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2012

Wo, J., Wang, G., Cui, Y., Su, Q., Liang, R., Shum, P. P., et al. (2012). Refractive index sensor using microfiber-based Mach-Zehnder interferometer. *Optics Letters*, 37(1), 67-69.

<https://hdl.handle.net/10356/98012>

<https://doi.org/10.1364/OL.37.000067>

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Refractive index sensor using microfiber-based Mach-Zehnder interferometer

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Received September 9, 2011; revised November 4, 2011; accepted November 15, 2011;
posted November 16, 2011 (Doc. ID 154216); published December 24, 2011

A simple and robust refractive index (RI) sensor based on a Mach-Zehnder interferometer has been demonstrated. A section of optical microfiber drawn from silica fiber is employed as the sensing arm. Because of the evanescent field, a slight change of the ambient RI will lead to the variation of the microfiber propagation constant, which will further change the optical length. In order to compensate the variation of the optical length difference, a tunable optical delay line (ODL) is inserted into the other arm. By measuring the delay of the ODL, the ambient RI can be simply demodulated. A high RI sensitivity of about 7159 $\mu\text{m}/\text{refractive index unit}$ is achieved at microfiber diameter of 2.0 μm . © 2011 Optical Society of America

OCIS codes: 060.2370, 120.3180, 230.3990.

Refractive index (RI) sensing has had rapid development due to their important meaning in measuring gas and liquid concentration and monitoring the compound materials solidification for industrial applications. Recently, there has been great interest in fabricating the optical devices with micrometer or nanometer diameter for RI sensing because of their advantages such as low cost, small size, and low loss [1–4]. Light guided along the microfiber/nanofiber can support very large evanescent field, which enables strong coupling between the microfiber and its environment [5,6]. Various approaches have been exploited, including microfluidic channel [7], optical liquid ring resonator [8], microfiber loop [9], microfiber coil [10,11], and microfiber Bragg grating [12,13]. In these approaches, though a relative high sensitivity has been obtained, complex and bulky techniques are required to fabricate the sensor.

The Mach-Zehnder interferometer (MZI) is one of the most widely used structures in optical and photonic devices. Sensors and modulators based on the MZI have been demonstrated due to its high sensitivity to the surrounding medium. So here a question arises naturally: can we assemble an MZI utilizing the evanescent field of microfiber for RI sensing? Actually, the MZI and other devices assembled with optical microfibers or nanofibers have been reported [14,15]. However, the path-length difference has to be controlled by complex micromanipulation, and the insertion loss is relatively large. Furthermore, the mathematic relation between the measurand and the RI are mostly nonlinear, which is inconvenient for the measurement.

In this Letter, we report the experimental demonstration of an MZI-structure-based RI sensor. The sensor is assembled by using a section of optical microfiber in the sensing arm and an optical delay line (ODL) inserted to the reference arm. Because of the strong evanescent field of microfiber, a slight change of the ambient RI will lead to the variation of the microfiber propagation constant as well as the optical length difference of

the MZI. By means of a tunable ODL, this variation of optical length difference can be easily and precisely compensated. The sensor reveals the advantages of simple fabrication, high sensitivity, high linearity, and low insertion loss. A high sensitivity of 7159 $\mu\text{m}/\text{refractive index unit}$ (RIU) within the RI range from 1.33 to 1.37 is obtained for the 2.0 μm diameter microfiber in the experiment.

The schematic configuration of the MZI-based RI sensor is shown in Fig. 1.

