Fiber Optic Refractometer Based on Leaky-Mode Interference of Bent Fiber

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Abstract—In this letter, we present a novel fiber-optic Mach–Zehnder interferometer based on leaky-mode generation from fiber bending and experimentally demonstrate it that is used as a fiber-optic refractometer. The interferometer is simply constructed using a standard single-mode fiber with two fiber bending regions connected by a section of straight fiber. The phase difference is from the optical path difference between the core mode and leaky modes from the designed bending fiber structure. Refractive index (RI) sensors with different parameters have been fabricated and tested in NaCl solutions with different RIs in the range of 1.3288–1.3606, and a maximum RI sensitivity of $-204$ nm/RIU (refractive index unit) is achieved on a sensor with a 4-cm straight fiber length and 5-mm bending radius. Experimental results have confirmed that there are two dominant cladding modes interfering with the core mode. The RI sensitivities of the sensors with a uniform bending radius are independent of the straight fiber length; as a result, precise control of the fiber length is not required, which makes the sensor production cost-effective.

Index Terms—Single-mode fiber, fiber optics sensor, interferometer, leaky-mode.

I. INTRODUCTION

FIBER-OPTIC refractive-index (RI) sensors have been extensively investigated recently [1], [2], which have many distinctive advantages over traditional RI sensors, such as high sensitivity, miniature size, immunity to electromagnetic interference, and multiplexing capability [3]. Many fiber-optic refractometer configurations have been studied, including optical fiber coil resonators [4], cladding mode fiber Bragg gratings [5], [6], single mode-multimode-single mode structures [7]–[9], microfiber interferometers [10], in-line fiber interferometers [11], [12], femtosecond laser micromachining microhole interferometers [13], [14], long-range surface plasmons on Mach-Zehnder interferometer (MZI) [15], and silicon-nanowire tips [16]. Although some of these methods possess high RI sensitivity, the sensing elements in these methods are typically fragile, and the sensors are unstable for practical applications. In addition, these methods usually involve special equipment, and bulky optical setup, which increase the cost and complexity of fabrication and operation.

Little study has been carried out on refractometers based on bent single-mode fiber. Most of the previously published investigations on bent fibers focused on the prediction and reduction of bend loss, which is regarded as an adverse effect for light transmission [17]–[21]. Recently, there are some studies employing bent fibers as optical sensing elements based on bending loss [22], [23], and most of them are intensity demodulated. The previous report based on standard optical fiber in Ref. [22] has some advantages, such as a single-wavelength source is not required; its modulation method is based on bend loss which is equivalent to intensity modulation; however, intensity modulation is easily affected by light source or external environments; additionally, the cladding diameter should be reduced by chemical etching process which increases the complexity of sensor fabrication. Therefore, intensity demodulated fiber-optic RI sensors often have limited sensitivity and limited RI resolution, particularly for small RIs. In this letter, we propose and demonstrate a smart fiber-optic refractometer based on optical interferometry and bending loss. A MZI consists of a section of straight bare standard single-mode fiber (SMF) in-between two bent bare fibers with a selected bending radius utilized as mode couplers. Experimental results show that the sensors have high RI sensitivities with a maximum RI sensitivity of $-204$ nm/RIU achieved by a sensor with a 4-cm straight fiber length (the length of the fiber between two bending regions) and 5-mm bending radius. We also found that the sensitivity of sensors with different straight fiber length show similar RI sensitivities, so that the sensors can be miniaturized by reducing the straight fiber length without sacrificing the RI sensitivity. Compared with previously reported fiber refractometers, it has advantages of simple configuration, easy fabrication and low cost. In addition, there are no splicing points in sensor construction, leading to better mechanical strength and suitable for practical applications.

II. SENSOR DESIGN AND OPERATING PRINCIPLE

The sensor structure is schematically shown in Fig. 1. It is fabricated by bending two sections of a single-mode fiber (SMF) with uniform bending radius separated by several centimeters. Both coating of the bending and straight sections of this sensor is stripped off, which will improve both interference visibility and the interference relationship between the surroundings and optical signal. The lead-in bent SMF couples the fundamental core mode to several cladding modes while the lead-out bent SMF re-couples the cladding modes back to the core mode at the lead-out bent SMF, where the modes interfere with each other. Therefore, the different optical paths of the core mode and cladding modes form a MZI. As shown in Fig. 1, when the core mode of the lead-in SMF enters the bending region, the light power is split into two portions:
Firstly, due to the bending loss, the light from the SMF is partially leaked into the cladding of SMF and the excited several cladding modes propagate along the fiber; secondly, the residual energy propagates as the core mode. At the second bending region, the cladding modes are coupled back to the core mode where interference occurs among the cladding modes and the core mode, and the interference spectrum is detected by an optical spectrum analyzer (OSA).

