



# Temperature-insensitive refractive index sensor based on in-fiber Michelson interferometer

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## ABSTRACT

A novel intensity-modulated refractive index sensor based on an in-fiber Michelson interferometer is demonstrated by splicing a section of thin core fiber between two standard single mode fibers. Such a refractive index sensor exhibits an ultrahigh sensitivity of  $-208.24$  and  $125.44$  dB/RIU at the refractive index of  $1.440$  and  $1.500$ , respectively. The refractive index sensor is insensitive to temperature and thus solves the cross-sensitivity problem between temperature and surrounding refractive index. Moreover, the promising RI sensor has the advantages of short size (less than  $2$  mm) and easy fabrication.

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## 1. Introduction

In recent years, fiber optic refractive index (RI) sensors in the field of chemical and biomedical applications has attracted significant attentions of researchers due to the advantages of their small size, high sensitivity, short response time, anti electromagnetic interference, and corrosion resistance. One has developed various in-fiber RI sensors based on typical in-fiber devices such as fiber Bragg gratings (FBGs) [1], long period fiber gratings (LPFGs) [2–4], Mach-Zehnder interferometers (MZIs) [5], surface plasmon resonance (SPR) [6], Fabry–Perot interferometers (FPIs) [7,8], Michelson interferometers (MIs) [9–13], and photonic crystal fibers (PCFs) [14]. However, complicated fabrication techniques, such as femtosecond laser micromachining [10], repeated arc discharges [12], fiber tapping [13], and chemical etching [9], have employed to achieve refractive index sensors above. For example, a fiber in-line Michelson interferometer tip sensor based on open micro-cavity was fabricated by femtosecond laser micromachining [10]. A miniature core-offset RI sensor was created by means of repeated arc discharges, resulting in melting a fiber end into a rounded tip to excite high order cladding modes [12]. A refractive index sensor based on a Michelson interferometer was demonstrated by tapering abruptly a single mode fiber (SMF) and coating gold on the fiber

end fact [13]. In addition, the wavelength-modulated refractive index sensor usually is sensitive to temperature [9,15,16] so that the cross-sensitivity problem between temperature and surrounding refractive index has to be solved in practical sensing applications [17–20].

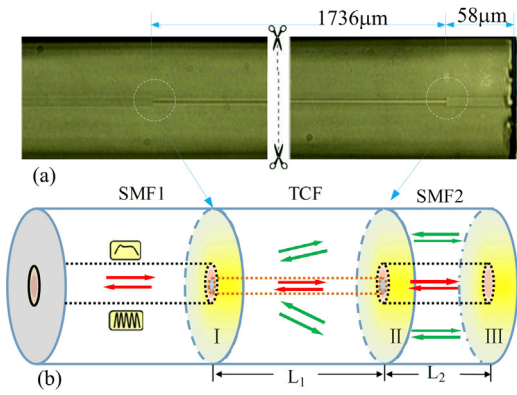
In this paper, a novel intensity-modulated refractive index sensor based on in-fiber Michelson interferometer was demonstrated by splicing a section of thin core fiber between two standard SMFs. Such a RI sensor is insensitive to temperature and thus solves the cross-sensitivity problem between temperature and surrounding refractive index. The MI-based RI sensor exhibits an ultrahigh sensitivity of  $-208.24$  and  $125.44$  dB/RIU at the refractive index of  $1.440$  and  $1.500$ , respectively.

## 2. Device fabrication

Microscope image and schematic diagram of our proposed refractive index sensor based on a Michelson interferometer are shown in Fig. 1. One end of a standard SMF (Corning, SMF-28), i.e. SMF1, with a core/cladding diameter of  $8.2\text{ }\mu\text{m}/125\text{ }\mu\text{m}$  was connected to a broadband light source with a wavelength range from  $1250$  to  $1650\text{ nm}$  (Fiber Lake ASE-LIGHT SOURCE) and an optical spectrum analyzer (OSA, YOKOGAWA AQ6370C) with a resolution of  $2\text{ nm}$  via a  $3\text{ dB}$  coupler in order to observe the reflection spectrum in real time during the fabrication of the MI-based sensor sample. After the right end of SMF1 was cleaved by use of a cutting knife (Fujikura DT-30), the observed reflection spectrum