The MZI is composed of two 1:1 couplers, a section of microfiber as the sensing arm exposed to the measurand, a tunable ODL as the reference arm for compensating the variation of the optical length difference, and an optical attenuator for balancing the power of these two arms. An amplified-spontaneous-emission-based broadband light source (BBS) with about 100 nm bandwidth is launched into the MZI through coupler 1 and then bifurcated into two parts. After travelling through the sensing arm where the measurand accesses to the evanescent field of microfiber, the signal light meets with the reference light in

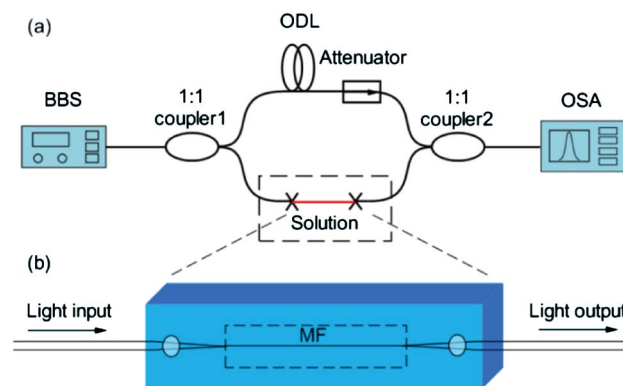


Fig. 1. (Color online) (a) Schematic configuration of the MZI-based RI sensor; (b) schematic diagram of the sensing arm. BBS, broadband light source; ODL, optical delay line; OSA, optical spectrum analyzer; MF, microfiber.

coupler 2. Then the output is observed by an optical spectrum analyzer (OSA). The phase shift caused by the RI change is measured by the interferometric spectrum, and the specimen information can thus be retrieved.

When the ambient RI varies, the phase shift of the sensing arm can be described as

$$\Delta\phi_{\text{MF}} = (\beta_1 - \beta_2) \cdot L = \frac{2\pi}{\lambda} \cdot \Delta Q_{\text{MF}} = \frac{2\pi}{\lambda} \Delta n_{\text{eff}} L, \quad (1)$$

where β_1 and β_2 are the initial and instant propagation constant of the light before and after changing the RI, respectively; ΔQ_{MF} is the optical length change of the microfiber; L is the length of the microfiber, λ is the wavelength of the input light, and Δn_{eff} is the effective index change of the microfiber.

Since Δn_{eff} is largely dependent on the ambient RI, the optical length and the phase shift of the sensing arm will change with the RI as well. The propagation constant (β) can be obtained by solving the eigenvalue equation of a circular cross-section waveguide in cylindrical coordination [16]:

$$\left\{ \frac{J_1'(U)}{U J_1(U)} + \frac{K_1'(W)}{W K_1(W)} \right\} \left\{ \frac{n_1^2 J_1'(U)}{n_2^2 U J_1(U)} + \frac{K_1'(W)}{W K_1(W)} \right\} = l \left(\frac{n_1^2}{n_2^2} \cdot \frac{1}{U^2} + \frac{1}{W^2} \right), \quad (2)$$

where J_l and K_l are the Bessel function of the first kind and the modified Bessel function of the second kind, respectively, $U = a \sqrt{n_1^2 k_0^2 - \beta^2}$, $W = a \sqrt{\beta^2 - n_2^2 k_0^2}$, $V^2 = U^2 + W^2$, $k_0 = 2\pi/\lambda$, and a is the radius of the microfiber.

Figure 2 shows the calculated β versus the ambient RI of different diameter microfiber operating at 1550 nm. It can be seen that the β increases with the ambient RI (n_2), resulting in the phase shift change of the sensing arm, according to Eq. (1). As the microfiber diameter decreases, the β increases faster with the ambient RI, indicating that thinner fiber is more sensitive to the ambient RI variation.

For aqueous solution sensing, the RI varies from 1.33 to 1.37. The inset in Fig. 2 displays that the linear coefficients (K) for the microfiber with the diameter of 2, 3, and 4 μm are 1.0620, 0.4099, and 0.1966, respectively,

