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In-fiber modal interferometer formed by offset-splicing in air-core photonic bandgap fiber

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ABSTRACT

We present a compact in-fiber Mach–Zehnder interferometer (MZI) formed by an offset splicing technique in air-core photonic bandgap fiber (PBF). The MZI is implemented by using two cascaded offset-splicing joints which act as beam splitter and combiner. The influences of lateral offset amount and interferometer length on the performance of MZIs were investigated experimentally. Several in-fiber MZIs with different interferometer lengths were built and it is found that the interference dip wavelength spacing is inversely proportional to the interferometer length. The MZI relies on the interference occurring between the fundamental core mode (FCM) and a surface mode (SM) of the PBF. The potential applications of the proposed in-fiber MZI were further investigated as temperature and strain sensors. The temperature and longitudinal strain sensitivities of the MZI were measured to be 211.89 pm/(°C m) and -0.6 pm/με, respectively.

1. Introduction

Air-core photonic bandgap fiber (PBF) with an air core surrounded by an array of periodic air holes in fiber cladding has been widely studied in the last decade [1–3]. Since the light is guided in the air-core, unique characteristics such as lower Rayleigh scattering, higher damaged threshold, reduced nonlinearity, novel dispersion characteristics and extremely low-loss transmission have been obtained. These optical properties make the air-core PBF attractive not only in optical fiber communications but also in optical fiber sensing applications. In recent years, novel PBF-based devices and sensors have been developed, such as long period grating (LPG) [4], polarizer [5,6] and tapers [7,8], by using various post-processing techniques like CO_2 laser irradiation or hydrogen flame heating.

Conventional single mode fiber (SMF) based in-fiber Mach–Zehnder interferometers (MZIs) have attracted considerable interests owing to their compactness, simplicity and high sensitivity. They have been used in many applications such as wavelength filters, refractive index, temperature and strain sensors [9–11]. Recently, many novel in-fiber MZIs were formed by using different fibers and techniques [12–24]. Yuan et al. have demonstrated a tapered fiber method to sandwich a section of twin-core fiber into a SMF [12]. Pang et al. have proposed an in-fiber Mach–Zehnder interferometer based on double cladding fibers for refractive index sensor and the resolution can reach 1.2×10^{-5} [13]. Li et al. have reported a Mach–Zehnder interferometer sensor based on concatenated ultra-abrupt tapers on thinned fibers and etched the MZI fiber claddings to improve the sensitivity of refractive index measurements which is 664.57 nm/RIU [14]. Jiang et al. have present an MZI in a conventional SMF fabricated by concatenating two microcavities separated by a middle section for high-temperature sensing, in the range of 500–1200 °C, with a sensitivity of 109 pm/°C [15]. Similarly, many MZIs based on index-guiding photonic crystal fiber (PCF) were reported [16–23], which were generally implemented by utilizing LPG [16–19], offset splicing [20], tapering [21] and air-hole collapsing [17,20,22–23]. Moreover, the MZI formed in air-core PBF was recently reported through the technique of tapering [7] and splicing [24].

In this paper, we present compact in-fiber modal MZIs in air-core PBF based on two cascaded offset-splicing joints (OSJs) which are formed by using a commercial fusion splicer. The MZIs were fabricated by offset-splicing a section of air-core PBF with SMFs at both ends, which lead to the excitation of surface modes (SMs) besides the fundamental core mode (FCM). The first OSJ acts as a beam splitter which couples a part of the FCM power into the SMs. To make the SMs interfere with the FCM, another OSJ is formed, which functions as a beam combiner. The distance between the two OSJs corresponds to interferometer length of the PBF-based MZI. Multiplying it with the effective refractive index of each

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excited mode gives the optical path length of the corresponding arm of the MZI. The FCM and SM propagate through different optical paths along the fiber, and the resulting interference fringe depends on the optical path difference between the coupled modes. By using such a simple but effective method, the in-fiber interferometers can be easily implemented. Different lateral offsets in the MZIs were investigated in order to obtain a high interference fringe contrast and a low insertion loss. Meanwhile, the effect of the interferometer length on the performance of the proposed MZIs was explored experimentally. The possible modes involved in the interference process were also investigated theoretically and experimentally. Finally, we demonstrated the potential applications of the proposed interferometer as temperature and longitudinal strain sensors and tested the responses of the interference fringe dip wavelengths to temperature and strain.

2. Fabrication and properties of in-fiber MZIs

To build an in-fiber modal MZI, we need one element or device which excites two co-propagating modes and another to recombine them. In our case, the excitation and recombination of modes are realized by two cascaded OSJs. Fig. 1(a) illustrates the schematic of the in-fiber modal MZI based on two OSJs and Fig. 1(b) shows the cross section of the PBF (Crystal Fiber A/S HC-1550-02) used in the experiment, which has low loss transmission window from 1490 nm to 1680 nm. The PBF has an air core with a diameter of 10.9 μm, surrounded by a photonic crystal cladding comprising a triangular array of air holes in a silica background. The air-filling ratio is 0.965 and the average spacing between two adjacent cladding air holes is 3.8 μm. As shown in Fig. 1, the distance *L* between two OSJs represents the interferometer length. At the first splicing joint (OSJ1), a part of the FCM power is coupled to a SM. At the second slicing joint (OSJ2), the SM power is coupled back to the FCM. As the FCM and SM travel through different optical paths, a series of interference fringes will be produced.

