(a). The air holes of the DSHF in the taper region are still exist, which means the DSHF is not collapsed. The diameter of the taper waist is 33 μm. A smaller taper waist diameter could improve the RI sensing sensitivity because the evanescent field of the travelling light is stronger [17], however, it will reduce the mechanical strength of the sensor. Considering the factors of extinction ratio, sensitivity and mechanical strength, we chose the following tapering diameter of the DSHF to fabricate the interferometer, 33 μm, 45 μm, 52 μm. After tapering, a quasi-sine interference spectrum is achieved, as shown in Fig. 2(b).

2.2. Working principle

For the proposed interferometer, due to the decrease of the core diameter of the DSHF, the high order modes of the cladding modes are easily excited in the taper region of the DSHF. The two gradient regions in the taper section act as the splitting and combining couplers. At the first gradient region, the core mode of the DSHF is split into the fundamental mode and high-order modes of the cladding, and at the second gradient region, the split modes are recombined into the core of the DSHF. The interference occurs between the fundamental mode and the high-order mode of the DSHF. Meanwhile, some other high-order modes are also produced, which participate in the interference and slightly modify the envelope of the interference spectrum. It's worth noting that the light also conducts in the core of the DSHF, however here external RI main influencing cladding mode, so we mainly research the change of the cladding mode. It is well known that the propagation constant of the cladding mode (corresponding to effective RI) is influenced by the RI of the surrounding environment.

The spectrum characteristics of the SMF-tapered DSHF-SMF interferometer can be described with the two beam interference model

$$I = I_1 + I_2 + 2\sqrt{I_1 I_2}\cos\left(\frac{2\pi\Delta n_{eff} L}{\lambda}\right) \quad (1)$$

where I_1 and I_2 represent the intensities of the fundamental mode and the cladding mode of the proposed interferometer, respectively; λ is the operating wavelength; L is distance of the taper region of the DSHF; and $\Delta n_{eff} = n_1 - n_2$ is the effective RI difference between the fundamental and cladding modes, where n_1 and n_2 are the effective RIs of fundamental mode and cladding mode.

As the phase difference satisfies the condition $2\pi\Delta n_{eff} L = (2m+1)\pi$, m = 0, 1, 2, ⋯, where m represents an integer, the resonant dips will appear at the wavelengths of

$$\lambda_m = \frac{2\Delta n_{eff} L}{2m+1} \quad (2)$$

When the external RI of the solution tested changes, due to the cladding modes are sensitive to the RI of the solution surrounding the fiber sensor, the effective RI of the cladding mode changes but the fundamental mode remains unchanged. Thus this device can be used as an external RI or chemical solution sensor. The shift value $\Delta\lambda_m$of the wavelength dip is given by

$$\Delta\lambda_m = \frac{2L(\Delta n_{eff} + \Delta n)}{2m+1} - \frac{2L\Delta n_{eff}}{2m+1} = \frac{2L\Delta n}{2m+1} \quad (3)$$

where $\Delta n$is the variation value of the cladding mode when the surrounding RI changes. According to the evanescent field theory, the evanescent field may be enhanced. Therefore, the SMF-tapered DSHF-SMF structure theoretically has better RI sensing characteristics.

3. Experiments and discussion

To demonstrate the SMF-tapered DSHF-SMF interferometer's RI sensitivities at different diameters of the tapered DSHF, three sensing heads with taper diameters of 33 μm, 45 μm, and 52 μm were fabricated for experimental test, respectively. The sensors were put in a NaCl solution with NaCl/water ratio of 1:4 (RI of 1.3676). Then a series of NaCl solutions with NaCl/water ratio of 2:9, 1:5, 1:6, 2:15, 2:19, 1:12, 1:15, and 1:19, which corresponds to RI of 1.3644, 1.3618, 1.3576, 1.3532, 1.3493, 1.3461, 1.3435, and 1.3414, respectively were used in the experiment. Firstly, the interferometer with 52 μm diameter of the