High sensitivity refractive index sensor based on the semicircular bent fiber

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Abstract
A refractive index sensor based on a semicircular bent fiber is presented. The interference occurs between the cladding mode excited in the bending region and the core mode. The experimental results show that the resonant dip wavelength decreases linearly with the increase of the refractive index of the surrounding environment and the sensitivity of the sensor increases linearly with the increasing of the bending radius. A high sensitivity of 1031 nm per refractive index unit is obtained over the refractive index range of 1.3324 to 1.3435 by using a bent fiber with a bending radius of 500 μm.

1. Introduction
Recently, sensors based on the bent fiber have been extensively investigated due to their easy fabrication method and simple configuration. Acoustic, temperature, displacement sensors have already been reported using bending-induced birefringence in a fiber [1–6]. Evanescent wave sensor [7] and refractive index (RI) sensor [8] have also been realized based on the bending-induced transmission loss. However, loss modulated sensors are easily affected by the shift of the light source power, which limited their applications. To solve the problem and take the advantage of the cladding mode of the fiber is sensitive to the RI of the surrounding environment, interference effect between the cladding mode and the core mode or different fiber modes in a bent fiber has been exploited for RI sensing applications [9–14]. For examples, Luo et al proposed an RI sensor based on a C-shaped ultrathin fiber taper [10], a sensitivity of 658 nm per refractive index unit (RIU) for an RI range of 1.333 to 1.353 was achieved. Liu et al proposed an ‘S’-like tapered fiber and the sensitivity as high as 4000 nm/RIU was obtained in the RI range of 1.424 to 1.435 [11]. To eliminate the temperature cross-sensitivity, Zhang et al demonstrated an RI sensor using a hybrid structure with an LPG and a bent-fiber intermodal interferometer. The sensitivity of the structure is 183.44 nm/RIU at an RI range of 1.3269 to 1.3721 [12]. Even though the sensors based on the bent tapers have higher sensitivities, thinner waist diameter of the tapers would cause the structure more fragile. In this letter, an RI sensor based on the semicircular bent fiber that fabricated on the untapered fiber was proposed. The sensitivity of the sensor increases linearly with the increasing of the bending radius. A sensitivity as high as 1031 nm/RIU was obtained in the RI range of 1.3324 to 1.3435 by using a bent fiber with a bending radius of 500 μm.

2. Operation principle
Figure 1 shows the schematic of the light transmitted in the bent fiber structure. Before entering into the bending region, light guided in the fiber is mainly confined in the fiber core, which is usually called core mode. After entering into the bending structure, part of light in the core mode will be coupled into the fiber cladding mode because of the decreasing of the incident angle of the core mode at the interface of the fiber core and fiber cladding. And at the interface of the fiber cladding and the surrounding environment, part of the cladding mode will be leaked into the surrounding environment, which mainly contributes to the transmission loss of the bending fiber structure. The cladding mode will be coupled back to the fiber core when leaving the bending
structure. Because the effective refractive indices (ERIs) of the core mode and cladding mode are different, interference will be formed after the cladding mode is coupled back to the core of the fiber.

The phase difference $\phi$ between the core mode and cladding mode can be expressed as

$$ \phi = kL(n_{\text{eff}} - n_{\text{cl}}^{\text{eff}}) $$

where $k$ is the wave number, $L$ is the bending length of the structure, $n_{\text{eff}}^{\text{core}}$ and $n_{\text{cl}}^{\text{eff}}$ are the ERIs of the core mode and cladding mode, respectively. The resonant dip wavelength $\lambda_{\text{dip}}$, where light intensity is lowest, can be expressed as

$$ \lambda_{\text{dip}} = 2L(n_{\text{eff}}^{\text{core}} - n_{\text{cl}}^{\text{eff}})/(2m + 1) $$

where the $m$ is an integer.

Starting from equation (2) and considering that $n_{\text{eff}}^{\text{core}}$ almost keeps constant when the RI of the surrounding environment changes, the theoretical sensitivity of the structure can be given by

$$ S_{\text{th}} = d\lambda_{\text{dip}}/dn_{\text{en}} = -2Ld(n_{\text{eff}}^{\text{core}})/dn_{\text{en}}/(2m + 1) $$

where $n_{\text{en}}$ is the RI of the surrounding environment. It can be seen that $\lambda_{\text{dip}}$ shifts to a shorter wavelength with the increasing of $n_{\text{en}}$. According to equations (2) and (3), both the sensitivity of the sensor and the resonant wavelength increase linearly with the increasing of bending length. Since the bent structure with larger bending radius has longer length, it can be concluded that sensitivity of the sensor that has a larger bending radius is higher.

3. Experiment results and discussions

To verify the theoretical predictions, in experiment, the semicircular bent structures with different bending radius $R$ were fabricated, and their responses to the changing of $n_{\text{en}}$ of the surrounding environment were also tested. The schematic of the fabrication of the semicircular bent fiber structure is shown in figure 2(a). The bent structure was fabricated on a standard telecommunication single-mode fiber (Corning SMF-28e), by flame-heated treatment. It should be emphasized that before the heating, the jacket surrounding the bare fiber with a length of 5 mm should be totally stripped. During the heating process, one end of the bare fiber was bent around a solid cylinder with a diameter of 400 $\mu$m at an angle of 180° while the other end was fixed on a stage. At the same time, the transmission spectrum of the SMF was monitored by an optical spectrum analyzer (OSA) with a broadband light source (BBS) with a wavelength window from 1500 to 1600 nm used as the input light source. By adjusting the heating time and the heating length of the fiber, the bent radius can be controlled. Figure 2(b) shows the steps of the fabrication of the semicircular bent fiber structure. The optical microscopic image of the semicircular bent fiber structure is shown in figure 2(c).