To fabricate an in-fiber MZI, a section of PBF is fusion spliced to SMF-28 fiber at both ends. Small lateral offset at both OSJs was induced intentionally by operating the commercial fusion splicer (Ericsson FSU 975) in a manual splicing mode. To effectively build an in-fiber MZI, some important parameters, such as the amount of lateral offset, the interference length of the MZI, and the discharge condition for fusion splicing, need special considerations and investigation during the MZI fabrication process. The optimized discharge arc conditions for fusion splicing, such as discharge current and discharge time, have been investigated previously and adopted directly here [25].

To investigate the influence of the lateral offset on the performance of MZI, we have built several MZIs with different lateral offset values. Considering the insertion loss induced by the lateral misalignment during the offset-splicing process, we initially spliced the first OSJ without a lateral offset. In this case, the splice loss is relatively low and the higher order modes involved in the interference process can also be excited which is due to mode-field mismatch at the splicing joint [25]. Looking at the data in Table 1, the fundamental mode in the SMF-28 fiber is $\omega_{SMF}=10.4$ μm, whereas in the PBF, $\omega_{PBF}=7.5$ μm. Thus we obtain an abrupt change of the waveguide properties which means that at the splice joint we have an abrupt taper [26]. Also, as shown in [22], the fundamental mode field coming out of the SMF will broaden due to diffraction in the region of collapsed holes. For this reason, the fundamental mode distribution of the SMF-28 fiber cannot adapt smoothly to the FCM distribution of the PBF and couples parts of power to higher order modes. After the first OSJ without lateral offset was formed, the second OJS was made and the lateral offset was manually tuned. By using this method, several MZIs with different lateral offsets and different interferometer lengths were constructed. By using a broadband source (BBS) and an optical spectral analyzer (OSA), the transmission spectrum was measured and is shown in Fig. 2, the first OSF was made without lateral offset, and the second OJS's lateral offset values change from 1 μm to 8 μm. To show the interference fringe pattern more clearly, the data has been normalized with respect to the optical source spectrum.

As shown in Fig. 2, the interference fringes were observed in the wavelength range from 1500 to 1550 nm. The spectrum is

Table 1
Fiber diameters of the SMF-28 fiber and the HC-1550-02 PBF at 1550 nm.

Parameter	SMF-28 (μm)	HC-1550-02 PBF (μm)
Mode field diameter	10.4	7.5
Core diameter	8.3	10.9
Cladding diameter	125	120

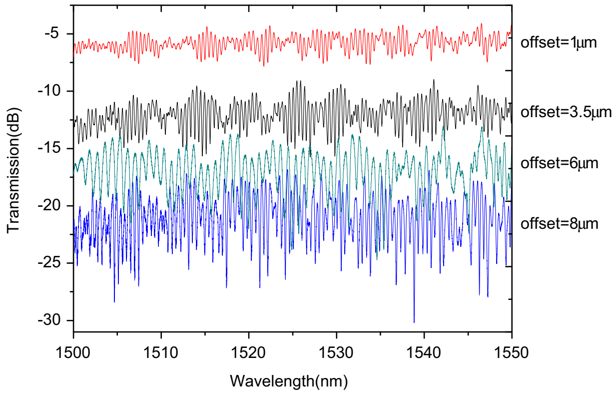

Fig. 2. The transmission spectra of in-fiber MZI with different lateral offsets.

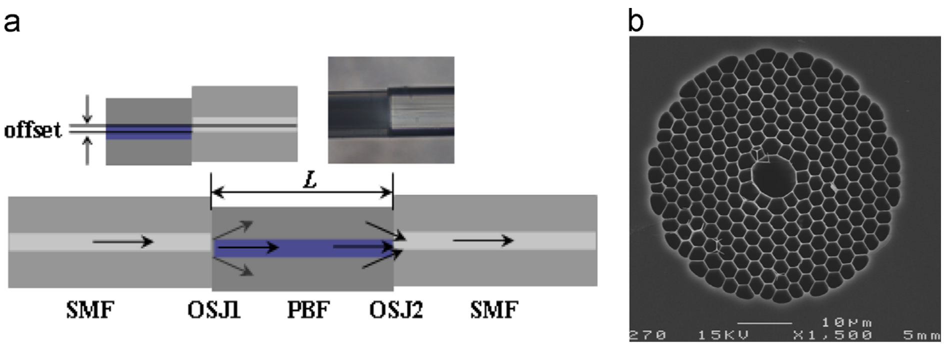

Fig. 1. (a) Schematic of the MZI based on two cascaded OSJs. (b) The cross section of the PBF used in the experiment. The inset shows microscope image of the OSJ.