Full length article

Refractive index and strain sensor based on twin-core fiber with a novel T-shaped taper

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Abstract

A compact in-fiber Mach–Zehnder interferometer (MZI) based on twin-core fiber (TCF) with a novel T-shaped taper is proposed and demonstrated. The taper was firstly fabricated by a short section of TCF, and then spliced with a section of cleaved single mode fiber (SMF). When the light transmit into the TCF, multiple modes will be excited and will propagate within the TCF. In experiment, the proposed device had a maximum interferometric extinction ratio about 17 dB. And the refractive index (RI), strain, and temperature response properties of the sensor have been investigated, which show a relatively high RI, strain sensitivity and low temperature cross sensitivity. Hence, the sensor can be a suitable candidate in the biochemical and physical sensing applications. And due to its easy and controllable fabrication, the novel drawing technology can be applied to more multicore optical fibers.

1. Introduction

In recent years, fiber-based sensors have been playing increasingly roles in many applications, like bridge security monitoring, biochemical sensing and power system monitoring due to their numerous advantages like small size, immunity to electromagnetic interference, remote sensing capability and high sensitivity. In previous work, numerous fiber configurations have been developed, such as fiber Bragg gratings (FBGs) [1–3], long-period gratings (LPGs) [4,5]. Aside from the large sensing range and high sensitivity, they require precise and expensive phase masks or CO2 laser pulses. Tapered fiber is another configuration of the fiber sensors, like tapered SMF [6,7] and tapered MMF [8], the underlying operating principle of the sensors based on tapered structure is multimode interference excited around tapered region, which can form a MZI and simultaneously coupling the light to fundamental mode and high-order cladding modes.

Some multicore fiber (MCF) based fiber sensors have also been reported. A magnetic-field sensor based on tapered all solid waveguide-array fiber has been proposed [9]. In 2015, an all fiber Mach–Zehnder interferometer using a few millimeters multicore fiber spliced between two SMFs as a sensing element was also reported. In this case, the sensing head was subjected to curvature [10]. A shape sensor based on a multicore fiber optic cable was also presented [11]. The method utilizes discrete strain measurements obtained in each core to create a continuous representation of fiber curvature and torsion. In our previous investigations, we experimentally demonstrated a fiber-optic sensor using fiber ring cavity laser based on multipath MZI, which consists of a segment of MCF [12]. In order to increase the sensing sensitivity, we proposed a sensor structure based on a middle tapered four core fiber with different length, which has shown good linearity in terms of the spectral wavelength versus the range of refractive indices from 1.34 to 1.37 [13].

However, as mentioned above, all of the sensors based on some tapers are often firstly spliced together, then tapering the fusion point, this kind of tapers are often difficult to control the coupling, and too small taper would seriously reduce the mechanical properties of the sensor. In this paper, we fabricate a novel T-shaped taper to form the Mach-Zehnder interferometer with an all-solid twin-core fiber, the fabrication of the proposed sensor is simple. Due to the multipath evolutions of light during the TCF, the mode induced interference pattern can used for measurement. The RI, strain and temperature response characteristics of different peaks of the sensor are investigated. For the interference peak, a maxima wavelength shift of 0.24 nm for 1% change of RI was measured in the range of 1.3388–1.3908, which is comparable to that of the LPG pair sensor, while the fabrication process was much simpler and faster than that of the LPG pair sensor. A high strain sensitivity of 4.61 pm/µe and a low temperature sensitivity of 0.002 nm/°C in the temperature range of 30–80 °C were also obtained, which shows that this sensing structure is a promising technology.
2. Working principle

Fig. 1 shows the schematic diagram of the proposed TCF-based interferometer with two tapers.