Glycerol aqueous solutions with different RIs were used to test the $n_{\text{en}}$ response of the fabricated structure. Six volume ratios of pure water and pure glycerol, 100:0, 99:1, 98:2, 97:3, 96:4, and 95:5, were chosen in preparing the solutions. The volume of water and glycerol were well controlled by using a syringe. The RIs of the solutions $n_{\text{en}}$ can be calculated according to Gladstone-Dale relation [15]

$$ n - 1 = \phi_1(n_1 - 1) + \phi_2(n_2 - 1) $$

where $\phi_1$ and $\phi_2$ are the volume fractions of the water and glycerol, $n_1 = 1.3324$ and $n_2 = 1.4715$ are refractive indices of water and glycerol at 589 nm at room temperature of 25°C. The calculated RIs are
1.3324, 1.3338, 1.3352, 1.3366, 1.3380, and 1.3394, respectively. Figure 3 shows the transmission spectra of the bent structure with $R = 480 \, \mu m$ that immersed into the six different solutions. The recorded transmission spectra were obtained by subtracting the spectrum of the light source from the transmission spectra of the bent fiber. It should be noted that before each measurement, the structure was cleaned by using alcohol to remove the residual glycerol solution.

As shown in figure 3, when the bent structure is immersed in pure water, $\lambda_{\text{dip}}$ is observed to be 1551.2 nm for the light window used in the experiment. The depth of the dip decreases with the increasing of $n_{\text{en}}$, which can be explained that more lights will be leaked to the outside of the fiber when $n_{\text{en}}$ increases. When the RI of the solution is larger than 1.3394, the transmission depth becomes less than 4.5 dB, which is not large enough for wavelength shift measurement. Therefore, the measurable RI range of the device is from 1.3324 to 1.3394. The relationship between the resonant dip wavelength $\lambda_{\text{dip}}$ and the RI of the solution $n_{\text{en}}$ is plotted in figure 4(a). It can be seen that $\lambda_{\text{dip}}$ decreases linearly from 1551.2 to 1544.8 nm when $n_{\text{en}}$ increases from 1.3324 to 1.3394, so the experimental sensitivity $S$ of the device is 914 nm/RIU. Figure 4(b) shows the relationship between the resonant dip wavelength $\lambda_{\text{dip}}$ and $n_{\text{en}}$ for the structure with $R = 500 \, \mu m$. For the bent structure with a bending radius of 1000 $\mu m$ or higher, the sensitivity obtained in the experiment is almost zero. The reason can be explained that, for a bent structure with larger bending radius, the cladding mode is harder to be affected by the surrounding environment. Figure 5 plot the relationship between the sensitivity $S$ and the bending radius $R$ and the relationship between the resonant dip $\lambda_{\text{dip}}$ wavelength and the bending radius $R$. The resonant dip wavelength $\lambda_{\text{dip}}$ is observed to be at 1522 and 1560 nm for the bent structure with $R = 420$ and 500 $\mu m$, the corresponding sensitivity $S$ are 603 and 1031 nm/RIU, and the measurable RI range are 1.3324–1.3407 and

![Figure 2](image1.png)

**Figure 2.** (a) Schematic of the fabrication of the semicircular bent fiber structure. (b) Steps of the fabrication of the semicircular bent fiber structure. (c) Optical microscopic image of the fabricated bent fiber structure with a bending radius and angle of 480 $\mu m$ and 180°, respectively.

![Figure 3](image2.png)

**Figure 3.** Transmission spectra of the sharply bent fiber with $R = 480 \, \mu m$ that immersed into glycerol solutions with different volume ratios.
1.3324–1.3435, respectively. It can be seen that the sensitivity \( S \) of the sensor and the resonant dip \( \lambda_{\text{dip}} \) both linearly increase with the increasing of the bending radius \( R \).

4. Conclusion

In summary, a fiber sensor based on a semicircular bent fiber has been demonstrated. In the bending region, part of the core mode is coupled to the cladding mode. After leaving the region, the cladding mode will be coupled back to the core mode. Because the ERI of the core mode and the cladding mode are different, interference will be formed at the output end of the fiber. Both the theoretical and experimental results show that the resonant dip wavelength and the sensitivity of the bent structure to the RI of the surrounding environment increase linearly with the increasing of the bending radius of the structure, and the resonant dip wavelength shows a blue shift as the increasing of the RI of the surrounding environment. According to the experiment, a sensitivity as high as 1031 nm/RIU was obtained for the bent structure with bending radius of 500 \( \mu \text{m} \) for the RI of the surrounding environment in a range of 1.3324 to 1.3435.

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Figure 4. The relationship between the resonant dip wavelength \( \lambda_{\text{dip}} \) and the RI of the solution \( n_{\text{en}} \) for the bent structure with (a) \( R = 480 \mu \text{m} \) and (b) \( R = 500 \mu \text{m} \). The points represent the experimental results and the red solid lines are linear fitting.

Figure 5. The sensitivity \( S \) and the resonant dip wavelength \( \lambda_{\text{dip}} \) versus the bending radius \( R \).
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