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**Fig. 1.** (a) Microscope image and (b) schematic diagram of the created Michelson interferometer sample. Note that the image is cut off to illustrate the spliced joints of the sample.

was illustrated in Fig. 2(a). Secondly, the cleaved right end of SMF1 was spliced with a thin core fiber (Nufern, UHNA3), i.e. TCF, with a core/cladding diameter of 4 μm/125 μm by use of a commercial fusion splicer (Fujikura FSM-60s). Before and after the right end of the TCF was cleaved, the observed reflection spectra were illustrated in Fig. 2(b) and 2(c), respectively. Interference fringes shown in Fig. 2(c) result from the Fabry–Perot interference between the two end facets of the TCF. Thirdly, another standard SMF (Corning, SMF-28), i.e. SMF2, was spliced with the cleaved right end of the TCF. Before and after the right end of SMF2 was cleaved, the observed reflection spectra were illustrated in Fig. 2(d) and 2(e), respectively. Interference fringes shown in Fig. 2(e) result from the

Michelson interference between the reflected core and cladding modes at the cleaved right end of SMF2, as discussed below.

Since SMF1 has a larger core diameter than the TCF, light propagating through SMF1 will divide into two parts: the core mode with a major energy and the cladding modes with a minor energy, at the interface, i.e. interface-I, between SMF1 and the TCF and then are reflected at the cleaved right end of the TCF. The reflected core and cladding modes will interfere with each other, i.e. Michelson interference, in the core of SMF1. Since the reflected core mode has a much larger energy than the reflected cladding modes, low interference fringe visibility is observed in the reflection spectrum, as shown in Fig. 2(c). In case SMF2 is spliced with the right end of the TCF, the core mode reflected at the cleaved right end facet, i.e. interface-III, of SMF2 will propagate through SMF2 and then transfer partially into the cladding modes at the interface, i.e. interface-II, between the TCF and SMF2, which results in the decrease of the reflected core mode and the increase of the reflected cladding modes in the TCF. Consequently, the reflected core mode has a similar energy to the reflected cladding modes so that high interference fringe visibility was observed in the reflection spectrum, as shown in Fig. 2(e).

As shown in Fig. 1(b), optical distance difference between the reflected core and cladding modes can be given by

$$\Delta d = L_1 \Delta n_{TCF}^m + L_2 \Delta n_{SMF2}^m \quad (1)$$

where  $L_1$  and  $L_2$  is the length of the TCF and SMF2, respectively;  $\Delta n_{TCF}^m$  and  $\Delta n_{SMF2}^m$  are the effective RI difference between the core mode and the  $m$ th order cladding mode in the TCF and SMF2, respectively; so the interference intensity can be calculated by

$$I = I_1 + I_2 + 2\sqrt{I_1 I_2} \cos(\Delta\Phi) \quad (2)$$

where  $I_1$  and  $I_2$  are the intensity of the core and cladding modes, respectively;  $\lambda$  is the wavelength of the propagating light. According to phase matching condition as

$$\Delta\Phi = \frac{4\pi(L_1 \Delta n_{TCF}^m + L_2 \Delta n_{SMF2}^m)}{\lambda_m} = (2m+1)\pi \quad (3)$$

So free spectral range (FSR) in the interference fringe can be calculated by

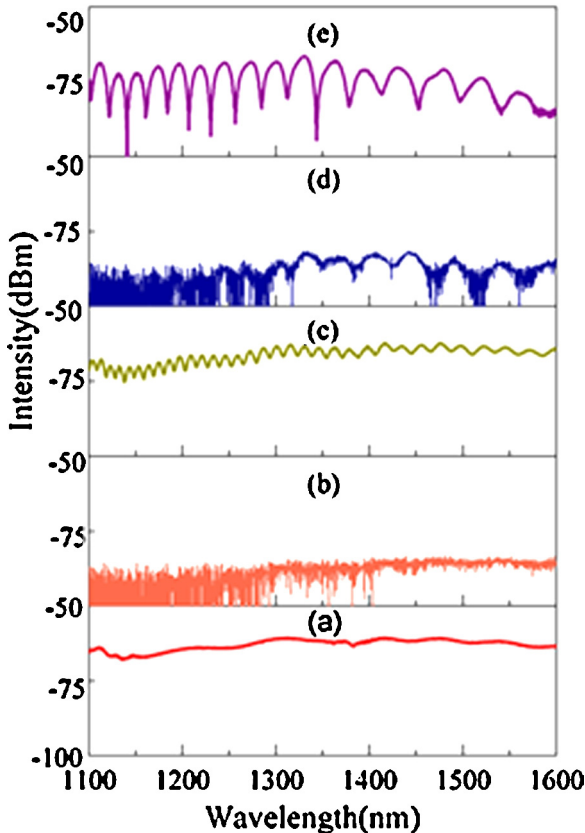
$$FSR = \frac{\lambda^2}{2(L_1 \Delta n_{TCF}^m + L_2 \Delta n_{SMF2}^m)} \quad (4)$$

