Sensitivity-enhanced refractive index sensor by using tapered thin-core fiber based inline Mach-Zehnder interferometer

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ABSTRACT

A sensitivity-enhanced optical fiber refractive index sensor based on inline Mach-Zehnder interferometer is proposed. The sensor head is formed by splicing a tapered thin-core diameter fiber between two sections of single mode fibers. The taper (less than 1 mm) plays an important role in improving the sensitivity of the sensor. The sensitivity of refractive index is measured to be 0.447 nm for a 1% change of refractive index in the typical refractive index range of 1.333-1.3725. The whole fabrication process (including splicing and tapering) can be operated by a commercial fiber splicing machine. The proposed sensor also shows the merits of simple structure, low cost, and easy fabrication.

Keywords: refractive index sensor, Mach-Zehnder interferometer, thin-core fiber, tapered fiber.

1. INTRODUCTION

Fiber-optic refractive index (RI) sensors are of considerable interest due to its advantages of small size, high sensitivity, immunity to electromagnetic interferences, and flexibility of directly embedding into the system structure. A number of optical fiber RI sensors have been developed, such as fiber Bragg gratings (FBGs) [1, 2], long-period gratings (LPGs) [3], and LPG pairs [4]. However, grating-based sensors (FBG, LPG) require precise and always expensive phase masks and photolithographic procedures.

More recently, inline fiber interferometers have been intensively studied for RI sensing. Among them, core mismatch [5, 6], fiber tapers [7], and photonic crystal fiber [8] have used to form interferometers in RI sensing applications. Compared to the grating-based sensor, the inline fiber interferometers feature the advantages of high sensitivity, relatively low cost and ease of fabrication.

In this paper, we present an improved inline Mach-Zehnder Interferometer (MZI) for highly sensitive RI sensing, which is formed by simply splicing a tapered thin-core fiber (TCF) between two sections of single mode fibers (SMFs). The fiber taper region is very small, but can significantly enhance the sensitivity of the sensor. The maximum wavelength shift of 0.447 nm is measured in the RI change of 0.01, which is almost 1.6 times higher than that of MZI with no taper. The sensing sensitivity is higher than that of LPG pair sensor, while the fabrication process is much simpler and faster.

2. SENSING PRICIPLE

The structure of the proposed RI sensor is shown schematically in Fig. 1. A section of uncoated TCF is spliced with two sections of SMFs. The TCF used in our experiment (Yangtze Ltd., BI1012-A) has the core/cladding diameter of 4.8/125 μm, with a cut-off wavelength of 1260 nm. A slightly lateral offset between the SMF and TCF is made to obtain a high extinction ratio. At the SMF-TCF interface, part of light can be coupled into cladding of the TCF due to mode mismatch. After propagating through the TCF, the excited cladding modes will be re-coupled into the core of the SMF at the second spliced point. The cladding modes will interfere with the core mode due to the phase difference, which can be described as

$$\Phi^{j} = \frac{2\pi(n_{core}^{eff} - n_{cl,j}^{eff})L}{\lambda} = \frac{2\pi\Delta n_{j}^{eff} L}{\lambda} \tag{1}$$

Optical Sensors and Biophotonics III, edited by Jürgen Popp, Dennis L. Matthews, Jie Tian, Chih-Chung Yang,
Proc. of SPIE-OSA-IEEE Asia Communications and Photonics, Vol. 8311, 83110C · © 2011 SPIE-OSA-IEEE
CCC code: 0277-786X/11/$18 · doi: 10.1117/12.904486

where n_{core}^{eff} and $n_{\mathrm{cl,j}}^{\mathrm{eff}}$ are the effective RI of the core and the *j*th cladding modes, respectively; Δn_j^{eff} is the effective RI difference between the core mode and the *j*th cladding mode; *L* is the interferometer length and λ is the light wavelength in vacuum.

