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Temperature-independent refractometer based on a tapered photonic crystal fiber interferometer

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ABSTRACT

A temperature-independent refractometer by using a tapered photonic crystal fiber (PCF) based Mach–Zehnder interferometer (MZI) is proposed and experimentally demonstrated. It is fabricated by sandwiching a tapered PCF of 29 mm long between two standard single mode fibers (SMFs) with the fully collapsed air holes of the PCF in the fusion splicing region. It has been found that tapering the PCF greatly enhances the sensitivity of the refractometer. A maximum sensitivity of 1529 nm/RIU (refractive index unit) is achieved within the range from 1.3355 to 1.413. The refractometer is nearly temperature-insensitive due to the ultra low temperature dependence of the used.

1. Introduction

Refractometer is an important equipment for laboratory and industry usages owing to its numerous applications in industrial processing, environmental monitoring, clinical analysis, quality controlling in food industries and different biological or chemical specimens studying, etc. Optical fiber sensors are attractive, owing to their small size, flexibility in design, immunity to electromagnetic interference, network compatibility, and the capability for remote and insitu measurement.

Recently, a compact in-line photonic crystal fiber (PCF) based Mach–Zehnder interferometer (MZI) built via fusion-splicing was reported and attracted a lot of research interests [1–6]. It consists of a stub of PCF being spliced between two standard single mode fibers (SMFs). In the splicing regions, air holes of the PCF are fully collapsed, thus cladding modes are excited in the first splicing region and recombine with the residual core mode in the second splicing region. Interference is therefore occurred between the excited cladding modes and the core mode. Because the cladding modes are sensitive to the external environment, the formed MZI is suitable for measuring refractive index (*RI*) of analyte surrounding the PCF [7]. However, this kind of sensor suffers from low sensitivity. So the PCF tapering is a possible solution for enhancing and increasing the *RI* sensitivity. Recently, tapered PCF–MZI structure with enhanced sensitivity has been studied by using the acid etching method [8,9].

In this paper, an alternative method by using a fusion tapered PCF is proposed and experimentally demonstrated. Through this method, the smaller taper with micro-sized figure can be precisely controlled by the commercial fiber taper processing system for avoiding the harmful acid etching. The principle, sensing scheme, results and conclusion are discussed in the following sections.

2. Design and principle

The schematic diagram of the proposed sensor head is shown in Fig. 1(a). A biconical taper with a waist diameter of 71.7 μm, a taper length of 4 mm was fabricated at the middle of the PCF–MZI as shown in Fig. 2. The light which comes from the optical power source passes through the SMF to the tapered PCF through the collapsed air hole region. When it enters the collapsed PCF region, the core mode of SMF is converted to cladding mode of PCF, it also means that the cladding modes will be excited and propagate inside the PCF cladding region. However, when the cladding modes of PCF reach the taper region, they further expand to the cladding by the PCF taper, they will easily interact with the external environment due to the decrease in the diameter of the PCF in this region. So tapering PCF is effective to increase the measurement sensitivity. The cladding modes will continue to propagate inside the PCF cladding region after leaving the taper region and they will recouple and recombine with the core mode at the other collapsed air hole region. The corresponding transmission function of the interferometer can be expressed as [7]

$$I = I_{core} + I_{cladding} + 2\sqrt{I_{core} I_{cladding}}\cos(\delta) \quad (1)$$

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where I is the intensity of the interference signal, and I_{core} and $I_{cladding}$ are the intensities of the core and cladding modes, respectively. δ is the phase difference of the core mode and cladding modes, it can be defined as

$$\delta = \frac{2\pi}{\lambda}\int_L (n_{cladding} - n_{core})dz \tag{2}$$

where λ is the wavelength. n_{core} and $n_{cladding}$ are the effective indices of the core and cladding modes, respectively. If the tapered PCF is surrounded by a certain analyte with refractive index of n_α, while n_{core} is constant because the core mode is isolated from the external environment, $n_{cladding}$ changes with n_α owing the effect of the analyte over the cladding modes. Transmission of the proposed sensor depends directly on the phase difference between the core mode and cladding modes. Such a phase difference depends on the refractive index of the medium surrounding the taper and also on the length of the interferometer. The MZI length can be modified by minor elongations of the tapers. Therefore, a modal interferometer can be exploited for refractive index sensing [10,11]. Thus, the refractive index sensitivity S, defined as the ratio of the interference wavelength (λ_i) shift to the corresponding change of n_α, is [12]

$$S = \frac{d\lambda_i}{dn_\alpha} = \frac{\lambda_i}{n_{cladding} - n_{core}}\frac{\partial(n_{cladding} - n_{core})}{\partial n_\alpha} \tag{3}$$