During the weakly tapered region, the light will split into multiple optical paths, along the core and the cladding, respectively, and then recombine at T-shaped taper. Due to the fact that the interference pattern is mainly formed by the core mode and cladding modes, the interference intensity can be expressed as [14]

\[ I = I_o + \sum_{m}^{m_{cl}} + \sum_{m}^{m_{cl}} 2\sqrt{I_c I_{cl}} \cos \phi_m \]

(1)

where \( I, I_c, I_{cl} \) are the intensity of the interference signal, the light intensity of the core, and the mth cladding mode, respectively. And \( \phi_m \) is the phase delay, which can be approximated as

\[ \phi_m = \frac{2\pi \Delta n_{eff} L}{\lambda} \]

(2)

where \( \Delta n_{eff} \) is the effective indices difference between the core and the mth cladding modes, \( L \) is the interaction length between two tapers, and \( \lambda \) is the input wavelength. According to the interference theory, the interference signal reaches the minimum value when the following condition is satisfied

\[ \frac{2\pi \Delta n_{eff} L}{\lambda_m} = (2m + 1)\pi \]

(3)

where \( m \) is an integer, \( \lambda_m \) is the wavelength of the mth order interference dip. The equation indicates that both the change of \( \Delta n_{eff} \) and the interaction length resulting from ambient RI and strain can induce the interference attenuation peak shift.

3. Experimental and results

To fabricate the sensor, firstly, we spliced a segment of TCF with normal SMF by a commercial fusion splicer (Ericsson, FSU-975) with the SMF splicing program. In order to make light into the TCF more effective, a weak taper was fabricated by splicer. The tapered region with the length about 446 \( \mu \)m and the waist about 112 \( \mu \)m, as shown in Fig. 2(a). Then the TCF cleaved by a high precision fiber cleaver with a distance of about 5 cm away from the fusion splices. Here, we used the splicing program to form a pointed taper and aligned with another segment of SMF which cleaved already, as shown in Fig. 2(b). After the process above, the two pigtails of the fabricated device were connected to a broadband light source (BBS) (KOHERAS, SuperK Uersa) 1200–2400 nm and an OSA (YOKOGAWA AQ6375) with resolution bandwidth set at 0.05 nm, respectively. Finally, the pointed taper was spliced with the SMF with a discharging current of 10.5 mA and time of 7 s, then a novel T-shaped taper was formed, as shown in Fig. 2(c), the tapered region with the length about 471 \( \mu \)m and taper waist about 44 \( \mu \)m was created at the interface between the SMF and TCF during the splicing process. The transmission spectrum was monitored by the OSA. Two tapered regions around the splicing interfaces can play the roles of splitting and combining the mode in the fiber [15]. At the first taper, the core mode of the lead-in SMF is split into the fundamental core mode and high-order cladding modes of the TCF; at the T-shaped taper, the split modes are recombine into the lead-out SMF. Compare with other traditional fiber taper, this novel fabrication structure can better guide the light coupling into the SMF, and can induce stronger multimode interference, which is very helpful for sensing applications. And transmission spectrum with higher extinction ratio can be achieved by a proper discharging parameters. Additionally, the TCF (Yangtze Optical Fiber And Cable Company Ltd, YOFC) has a cladding diameter of 125 \( \mu \)m, the diameter of each core is 9 \( \mu \)m and the core distance is 30.4 \( \mu \)m. The cross-sectional morphology of the TCF was observed by using an optical microscope, shown in Fig. 2(d).

The spectrum of the interferometer is presented in Fig. 3. The red line indicates the original light source spectrum and the black line indicates the interferometric spectrum of the sensor. With the sensor, a strong interference in the wavelength with the highest extinction ratio of 17 dB was achieved. Meanwhile, the FFT-spatial frequency spectra of Fourier transformed wavelength was achieved, as shown in Fig. 4, the solid line represents the spatial frequency spectra of original spectrum, and the dotted line represents the sensor used in our experiment. It clearly shows that there are more than three modes (dominant mode and weakly modes) involved in the interference patterns, the fabricated sensor can induce the interference between fundamental mode and high-
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