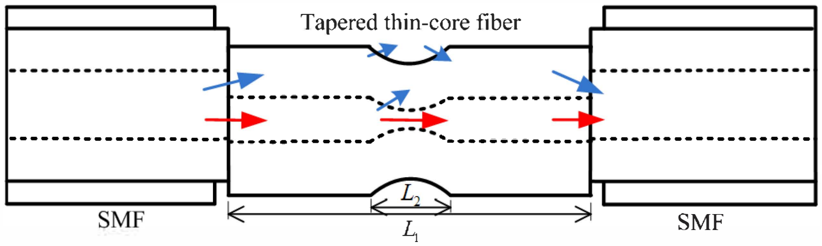


Fig. 1. Schematic diagram of the proposed sensor. L_1 and L_2 are the length of the thin-core diameter fiber and the taper length, respectively.

The free spectral range (FSR) can be approximately written as

$$\Delta\lambda \approx \frac{\lambda^2}{\Delta n_j^{eff} L} \tag{2}$$

The intensity of the interference reaches its transmission dips when Φ becomes an odd times of π. Then, equation (1) can be described as

$$\lambda_D = \frac{2\Delta n_j^{eff} L}{2n+1} \tag{3}$$

where λ_{D} is the wavelength of transmission dip, *n* is the integer. If RI of the surrounding medium increases, $n_{\mathrm{cl,j}}^{\mathrm{eff}}$ increases, while n_{core}^{eff} stays the same value. Δn_j^{eff} decrease by $\delta n_{\mathrm{cl,j}}^{\mathrm{eff}}$, and λ_{D} will shift to shorted wavelength by $\delta\lambda_{\mathrm{D}}$..

$$\delta\lambda_D \approx 2L\delta n_{cl,j}^{eff} \tag{4}$$

Based on (4), it is possible to measure the environmental RI by monitoring the change of $\delta\lambda_{\mathrm{D}}$ Equation (4) also indicates that the sensitivity of the interferometer is dependent on both the length *L* and the effective RI change of cladding mode. Since too long length means it is hard to make a compact sensor, so we use the method of exciting higher order cladding modes to improve the sensing performance. For a specific RI change of the surrounding medium, the effective RI change of a higher order cladding mode is larger than that of a lower one, which means that the sensitivity of the RI sensor can be improved by exciting higher order cladding mode. In our experiment, the TCF is weakly tapered to excite higher order cladding modes. Compared to the total length of the interferometer, the taper zone is small (~700μm), while it is sufficient to enhance the sensitivity. In addition, the whole manufacturing process of the sensor, including the splicing and tapering process, can be handled by one commercial fiber fusion splicer. So the proposed sensor is simple to implement, and features the merits of low cost and relatively high sensitivity.

3. EXPERIMENT AND DISSCUSS

An Ericsson fusion splicer (modal FSU 975), with a built-in core-offset attenuator program, was used to produce the lateral offset between the SMF and the TCF. The broad band source on C-band was used and the output spectrum was monitored by the optical spectrum analyzer (OSA, Yokogawa AQ6370), with the wavelength resolution of 15 pm. Several MZIs were constructed, and the FSRs of the MZI with different TCF lengths were measured and shown in Fig. 2. It can be seen from Fig. 2 that the FSR is inversely proportional to the interference length, which is consistent with (2). Fig. 3(a) shows the photograph of the lateral offset, which is approximately 5 μm. A MZI has been fabricated with about 38mm long TCF, and a short taper was made by the same fusion splicer with the built-in taper program to improve the sensing sensitivity. The photograph image is shown in Fig. 3(b). The taper is in the center of the TCF, and the taper length and waist diameter are approximately 700 μm and 90 μm, respectively. The transmission spectra are shown in Fig. 4(a).

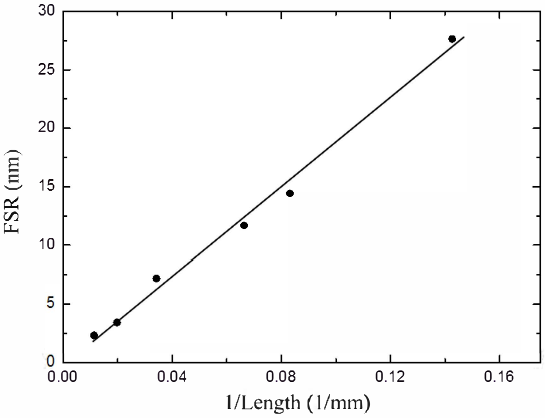


Fig. 2. Measured FSR of the fabricated MZIs with respect to TCF length.

