Optical Engineering

SPIEDigitalLibrary.org/oe

# Single-mode fiber refractive index sensor with large lateral offset fusion splicing between two abrupt tapers

Qi Zhang
Jun Zhou
Jinping Chen
Xiaoling Tan

SPIE

# Single-mode fiber refractive index sensor with large lateral offset fusion splicing between two abrupt tapers

**Qi Zhang, Jun Zhou, Jinping Chen, and Xiaoling Tan**
Ningbo University, Institute of Photonics, Faculty of Science, Ningbo, Zhejiang 315211, China
E-mail: zhoujun@nbu.edu.cn

**Abstract.** We propose a novel refractive index (RI) sensor based on a fiber Mach-Zehnder interferometer formed by large lateral offset fusion splicing between two abrupt tapers. The cladding modes are efficiently excited by transmitted light in the large misalignment junctions. The RI sensitivity of the sensor to surrounding RI change is measured, and the sensitivity of 100 nm/RIU is obtained, which is three to six times higher than that of fiber structures with only a pair of tapers or two offset junctions. Moreover, the sensor is made by a low-cost fabrication method. Thus, the proposed structure is beneficial to the RI sensing applications.  [DOI: 10.1117/1.OE.51.9.090502]

Subject terms: optical fiber; Mach-Zehnder interferometer; refractive index sensor.

Paper 120891L received Jun. 21, 2012; revised manuscript received Jul. 30, 2012; accepted for publication Aug. 9, 2012; published online Sep. 12, 2012.

## 1 Introduction

Optical fiber sensors have attracted great attention in refractive index (RI) sensing applications due to their compactness and high sensitivity. There are many methods for constructing in-fiber RI sensors, including fiber Bragg grating (FBG),[1] long-period grating (LPG),[2] photonic crystal fiber (PCF),[3] and single mode-multimode-single mode fiber structure.[4] Recently, many kinds of Mach-Zehnder interferometer (MZI) structures have been applied to the design and fabrication of in-fiber RI sensors, such as the two-taper MZI,[5] core-offset attenuators,[6] LPG pairs,[7,8] an improved sandwiched-taper MZI,[9] and PCF-based MZI structure.[10] A PCF-based LPG structure has been reported to have an excellent sensitivity: $\sim 10^{-7}$ RIU.[11] Although the sensitivity of these sensors is satisfactorily high, fabricating the grating-based (FBG or LPG) sensors often requires precise and expensive phase masks and stringent photolithographic procedures, so the cost is very high for practical application.

In this paper, a novel RI sensor based on a fiber MZI composed of two core-offset attenuators and two abrupt tapers is proposed. The structure can be simply fabricated by a conventional fusion splicer and shows high sensitivity to surrounding RI change.

## 2 Principles

Figure 1(a) shows the schematic diagram of the MZI formed by large lateral offset fusion splicing between two abrupt tapers. First, the input light ($I_{\text{in}}$) is split into two portions at the first abrupt taper: one ($I_1$) through the core and the other ($I_2$) through the cladding. At the first lateral offset splice joint, the optical signal $I_1$ is split into three optical paths: along the core, at the cladding of the intermediate SMF, and in the air near the cladding surface of the intermediate SMF. Then they are recombined at the second splice joint. Finally, the light traveling in the cladding and the light traveling in the core are coupled back into the core at the second abrupt taper to form interference fringes, which can be detected by measuring $I_{\text{out}}$. Since a light is transmitting through the structure, the effective propagation constant of the cladding modes could be obviously changed as the RI of the environment changes, so that we can use the fiber MZI as a RI sensor by measuring the phase shift of the interference fringe.

As described by Xia et al.[12] the interference signal reaches its minimum when the phase difference between cladding and core modes satisfies the following condition:

$$2\pi[n_{\text{eff}}^{\text{co}} - n_{\text{eff}}^{cl,j}]\frac{L}{\lambda_D} = (2k+1)\pi, \tag{1}$$

where $\lambda_D$ is the wavelength of the interference spectrum dip, $n_{\text{eff}}^{\text{co}}$ is the effective RI of the core mode, $n_{\text{eff}}^{cl,j}$ is the effective RI of the $j$'th order cladding mode, $L$ is the interferometer length, and $k$ is an integer. Therefore, the sensitivity can be expressed as:

$$\frac{d\lambda_D}{dn_{\text{ext}}} = \frac{-\lambda_D}{\Delta n_{\text{eff}}}\frac{\partial n_{\text{eff}}^{cl,j}}{\partial n_{\text{ext}}} \Big/ \left[1 - \frac{\lambda_D}{\Delta n_{\text{eff}}}\left(\frac{\partial n_{\text{eff}}^{\text{co}}}{\partial \lambda} - \frac{\partial n_{\text{eff}}^{cl,j}}{\partial \lambda}\right)\right], \tag{2}$$

where $n_{\text{ext}}$ is the RI of the surrounding medium, and $\Delta n_{\text{eff}}$ is the difference of the effective RIs of the core and the cladding mode.

## 3 Experiment and Results

A standard telecommunication single-mode optical fiber (Corning, SMF-28e) is used to fabricate the MZI structure shown in Fig. 1 by a conventional fusion splicer, and the fabrication steps of the taper structure and large lateral offset fusion are same as that described by Li et al. and by Duan et al.[13,14] Figure 2 shows a microscopic image of the taper structure (top) and the large lateral offset fusion (bottom). The parameters of two tapers are almost the same: a waist diameter of $\sim 55$ $\mu$m and a taper length of $\sim 139$ $\mu$m. There is a large offset of $\sim 50$ $\mu$m on the two lateral offset fusions. The distance $d$ between the two offsets is about 3 cm, and the length $L$ of the MZI is about 6 cm. Here, it should be noted that, as demonstrated in Tian and Yam,[15] the two lateral offset splice joints should have the offsets in the same or opposite direction along the same axis. Otherwise,

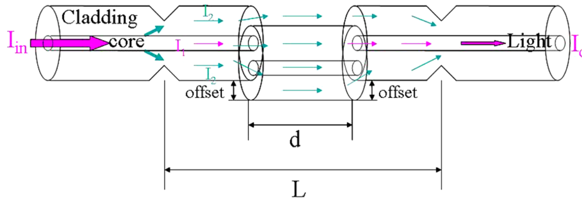


**Fig. 1** Schematic diagram of the MZI sensor consisting of two abrupt fiber tapers and two offset junctions.

0091-3286/2012/$25.00 © 2012 SPIE

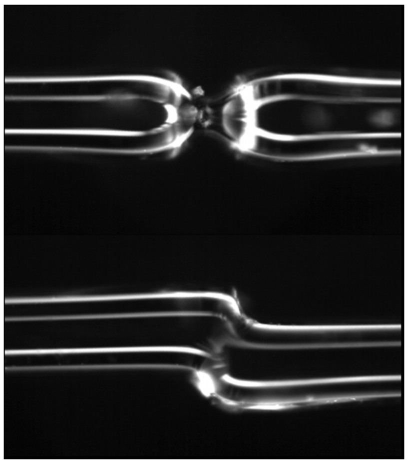

**Fig. 2** Microscope photographs of the sensor under 20X objective: tapered structure (top), large lateral offset fusion (bottom).

the modes $LP_{1m}$ coupled by the first lateral offset splicing joint will not be coupled back to the core by the second one, and the interference pattern will not be obtained.

Next, the fiber MZI is fixed and straightened on the platform to measure its response characteristics. A broadband light source (SL3700, B&A Technology, Shang Hai, China) is used to inject a light into the MZI, and its transmission spectrum is recorded by an optical spectrum analyzer (Agilent 86142B). When the MZI structure is immersed into deionized water (RI = 1.335), the attenuation spectrum is obtained by subtracting the source spectrum from the transmission spectrum, as shown in Fig. 3. As can be seen from Fig. 3, there is a little inhomogeneity in the spectrum, because more than two modes are involved in the interference pattern. In addition, it can be seen from the transmission spectrum that the MZI structure has a relatively large insertion loss. Thus, a light source with larger optical input power, such as 8 mW, is needed in our experiment.

In order to determine the cladding modes that construct the interference, the fast Fourier transform (FFT) of wavelength spectra is performed to get its corresponding spatial frequency spectra. As can be seen from Fig. 4, several mainly cladding modes were indeed excited dominantly, and there are also weakly excited cladding modes.