As shown in Eq. (4), the FSR depends strongly on the lengths, i.e.  $L_1$  and  $L_2$ , of the TCF and SMF2. So we can achieve a desired FSR by means of improving the length of TCF and SMF2, as described below.

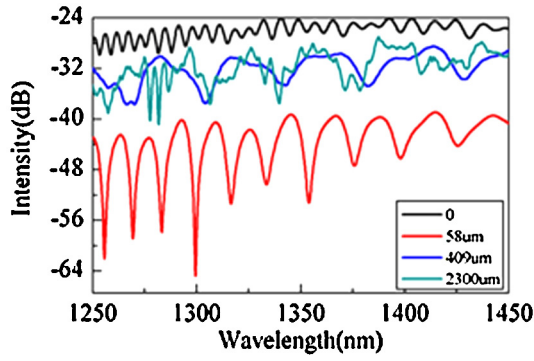
Interference fringe visibility in the reflection spectrum depends strongly on the intensity of the reflected core and cladding modes, which are decided by the lengths of the TCF and SMF2, the core diameters of the TCF and the standard SMF, and the spliced joints. So it is easy for us to enhance interference fringe visibility by means of cleaving gradually SMF2 to improve its length, as shown in Fig. 3, which is a critical advantage of our proposed in-fiber MI structure. In case the lengths of the TCF and SMF2 were improved to be 1736 and 58 μm, respectively, we achieved a desired interference fringe with a high visibility of up to 24 dB. In contrast, the observed fringe visibility of the RI interferometer sensor based on a rounded tip and core-off was only about 5 dB, as reported in ref. [12], in which repeated arc discharges have to done to reshape the fiber end into a rounded tip.

### 3. Index sensing application

We investigated the response of the MI sample to surrounding refractive index by means of immersing it into a series



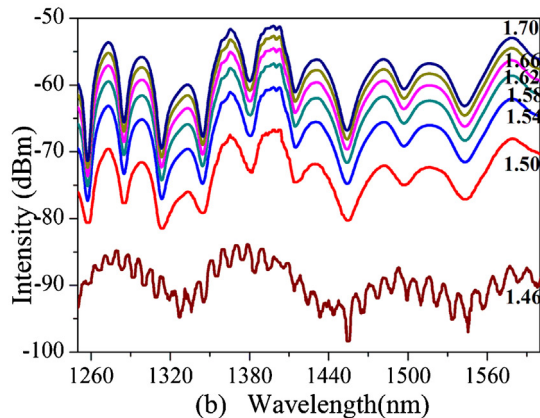
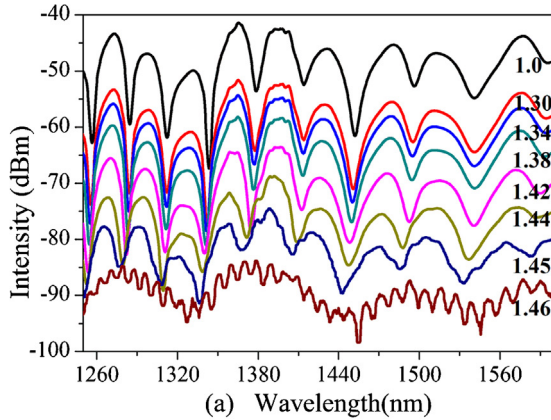
**Fig. 2.** Reflection spectra of (a) after the right end of SMF1, (b) before and (c) after the right end of the TCF was cleaved, (d) before and (e) after the right end of SMF2 was cleaved.