The phase difference between the core and the mth-order cladding mode after propagating through a fiber length can be written as:

$$\Delta \phi_m = \frac{2\pi}{\lambda} (n_{co,eff} - n_{cl,m,eff}) L = \frac{2\pi}{\lambda} \Delta n_{m,eff} (L_{str} + L_{arc})$$

(1)

where $n_{co,eff}$ and $n_{cl,m,eff}$ are the effective RIs of the fundamental mode and the mth-order cladding mode, respectively. $\Delta n_{eff} = n_{co,eff} - n_{cl,m,eff}$ is the effective RI difference between the fundamental mode and the mth-order cladding mode. $L_{str}$ is the length of the straight fiber between two bending regions, $L_{arc}$ is the arc length of bending region, $\lambda$ is the free-space wavelength. Thus, the wavelength of the dip $\lambda_m$ is given by:

$$\lambda_m = \frac{2\Delta n_{m,eff} \cdot (L_{str} + L_{arc})}{m}$$

(2)

When the sensor is subjected to external RI perturbation, the wavelength shift is:

$$\Delta \lambda = \frac{\delta \Delta n_{eff}}{\Delta n_{eff}} \lambda_m$$

(3)

where $\delta \Delta n_{eff}$ is the variation of $\Delta n_{eff}$ caused by surrounding RI change. From Eq. (3), the interference spectra will shift towards shorter wavelength when the surrounding RI increases. Surrounding RI can be detected and evaluated by measuring the resonance wavelength shift.

To verify the proposed model, we used a commercial standard SMF (Coning, SMF-28) to fabricate the designed sensor. The coating of a section fiber was stripped off by a wire stripper. A 5mm bending radius (the breakage threshold of the fiber used in our model is 3.5mm bending radius) was selected for the two bending fiber sections which function as the mode splitter or coupler, and a polymethyl methacrylate plate is used as a platform where the bending rigs (plastic cylinders, as shown in the inset of Fig. 1) are mounted on. There is a thread where the bent bare fiber stuck in on the root of the plastic cylinders. Two local bendings on SMFs are formed by winding the fiber onto the plastic cylinders with a central angle of about 90°. Using a lab-scale spectrum measurement system, we experimentally calibrated and tested the RI responses of the sensors with different straight fiber lengths. In this setup, a self-developed optical sensing interrogator with a spectral resolution of 4 pm was used to measure the optical spectrum of the sensor.

Figure 2(a) shows typical transmission spectra of these sensors with central angel of 90° and different straight fiber lengths, and a series of transmission dips appear on the transmission spectrum. In Fig. 2(a), there are two evident dips named as Dip 1 and Dip 2 in the two sensors with different straight fiber length. It is clear that the sensor with longer straight fiber length shows denser and narrower interference fringes. The spectrum was also numerically simulated using the beam propagation method (BPM). In the simulation, the effective refractive index of core and cladding, are respectively, 1.456 and 1.44525 and the diameters of the core and the cladding are 8 and 125 μm, respectively. As the bending radius decreasing, the higher cladding modes will be excited with the increasing insertion loss; however, the higher cladding modes have larger transmission loss, particularly in the bend region, that will translate into leaky modes. Figure 2(b) shows the experimentally-obtained and simulated transmission spectrum of the sensor with 90° central angle and 4 cm straight fiber length. We can see that the theoretical model agrees with the measured result reasonably well. The discrepancy between the calculated and the measured result could be due to the differences between the simulated and fabricated shape of the sensor. We selected a standard Gaussian light source in
above simulation. The transverse mode profiles with different bending radiuses are shown in the right column insets of Fig. 2, the profiles illustrated that the smaller bending radius will induce larger transmission loss.

To determine the number and power distribution of the modes involved in the interference pattern, and understand the influence of the bending central angle on sensor performances, we performed Fourier-transform on the spectra of the sensor with 4 cm straight fiber length and different central angles to obtain the spatial frequency spectra. Figure 3 illustrates transmission and spatial spectra of the selected configurations with different central angles. And it is obvious that the bending central angle has to exceed certain value in order to excite sufficient cladding modes for interference. In Fig. 3 (a), no fringes are observed in the interference spectrum very low light power is coupled to the high order mode due to the small central angle. Figure 3(c) shows an interference pattern that includes two higher-order cladding modes. Obviously, the power is primarily distributed in the two higher-order modes which will benefit temperature compensation. The mode coupling and interference mainly occur between the core mode and the dominant higher-order modes. But as shown in Fig. 3(b) and (d), there are one single dominant mode involved in the 60° and 115° central angle interference pattern. Therefore, we conclude that the central angle affects the number of the interference modes.