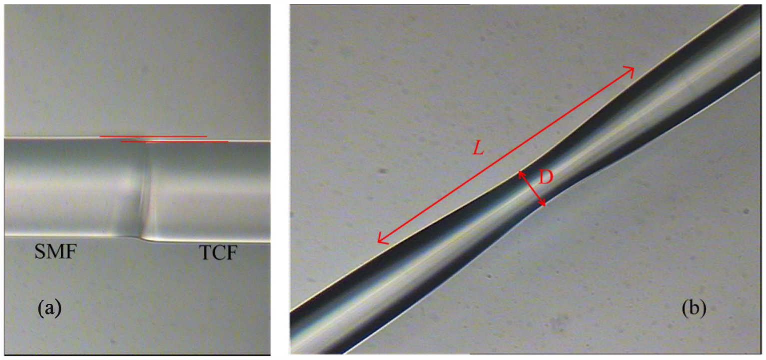
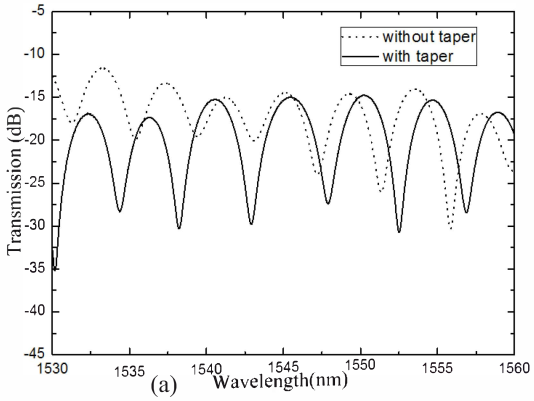


Fig. 3. Photographs of (a) the lateral offset between the SMF and TCF, and (b) the weak taper of the TCF.

The interference pattern shown in Fig. 4(a) was Fourier transformed to obtain the spatial frequency, as shown in Fig. 4(b). It can be seen in Fig. 4(b) that, there is indeed only one dominated cladding mode, along with other weak cladding modes. After tapering the TCF, two new cladding modes (spatial frequency at 0.052 #/nm & 0.08 #/nm) are excited, whose orders are higher than the dominated cladding mode because their spatial frequency are larger. If RI of the external medium change, the new excited cladding modes will modify the main interference patten. Because higher cladding modes means higher sensitivity to surrounding medium, so the tapered MZI will show a higher sensitivity than that without a taper.



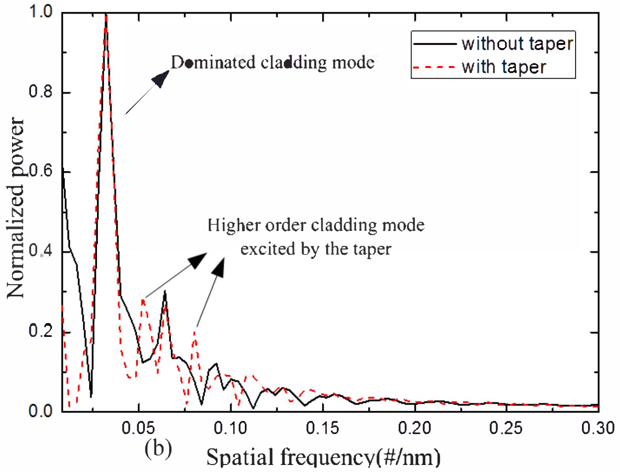


Fig. 4. (a)Measured transmission spectra of the MZI with the length of the TCF is 38 mm; (b) Spatial frequency of the MZI with the length of the TCF is 38 mm

The two fabricated MZIs were employed to evaluate its sensitivity to RI. The sensors were mounted on a glass plate with glue to keep straight and were immersed into a mixed solution with water and glycerol, whose RI ranged from 1.333 to 1.3725. The taper lengths of the two MZIs were 38 mm and 32 mm, respectively. The entire measurement was carried out under a constant temperature in order to avoid the impact by temperature. In order to make a comparison, the two MZIs were tested as RI sensors twice after the TCFs being tapered or not. And the operating procedure was as same as that of the sensor head without taper. The maximum wavelength shift of the transmission dips are plotted in Fig. 5 and 6. The experimental results show that the RI sensitivity can be significantly improved by tapering the TCF. For 1% change of RI, the wavelength shifts of the two sensors head are enhanced from -0.3450 nm to -0.4366 nm and -0.2830 nm to -0.4473 nm, respectively.