To test the RI sensitivity of the MZI sensor, the dip around the 1550-nm wavelength is recorded. The MZI structure is totally immersed into a glycerin solution, whose RI value can be changed by raising or lowering the concentration of glycerin. The RI of the glycerin solution is measured by the

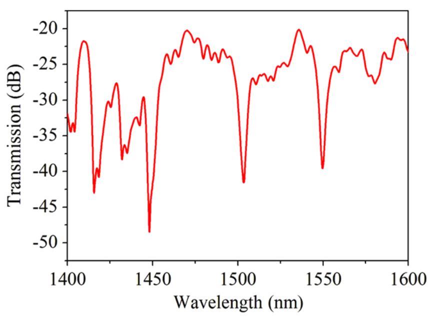


**Fig. 3** Transmission spectrum of the MZI in deionized water.

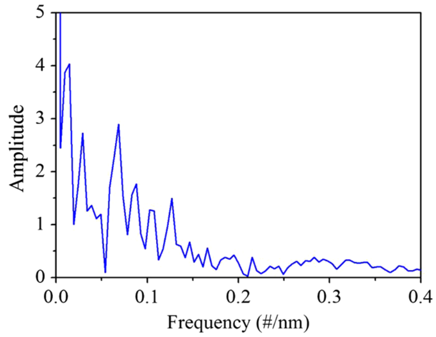


**Fig. 4** Spatial frequency spectra of the MZI in deionized water.

Abbe refractometer with the accuracy 0.001, and the RI values of the testing solution are increased from 1.3350 to 1.3706. The recorded transmission spectrum is shown in Fig. 5(a), and the dip has an obviously red shift with the increase of the external RI. As shown in Fig. 5(b), the response of the MZI sensor to RI change demonstrates good linearity and high sensitivity. The slope of linear fitting (i.e., the sensitivity) is 100 nm/RIU, which is similar to that of the sensor based on a fiber taper seeded long-period grating pair with a taper length of 16 mm,[16] and it is much higher than that of the sensor based on a tapered single-mode thin-core diameter fiber with a sensitivity of 59.1 nm/RIU.[17]

The red shift of the dip in the transmission spectrum corresponding to the RI increase of the glycerin solution can be explained as follows: For lower-order cladding modes, the

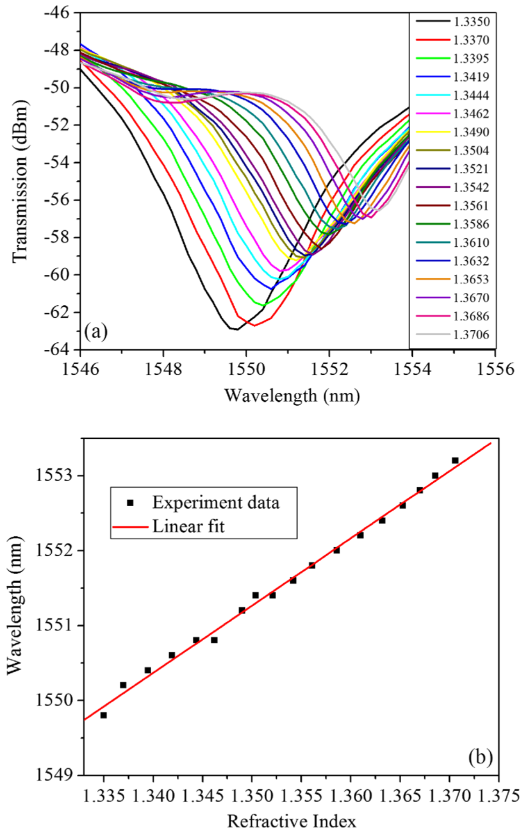


**Fig. 5** (a) The transmission spectra of the MZI at different RI of a glycerin solution; (b) The recorded dip wavelength as a RI function of glycerin solution.

change of $\Delta n_{\mathrm{eff}}$ is negative with the RI increasing in the external environment, and $\lambda_D$ will have a blue shift. In the case of higher-order cladding mode, the change of $\Delta n_{\mathrm{eff}}$ is positive with the RI increasing, resulting in $\lambda_D$ shifts to longer wavelengths. A similar mechanism is demonstrated in the sensitivity characteristic of long-period fiber gratings, where $\Delta n_{\mathrm{eff}}$ is negative for lower-order modes and positive for higher-order modes.[18] It should be noted that the temperature is kept constant (19°C), and the sensor is kept straight during all the measurements.