### III. Experiments and Discussion

Two sensors with 4cm and 5.5cm straight fiber lengths were fabricated for experimental demonstration of the RI sensing. We used the refractive index valued by an Abbe refractometer, which is a commercial standard electrical instrument for determining the solutions refractive index. The sensing region was immersed into NaCl solutions with different RIs ranging from 1.3288 to 1.3696. The wavelength shifts are shown in Fig. 4. Figure 4(a) and (b) are the transmission spectra of the sensor with 4cm and 5.5cm straight fiber length, respectively, when they were immersed into the solution of different RIs. The interference fringes show good visibility that is sufficient enough for interference signal demodulation. The fringes shifted towards the shorter wavelength while the RI increases, which agreed with Eq. (3). Observing the two dips (Dip 1 and Dip 2 in Fig. 2), we have found that the Dip 2 shifts to a shorter wavelength more quickly than Dip 1 in Fig. 4(a) but the opposite was observed in Fig. 4(b). Additionally, during the refractive index measurement, the visibility of the interference spectrum is reduced.

Figure 5 presents the dip wavelength shifts as a function of the surrounding RI (SRI) for above sensors. All wavelengths of these dips shift to shorter wavelengths monotonically when RI increases from 1.3288 to 1.3696. It indicates that different dips show different RI sensitivities for different sensors. The sensitivities for the Dip 1 and Dip 2 are, respectively, $-86$nm/RIU, and $-204$nm/RIU for the sensor with 4 cm straight fiber length, and $-198$nm/RIU and $-97$nm/RIU, respectively, for the sensor with 5.5 cm straight fiber length. The sensitivities of the Dip 2 in Fig. 4(a) and the Dip 1 in Fig. 4(b), the Dip 1 in Fig. 4(a) and the Dip 2 in Fig. 4(b) are close, showing that the sensitivity is not sensitive to the straight length, the experimental results show that a longer attenuation peak wavelength exhibits a larger shift than that at a shorter wavelength from identical cladding mode [24]. When the wavelength resolution of the OSI is 4pm, the corresponding resolutions of RI measurement are about $4.65 \times 10^{-5}$ RIU, $1.96 \times 10^{-5}$ RIU, $2.02 \times 10^{-5}$ RIU and $4.12 \times 10^{-5}$ RIU, respectively, that are for the Dip 1 and Dip 2 of the sensors with 4cm and 5.5 cm straight fiber length, respectively.

The simulated result of the sensor with 4cm straight length is shown in the subset to Fig. 5 (a). The calculated sensitivity are $-67.5$nm/RIU and $-175$nm/RIU for the Dip 1 and Dip 2, respectively, which are slightly lower than the experimental results. When wavelength-tracking method is used, sensors with different straight fiber lengths should have similar sensitivity, as demonstrated by the experiments, due to the identical cladding modes excited in the sensors. Experimental results
show that the RI sensitivities of the sensors with uniform bending radius is independent on the straight fiber length, which is beneficial to the miniaturization of the sensors. In addition precise control of the straight fiber length is not required for RI measurement, which simplifies the sensor fabrication. Additionally, we mainly focus on the investigation of the influence of the central angle on RI sensitivity. Through our experiment investigation, a maximum RI sensitivity about 204nm/RIU was obtained under a 90° central angle and 4cm straight fiber length, as shown as Fig. 6. As mentioned above, the cladding modes power is primarily distributed in the two higher-order modes when we select 90° central angle, which will benefit temperature compensation. The 90° central angle selected in our experiment is an optimum bending condition. Different high order modes will be excited under different bending angles. Also, the cladding modes propagated in cladding with different transmission loss. Thus, the cladding mode order is the main factor to influence the refractive index sensitivity. Eventually, the sensors with different central angles show different sensitivity.

IV. CONCLUSION

In summary, we proposed and demonstrated a novel fiber refractometer using a MZI based on a leaky-mode generation mechanism in bent fibers. The optical interference is generated from two fiber bending sections in a single mode fiber, and the straight fiber between these two bending parts is used as the sensing section for RI measurement. The designed sensing structure is operated in transmission mode. We have fabricated sensors with 5mm bending radius, in which two dominant cladding modes are excited and interfere with core mode. RI sensing is achieved by measuring the wavelength shift of the resonance dips in the transmission spectrum of the sensors. In the RI range of 1.3288 to 1.3696, a maximum RI sensitivity of −204nm/RIU was achieved by the sensor with a 4cm straight fiber length. Experimental results show that the RI sensitivities of the sensors with uniform bending radius is independent on the straight fiber length, so precise control of the length is not required, which makes the sensor production very cost-effective. Future works will be focused on RI sensitivity enhancement by optimizing sensor structure, parameters and materials.

REFERENCES