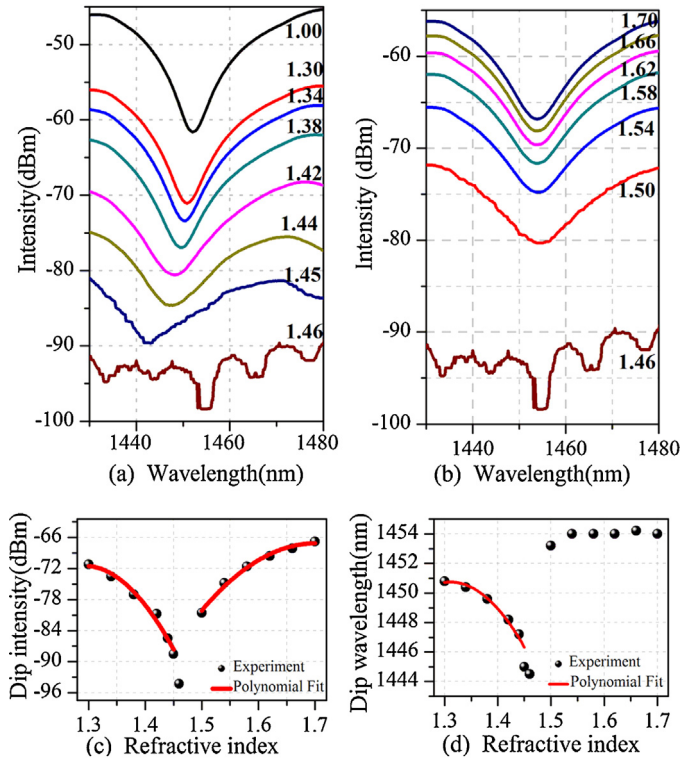
**Fig. 3.** Reflection spectra of the in-fiber Michelson interferometer while the length of SMF2 is improved to be 0, 58, 409 and 2300  $\mu\text{m}$ . Note that the zero length of SMF2 indicates that no SMF is spliced with the right end of the TCF.

of liquids, e.g. Refractive index matching liquid (Cargille Labs, <http://www.cargille.com>) with a RI from 1.300 to 1.700 at room temperature. Every time the MI sample was taken out from a liquid, it was carefully cleaned by use of alcohol to eliminate entirely the residual liquid on the fiber surface and then was immersed into another liquid.

As shown in Fig. 4(a), the intensity of the reflection spectrum decreased gradually while the surrounding refractive index was changed from 1.000 (air), 1.300 (liquid) to 1.460 (liquid). The reason for this is, that light reflected at the interface-III is gradually reduced with the increased surrounding refractive index,  $n_{so}$  from 1.0 to 1.460, according to Fresnel reflection,  $R = (n_{si} - n_{so})^2 / (n_{si} + n_{so})^2$



**Fig. 4.** Reflection spectrum evolution of the in-fiber MI sample immersed into a series of liquid with a refractive index (a) from 1.30 to 1.46, and (b) from 1.46 to 1.70.



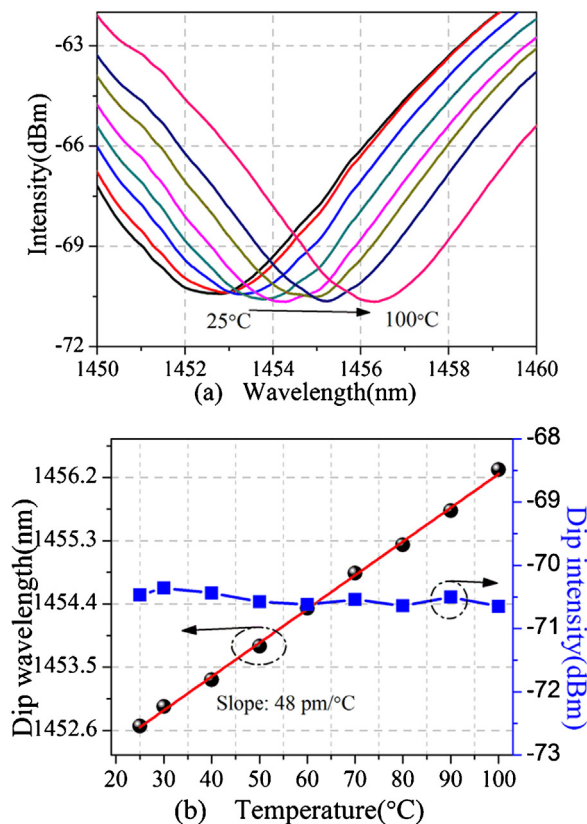
**Fig. 5.** Reflection spectrum evolution within the wavelength range from 1430 to 1480 nm while the surrounding RI changes (a) from 1.0 to 1.46 and (b) from 1.46 to 1.70; (c) The dip intensity of the interference fringe versus the surround RI; (d) The dip wavelength versus the surrounding RI.