## 4 Conclusions

In summary, we have demonstrated a novel RI sensor based on a fiber MZI formed by large lateral offset fusion splicing between two abrupt tapers. The response characteristic of the sensor is investigated, and the sensitivity of 100 nm/RIU is obtained, which is three to six times higher than that of previous fiber sensors with only a pair of tapers or two offset junctions. The simply fabricated method of our structure makes it low-cost and promising in the sensing applications.

### *Acknowledgments*

This work is supported by the National Natural Science Foundation of China (60977048, 61275153), the Zhejiang Natural Science Foundation (LY12A04002), the International Collaboration Project of Ningbo (2010D10018), the Ningbo Natural Science Foundation (2011A61090, 2012A610107) and the K. C. Wong Magna Fund of Ningbo University, China.

### *References*

1. A. Iadicicco et al., "Thinned fiber Bragg gratings as high sensitivity refractive index sensor," *IEEE Photon. Technol. Lett.* **16**(4), 1149–1151 (2004).
2. J. H. Chong et al., "Measurements of refractive index sensitivity using long-period grating refractometer," *Opt. Commun.* **229**(1–6), 65–69 (2004).
3. D. K. C. Wu, B. T. Kuhlmey, and B. J. Eggleton, "Ultrasensitive photonic crystal fiber refractive index sensor," *Opt. Lett.* **34**(3), 322–324 (2009).
4. Q. Wu et al., "High sensitivity SMS fiber structure based refractometer-analysis and experiment," *Opt. Express* **19**(9), 7937–7944 (2011).
5. Z. Tian et al., "Refractive index sensing with Mach-Zehnder interferometer based on concatenating two single mode fiber tapers," *IEEE Photon. Technol. Lett.* **20**(8), 626–628 (2008).
6. Z. Tian, S. S.-H. Yam, and H.-P. Loock, "Single-mode fiber refractive index sensor based on core-offset attenuators," *IEEE Photon. Technol. Lett.* **20**(16), 1387–1389 (2008).
7. O. Duhem, J. F. Henninot, and M. Douay, "Study of in fiber Mach-Zehnder interferometer based on two spaced 3-dB long period gratings surrounded by a refractive index higher than that of silica," *Opt. Commun.* **180**(4–6), 255–262 (2000).
8. T. Allsop et al., "A high sensitivity refractometer based upon a long period grating Mach-Zehnder interferometer," *Rev. Sci. Instrum.* **73**(4), 1702–1705 (2002).
9. D. Wu et al., "Refractive index sensing based on Mach-Zehnder interferometer formed by three cascaded single-mode fiber tapers," *Appl. Opt.* **50**(11), 1548–1553 (2011).
10. J.-N. Wang and J.-L. Tang, "Photonic crystal fiber Mach-Zehnder interferometer for refractive index sensing," *Sensors* **12**(3), 2983–2995 (2012).
11. Z. He, Y. Zhu, and H. Du, "Long-period gratings inscribed in air- and water-filled photonic crystal fiber for refractometric sensing of aqueous solution," *Appl. Phy. Lett.* **92**(4), 044105 (2008).
12. T. H. Xia et al., "Fiber-optic refractive-index sensors based on transmissive and reflective thin-core fiber modal interferometers," *Opt. Commun.* **283**(10), 2136–2139 (2010).
13. B. Li et al., "Ultra-abrupt tapered fiber Mach-Zehnder interferometer sensors," *Sensors* **11**(6), 5729–5739 (2011).
14. D. W. Duan et al., "In-fiber Mach-Zehnder interferometer formed by large lateral offset fusion splicing for gases refractive index measurement with high sensitivity," *Sensor. Actuator. B Chem.* **160**(1), 1198–1202 (2011).
15. Z. Tian and S. S-H. Yam, "In-line optical fiber interferometric refractive index sensors," *J. Lightwave Technol.* **27**(13), 2296–2306 (2009).
16. J.-F. Ding et al., "Fiber-taper seeded long-period grating pair as a highly sensitive refractive-index sensor," *IEEE Photon. Technol. Lett.* **17**(6), 1247–1249 (2005).
17. J. Shi et al., "A sensitivity-enhanced refractive index sensor using a single-mode thin-core fiber incorporating an abrupt taper," *Sensors* **12**(4), 4697–4705 (2012).
18. X. Shu, L. Zhang, and I. Bennion, "Sensitivity characteristics of long-period fiber gratings," *J. Lightwave Technol.* **20**(2), 255–266 (2002).