3. Experimental results and discussions

The experimental system of the proposed refractometer is shown in Fig. 1(b). To construct the tapered PCF–MZI, we employed a commercial single-mode PCF (LMA-10, NKT Photonics) consisting of a solid core surrounded by four rings of air holes. Diameters of the core, cladding and air holes are 11, 125 and 11.7 μm, respectively, air holes with an average diameter of 2.17 μm. The average separation between neighboring air holes is 5.3 μm. Fig. 3 shows a micrograph of the cross section view of the PCF. Firstly, the PCF–MZI was fabricated by splicing the ends of two SMF-28 fibers to the cleaved end of a 29 mm long PCF by using a conventional splicer (Fujikura FSM-40 S). The air holes of the PCF over a short region of ~108 μm long collapsed completely as shown in Fig. 4. Then the PCF was tapered at the middle position by using a Dowson_OC2020 fiber taper processing system, which provides precise process control. With this tapering process, a uniform waist tapered PCF with length of 4 mm and diameter of 71.7 μm was achieved. Total length of the whole sensor head was measured to be 34 mm. However, it is important to note that the MZI is based on optical path length, therefore, the taper length is important as the taper diameter. In the experiment, the longer the taper length, the higher the sensitivity. But the longer taper length with the thinner taper diameter will induce the collapse of the air holes of PCF, the structure of interferometer is also destroyed. So the proper taper length is important to the result of the experiment.

As shown in Fig. 1(b), the proposed sensor was held by two fiber holders across a water-repellent plastic dish. The sugar solution with different refractive indices (from 1.3355 to 1.413) was dropped into the dish. The dish was raised by a translation stage to make the fiber immerse completely in the droplet for measurement. The apparatus was situated on an stable optical table, and the experiments were performed at room temperature. The corresponding transmission spectra of the sensor at different refractive indices being applied on the sensor were measured by a combination of a broadband light source (BBS, Asef15296410) and an optical spectrum analyzer (OSA, Yokogawa AQ6370) with a resolution of 0.02 nm. Fig. 5 shows the normalized transmission spectra at different refractive indices from 1.3355 to 1.413 within the wavelength range of 40 nm from 1572 to 1712 nm. Fig. 6 shows that the wavelength shifts due to change of the surrounding *RI*. With the increasing of the *RI*, the dip wavelength of the transmission wave has a red-shift. Through the profile analysis of the curve as shown in Fig. 6, the maximal *RI* sensitivity of 1529 nm/RIU is achieved, which is much higher than recent results utilizing the same mechanism of photonic crystal fiber interferometer and biconical fiber tapers [7–9]. Fig. 7 shows that the discrepancy in the measurement results with the calculated data from the equation. The discrepancy is less than 4 nm.

The proposed tapered PCF–MZI was compared with the same originally untapered PCF–MZI. As shown in Fig. 6, the sensitivity is greatly increased after the PCF was tapered and much higher than previous results of this kind of PCF–MZI structure. If the tapering process can be optimized in the future, more uniformly tapered PCFs can be realized with higher sensitivities. Sensing based on the change of the refractive index is also feasible owing to the PCF can be coated with polymeric, sol gel, or metallic films

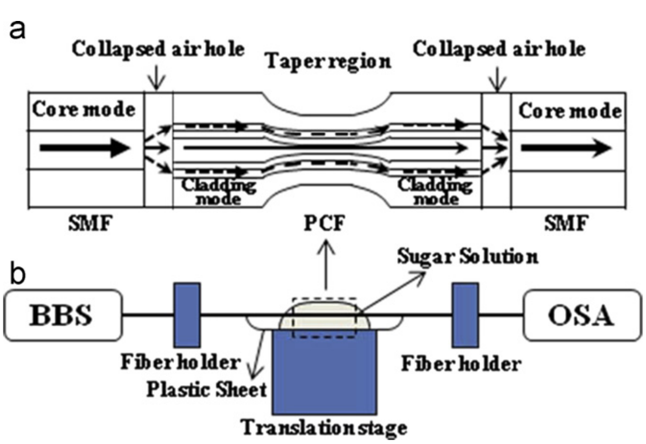

Fig. 1. Schematic diagram of the proposed refractometer.

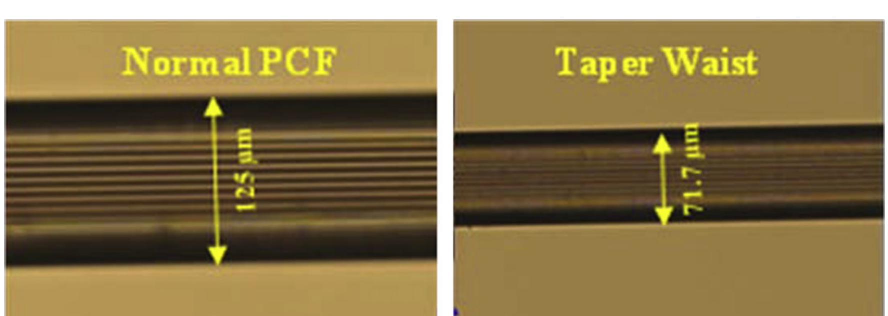

Fig. 2. Micrograph of side view of the PCF before (left) and after (right) tapering.