Polarization-dependent refractive index fiber-optic sensor based on the core-offset with a taper

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Abstract. A polarization-dependent refractive index sensor based on the in-fiber Mach-Zehnder interferometer which is constructed by core-offset fusion splicing a tapered polarization maintaining fiber (PMF) with a length of 20 mm between the core-offset and the taper is proposed. Due to the introduced high environment-sensitivity of the two orthogonal polarization modes in the PMF and the enhancing effect of the tapered PMF, the sensitivity of the fast axis and the slow axis up to ~-107.51 nm/RI and ~-74.54 nm/RI in the RI range between 1.333 and 1.381 is obtained, respectively. Such kinds of low-cost and highly sensitive fiber-optic RI sensors would find applications in chemical or biochemical sensing fields.

1. Introduction
Refractive index (RI) sensing based on the conventional optical fiber has been intensively studied in recent years, especially in chemical sensing field. The high-precision RI sensors are mainly depending on the Mach-Zehnder interferometer (MZI) technology, grating-based MZIs have a large range measurement and high RI sensitivity, but they require precise and expensive lasers to obtain the Fiber Bragg Grating (FBG) or Long-period Grating (LPG) [1, 2]. Recently, some special structures were proposed to fabricate the MZI-type RI fiber sensors, such as single mode (SM)–multimode (MM)–single mode (SM) fiber structure [3, 4], in-line two-tapered MZI [5, 6] and etc. All of these fiber-based structures are easily fabricated and much cheaper.

In this paper, an improved RI fiber sensor constructed by core-offset fusion splicing a tapered polarization maintaining fiber (PMF) with a length of 20 mm between the core-offset and the taper is reported. Unlike the normal taper, the proposed taper was made by two identical PMFs. Since a tapered fiber can enhance the evanescent field and the high environment-sensitivity of the two orthogonal polarization modes because of the birefringence of the PMF, a much higher accuracy of RI measurement is expected. The sensitivity of fast axis and slow axis up to ~-107.51 nm/RI and ~-74.54 nm/RI in the RI range between 1.333 and 1.381 is obtained, respectively. Compared with [5], the proposed RI sensor has larger measurement range, such kinds low-cost and highly sensitive fiber-optic RI sensor would find applications in chemical or biochemical sensing fields.

2. Experiments
The experimental setup is shown in Fig.1. A broadband source (BBS) was utilized as the input light. And the polarization state of the output light from the BBS was adjusted by a polarized controller (PC) to obtain a high fringe visibility. The output spectrum of the proposed structure was detected by an
optical spectrum analyzer (OSA: AQ6317B, Advantest, Japan) with wavelength resolution set to 0.2 nm.
The taper was made easily by using a special function of a commercial fusion splicer (Fujikura FSM-100P) with PMF1 and PMF 2 (PANDA, 1017-C, YOFC), the birefringence index of the PMF 1 and PMF 2 are $7.7024 \times 10^4$. The fast axis and slow axis of PMF1 and PMF2 are alignment with each other. And then, the end of the PMF 1 was mismatch fusion spliced with SMF (SMF-28), the core-offset size is about $4.5 \ \mu \text{m}$. The core and cladding diameters of the used SMF are $9 \ \mu \text{m}$ and $125 \ \mu \text{m}$, respectively. The applied PMFs have the same core and cladding diameters as the SMF. The length between the core-offset and the taper region is ~20 mm. Both sides of the sensing head were fixed and then immersed in the solution (sucrose solutions, ranging from 1.333 to 1.381).

![Fig.1](image)

Fig.1. Schematic diagram of the proposed RI sensor. (a) Microscopic image of the core-offset, (b) Microscopic image of the taper, (c) the partially enlarged drawing of the sensor head.

As shown in the inset of Fig. 1, When input light (black arrow) reaches the core-offset, core mode of the SMF is partly coupled into the cladding of the PMF to excite massive cladding modes (blue arrow), and the remaining light still propagates in the core as the fundamental core mode (red arrow). Then, the cladding modes are re-coupled into the fiber core by the taper to interfere with the fundamental core mode. Lengths of this kind MZI’s two arms are exactly same, but the optical lengths are different because of the different effective indices of each optical length [7]. Theoretically, phase difference between the core mode and the excited cladding modes of the formed MZI can be expressed as [8, 9],

$$\Delta \Phi = 2 \pi n_{\text{eff}}^m \frac{L}{\lambda}$$  \hspace{1cm} (1)