where  $n_{si}$  and  $n_{so}$  are refractive index of silica and surround medium (air or liquid), respectively. Note that the RI of the fiber material, i.e. silica, is about 1.460. In contrast, as shown in Fig. 4(b), the intensity of the reflection spectrum increased gradually while the surrounding refractive index was changed from 1.460 to 1.700. The reason for this is, according to Fresnel reflection, that light reflected at the interface-III is enhanced gradually with the increased surrounding refractive index,  $n_{so}$ , from 1.460 to 1.700. It can be seen from Fig. 4 that, while the MI sample was immersed into a liquid with a similar refractive index (1.460) to silica index, interference fringes with a small FSR of about 10 nm was observed in the reflection spectrum, which results from the Fabry–Perot interference between the interface-II and the interface-III, rather than the Michelson interference, due to the reduce of light reflected at the interface-III.

Reflection spectra within the wavelength range from 1430 to 1480 nm in Fig. 4 are illustrated in Fig. 5(a) and (b) to analyze quantitatively the response of the in-fiber MI sample to the change of surrounding refractive index. As shown in Fig. 5(c), the dip intensity of the interference fringe decreases with the increased surrounding RI from 1.0 to 1.46 and increases with the increased surrounding RI from 1.46 to 1.70. Therefore, such an in-fiber MI could be used to develop a promising intensity-modulated RI sensor. The sensitivity of the MI-based RI sensor is calculated to be  $-208.24$  and  $125.44$  dB/RIU at the refractive index of 1.440 and 1.500, respectively, via polynomial fitting method.

As shown in Fig. 5(d), the dip wavelength of the interference fringe also decreases with the increased surrounding RI from 1.0 to 1.46, which the wavelength sensitivity of RI sensor is calculated to be  $-72.87$  nm/RIU at the RI of 1.44, and hardly changes with the increased surrounding RI from 1.46 to 1.70, but the intensity modulation, rather than the wavelength modulation, was used in our proposed MI-based refractive index sensor in order to solve the





**Fig. 6.** Reflection spectrum evolution of the in-fiber MI sample (a) temperature rise from 25 to 100 °C with a step of 10 °C. (b) dip wavelength and corresponding dip intensity vary with temperature.

cross-sensitivity problem between temperature and surrounding refractive index, as described below.

#### 4. Temperature response

The cross sensitivity between surrounding refractive index and temperature has to be considered in the application of refractive index sensors. So we investigated the temperature response of the MI-based RI sensor by use of an oven with a temperature stability of  $\pm 0.2$  °C. While the temperature rose from room temperature, i.e. 25–100 °C, as shown in Fig. 6(a), the reflection spectrum of the MI-based sensor shifted toward a longer wavelength with a sensitivity of 0.048 nm/°C whereas the dip intensity of the interference fringe hardly changed. In other words, the dip intensity is insensitive to temperature. So our proposed intensity-modulated refractive index sensor based on the in-fiber MI is insensitive to temperature and thus solve the cross-sensitivity problem between temperature and surrounding refractive index.

#### 5. Conclusion

A compact in-fiber MI with a short size of less than 2 mm was created by splicing a section of thin core fiber between two standard SMFs. Interference fringes in the reflection spectrum have a high extinction ratio of up to 24 dB. Such an in-fiber MI could be used to develop a promising intensity-modulated refractive index sensor that exhibits an ultrahigh sensitivity of  $-208.24$  and  $125.44$  dB/RIU at the refractive index of 1.440 and 1.500, respectively. Moreover, the MI-based refractive index sensor solves the cross-sensitivity problem between temperature and surrounding refractive index

and could find potential applications in the fields of chemical and biomedical sensing, and environmental monitoring.

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