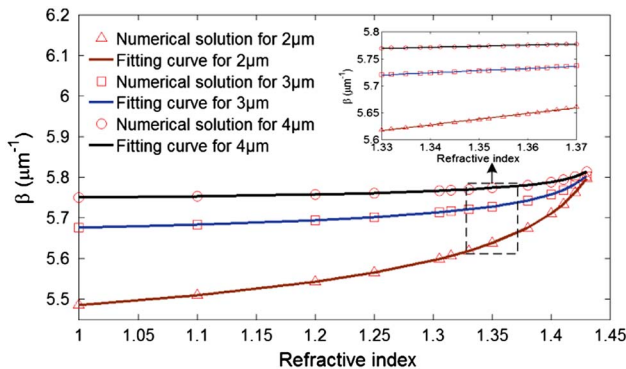


Fig. 2. (Color online) Calculated propagation constant (β) versus ambient RI of different diameters of microfiber operating at 1550 nm.

and the correlative coefficients are 0.9984, 0.9979, and 0.9975, respectively. It can be deduced that the β varies almost linearly with the RI, so the β change caused by RI variation can be expressed as

$$\Delta\beta = \frac{2\pi}{\lambda} \Delta n_{\text{eff}} = K \Delta n_2, \quad (3)$$

where $\Delta\beta$ and Δn_2 refer to the propagation constant and ambient RI variation, respectively. When the BBS is launched into the MZI, the free spectral range (FSR) of output can be estimated as follows [17]:

$$\text{FSR} = \Delta\lambda = \lambda_1 \lambda_2 / (\Delta Q), \quad (4)$$

where λ_1 and λ_2 are the spectral wavelength of two adjacent maximum or minimum, respectively. ΔQ is the optical length difference between the two arms. Thus, when there is a slight change of ambient RI, the optical length of the microfiber will change correspondingly, resulting in the variation of the FSR.

The spectral response of the MZI obtained from the OSA is shown in Fig. 3. A strong interference spectrum with an extinction ratio of as much as 15 dB is achieved, which is good for observing the variation of the FSR.

As shown in Fig. 3, the FSR varies inversely with the ΔQ . In order to simplify the measurement and obtain high sensitivity, a tunable OD L could be used to compensate the FSR caused by RI variation.

The variation of the ΔQ caused by the ambient RI can be derived as

$$d(\Delta Q) = \Delta n_{\text{eff}} L - n_1 \Delta l = \frac{\lambda}{2\pi} K \Delta n_2 L - n_1 \Delta l, \quad (5)$$

where n_1 and Δl are the RI and the delay of OD L. From Eqs. (4) and (5), in order to keep the FSR the same, we can tune the Δl to compensate the change of the first item $\lambda K \Delta n_2 L / 2\pi$ in Eq. (5), which brings simple measurement since Δl changes linearly with Δn_2 over the RI range from 1.33 to 1.37.

Based on the optical waveguide properties mentioned above, we propose to utilize the microfiber waveguide as a sensing element for detecting the RI variation of the aqueous solutions. Here the silica microfibers,

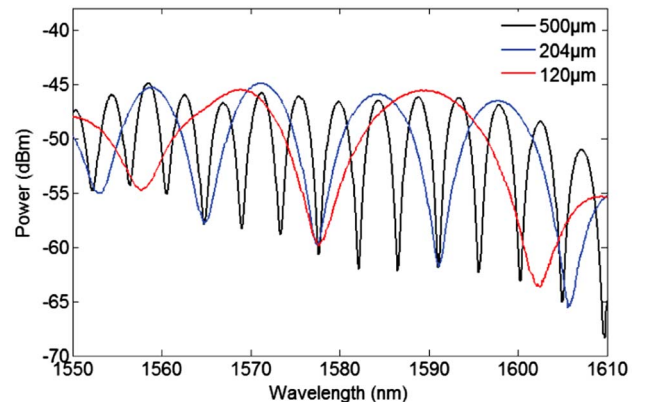


Fig. 3. (Color online) Measured spectrum of the MZI of different optical length difference.