Where $n_{\text{eff}}^m$ is the effective refractive index difference between the core and the $m_{\text{th}}$ cladding mode, $\lambda$ is the wavelength of the input light, $L$ is the length between PMF1 and PMF2. And the output intensity of the MZI can be described as,

$$I = I_1 + I_2 + 2\sqrt{I_1I_2} \cos(\Delta \Phi)$$  \hspace{1cm} (2)

Where $I_1$ and $I_2$ are the intensities of the light propagating along the fiber core and cladding, respectively.
Owing to the difference of the effective refractive index between the two orthogonal core modes and the excited cladding modes, the resonant dip wavelengths of the interference patterns corresponding to fast axis ($\lambda_f$) and slow axis ($\lambda_s$) polarization modes are different. By adjusting the PC at the appropriate state, initial interference patterns of the proposed MZI is recorded as shown in Fig.2, the resonant dip wavelength satisfies the equation of 

$$\Delta \Phi = (2k+1)\pi, \ k \text{ is natural number.}$$

According to [10], the resonant dip wavelength corresponding to fast axis ($\lambda_f$) and slow axis ($\lambda_s$) polarization modes can be described as,

$$\lambda_f = \frac{2(n_{\text{eff,f}} - n_{\text{eff,clad}}}^{\text{core,f}})L}{2k+1}$$

(3)

$$\lambda_s = \frac{2(n_{\text{eff,s}} - n_{\text{eff,clad}}}^{\text{core,s}})L}{2k+1}$$

(4)

Where $n_{\text{eff,f}}^{\text{core}}$ and $n_{\text{eff,f}}^{\text{clad}}$ are the effective refractive index of the core mode and excited cladding mode on the fast axis of the PMF, respectively. $n_{\text{eff,s}}^{\text{core}}$ and $n_{\text{eff,s}}^{\text{clad}}$ are the effective refractive index of the core mode and excited cladding mode on the slow axis of the PMF, respectively.

![Transmission spectra of the proposed RI sensor.](image)

**Fig.2. Transmission spectra of the proposed RI sensor.**

### 3. Experiments and results

From Fig.2 we can see that the wavelengths of fast axis and slow axis polarization mode are ~1521.3 nm and ~1587.8 nm, respectively. As expected, values of $n_{\text{eff,f}}^{\text{core}} - n_{\text{eff,f}}^{\text{clad}}$ and $n_{\text{eff,s}}^{\text{core}} - n_{\text{eff,s}}^{\text{clad}}$ will decreased with the increasing of the surrounding refractive index, so as the corresponding wavelengths to fast axis and slow axis.

The detected solution we selected was sugar solution, and the RI is ranging from 1.333 to 1.381. During the measurement, the sensing head was cleaned by ethanol solution twice each time, and the next test was conducted until the sensing head dried. The transmission spectra variations of the fast axis and slow axis polarization modes are shown in Fig.3.

Fig. 3 illustrates the spectral response of the fast axis and slow axis polarization modes with different RI. It can be seen that with the increasing of the RI, both of the resonant dip wavelengths of the fast axis and the slow axis were move to the direction of the short wavelength. The experimental results are agreed with the theoretical analysis. Since the tapered fiber can enhance the evanescent field and the fast axis and slow axis polarization modes are sensitive to the surrounding environment, the sensitivity of the proposed RI sensor has been greatly improved.
Fig. 3. Transmission spectra variations under different RI. (a) fast axis ($\lambda_f$), (b) slow axis ($\lambda_s$).

Fig. 4 shows the fitting line of the resonant dips of the interference patterns corresponding to fast axis and slow axis. It is indicated that there is a good linear relationship between RI and the wavelength. According to the results of the linear fitting, the sensitivity of the fast axis and the slow axis up to ~-107.51 nm/RI and ~-74.54 nm/RI in the RI range between 1.333 and 1.381 is obtained, respectively.

Fig. 4. Fitting line of the resonant dips of the interference patterns corresponding to: (a) fast axis ($\lambda_f$), (b) slow axis ($\lambda_s$).

4. Conclusion
A novel optic fiber sensor constructed by core-offset fusion splicing a tapered polarization maintaining fiber (PMF) with a length of 20 mm between the core-offset and the taper MZI has been proposed for RI measurement. The sensitivity of the fast axis and the slow axis up to ~-107.51 nm/RI and ~-74.54 nm/RI in the RI range between 1.333 and 1.381 is obtained, respectively. The simple fabrication process and the high precision show the proposed sensor has a great potential in chemical and biological sensing fields.

5. References
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