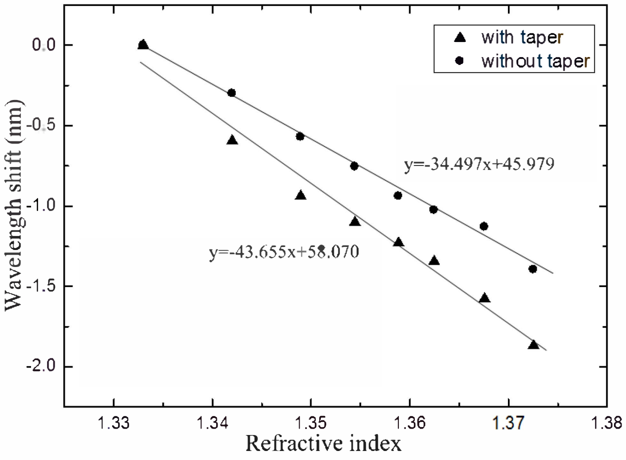


Fig. 5. Wavelength shifts of the sensors with length of 38mm

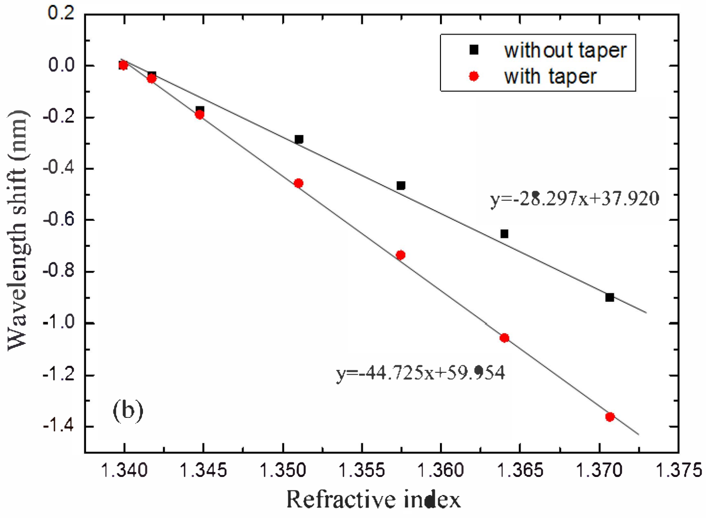


Fig. 6. Wavelength shifts of the sensors with length of 32mm.

It should be pointed out that the more abrupt taper in the TCF may lead to excite higher orders cladding modes, which means the sensing sensitivity could be much more enhanced. However, it would be more fragile for the taper with a short length and small waist. In addition, the maximum sensitivity (~ 0.44nm, with interaction length of ~32.5 mm) of the proposed sensor is higher than that of the LPG pair sensor (0.259nm), which has a 62 mm interaction length [4]. Obviously, the fabrication of our sensor is simpler and faster.

4. CONCLUSION

We have presented and demonstrated an inline MZI typed RI sensor by using a tapered thin core fiber. It is worth noting that the RI sensitivity of the sensor could be strengthened by using a larger length of interferometer. Since the length should not be too long for a compact sensor, so a short taper in the center of the TCF is made. Compared to the total length of the MZI, the taper region is very small (~ 70 μm), while can significantly improve sensing sensitivity. In addition, all the fabrication of the proposed sensor (including the splicing and tapering processes) can be achieved by a commercial fiber fusion splicer, so the proposed RI sensor also shows advantages of high sensitivity, low cost, and easy fabrication.

5. ACKNOWLEDGMENT

The work was jointly supported by the National Nature Science Fund of China (No. 60972032 and No. 60632010) and the National “863” Hi-tech Project of China.

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