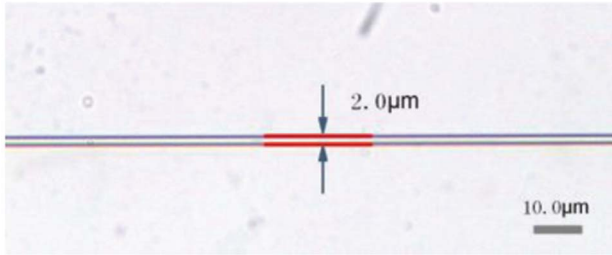


Fig. 4. (Color online) Microfiber image taken with an optical microscope.

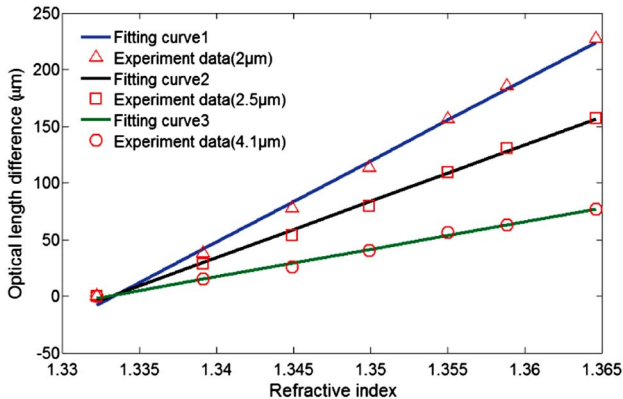


Fig. 5. (Color online) Optical length variation with the RI at different microfiber diameters.

approximately 2–4 μm in diameter and 6 cm in length, are fabricated by flame-heated adiabatically taper drawing of a single-mode fiber (SMF), which will support only single-mode guidance [3,18]. Figure 4 is the image of the 2 μm diameter microfiber taken with an optical microscope. The fiber shows excellent diameter uniformity and surface smoothness.

The RI sensing is experimentally demonstrated by immersing the microfiber into solutions of different NaCl concentration. The RI of the solution can be varied from 1.3322 to 1.3646 and it is calibrated by a refractometer with the resolution of 0.0001 RIU. Since the liquid RI is dependent on the temperature, the environment temperature is kept stable at 20 $^{\circ}\text{C}$ during the measurement so as to avoid the temperature effect [19,20]. Initially, the optical length difference of the two arms is set at a certain value that could be realized by adopting a fixed FSR. Once the RI is changed, the FSR will change since the optical length difference is different from the original state. Then we tune the ODL delay to take the FSR back to the initial value again and record the displacement of the ODL. Figure 5 shows the dependence of the ODL variation with the ambient RI at the microfiber diameter of 2, 2.5, and 4.1 μm . It can be found that the optical length difference changes almost linearly with the ambient RI. The curve slope of the 4.1 μm microfiber is 2427 $\mu\text{m}/\text{RIU}$, and much higher sensitivity of 4970 and 7159 $\mu\text{m}/\text{RIU}$ are obtained when the fiber diameter reduce to 2.5 μm and 2.0 μm , respectively. It proves that thinner fiber provides higher sensitivity. The reason is

that thinner fiber supports larger evanescent field, and consequently the propagation constant is more sensitive to the ambient RI variation, which can be calculated from Eq. (2).

In conclusion, we developed a simple and robust RI sensor based on an MZI structure. By employing the optical microfiber in the sensing arm and the ODL in the reference arm, high sensitive ambient RI detection could be realized over the RI range from 1.33 to 1.37. A good interference spectrum with the extinction ratio of as much as 15 dB was obtained and a further improved sensitivity of 7159 $\mu\text{m}/\text{RIU}$ was achieved with 6 cm length microfiber by decreasing the diameter to 2.0 μm . The sensing area dimension could be further reduced by employing special SMF with smaller diameter to be drawn or by introducing two fiber tapers at the ends of short length microfiber to couple the guided light. Furthermore, by utilizing the sensor structure, other parameters such as temperature and gas concentration can be detected as well.

This work was supported by the National Natural Science Foundation of China (60937002, 60907037) and the Fundamental Research Funds for the Central Universities, Huazhong University of Science and Technology (2011TS059).

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