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Fiber cladding SPR bending sensor characterized by two parameters*

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A fiber cladding surface plasmon resonance (SPR) bending sensor is realized by the cladding of the fiber structure. By employing coating film, the sensing zone is protected and the toughness of the sensor increases. Three different sensing probes are tested, the experiment results indicate that the two parameters (wavelength sensitivity and light intensity sensitivity) sensing performances of the eccentric butt joint structures are superior to that of hetero-core structure, and the SPR bending sensor based on hetero-core structure is stable and uneasy to damage. By employing hetero-core fiber and silver film, a fiber cladding SPR bending sensor with better stabilization and sensing performance is realized. The proposed fabricating method of sensing probe with coating film provides a new approach for fiber SPR-distributed bending sensor.

Keywords: surface plasmon resonance (SPR), bending sensor, eccentric butt joint, hetero-core fiber

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1. Introduction

Optical fiber sensing technology employs the external signal to modulate characteristic parameters of transmission optical wave in the fiber, then the modulated light wave signal is detected and demodulated to sense the external signal.[1] Optical fiber sensor is widely used in civil engineering, spacecraft and ship, geodynamics, medicine, power industry, military monitoring, intelligent structure, and other fields because of its advantages of flexibility, multiplexing, and remote sensing operation.[2–7] Generally, the fiber sensors can be broadly divided into three major categories, the fiber sensor based on interference principle,[2] the fiber sensor based on fiber grating,[3,4] and the fiber sensor based on optical fiber microstructure operation.[5–7] Fiber SPR sensor is a relatively simple fiber sensor based on microstructure operation. As a research hotspot in recent years, fiber SPR sensor has been proved to be applicable to food safety, biomedical detection, chemical analysis, and other fields.[8–10]

Surface plasmon resonance (SPR) is essentially the collective resonance of the evanescent wave generated by the incident light wave and the plasma wave on the surface of the medium under specified conditions. A sharp valley (peak) can be observed in the output spectrum because of the decreasing of light power due to the coupling of the surface plasma wave and the light at certain wavelength. Generally, fiber SPR sensor uses fiber as the basal layer, metal film as the sensing layer, and test media as the covering layer to realize the Kretschmann structure. In order to satisfy the resonance condition, the incident light needs to be exposed to the interface between the metal film and the substrate. Because of the special transmission structure, the light beam is bound in the fiber core. Thus, in order to construct the fiber SPR sensing structure, special operation needs to be taken to expose the fiber core to contact with the metal film. The common methods include corrosion,[11] grinding,[12] fused biconical taper,[13] *etc*., which have the complex operation. And bending is one of the methods to expose the transmission beam for fiber. After bending, the cladding mode is excited or changed, and the sensing film can be directly coated on the outside of the cladding, so the structure is simple and the operation is relatively convenient. Therefore, the optical fiber SPR sensor based on the characteristics of bent optical fiber has been proved to be applicable to the sensing of various parameters, especially the curvature sensor.[14,15] Wang employed a macrobending single mode fiber to test the low refractive index solution,[16] Jing employed a side-polished macrobend plastic optical fiber to realize the refractive index sensing[17] and Christopher employed a u-bent plastic optical fiber to realize the SPR- and LSPR-based compact plasmonic sensors.[18] However, they all bend the fiber to a fixed shape, the specific

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research about fiber SPR curvature sensor is very scarce, and mostly of reported research are based on bending loss.

Based on the above analysis, we study the performance of three different fiber cladding SPR bending sensors, and perform the two-parameter sensing. By analyzing the transmission spectrum of three sensor probes, comparing their maximum wavelength sensitivity, maximum peak sensitivity, and variation trend of half height and width (FWHM), the characteristic of each sensor is obtained. The proposed sensing probe fabrication method of covering with coating film provides a new research direction for distributed curvature sensing of fiber SPR.

2. Sensing structure and principle

In order to obtain the cladding mode of optical fiber, we choose three structures for analysis. By Rsoft, we simulate the optical field distribution of three different structures in straight and bending as shown in Fig. 1, and light injection method is shown in the insets. In Figs. 1(a) and 1(b), we employ the single mode fiber eccentric spliced with the single mode sensing probe to inject light. In straight transmission, the cladding mode is excited first, and the core mode is excited in the transmission process, the light intensity of the fiber cladding is greater than that of the fiber core. However, when the probe is bent, the cladding mode is excited and propagating along the cladding until it passes over the maximum curvature, the core mode is excited. At the maximum curvature, the cladding light intensity is inclined to one side. The similar calculation results of the graded index multimode fiber sensing probe eccentric spliced with single mode fiber are shown in Figs. 1(c) and 1(d). Figures 1(e) and 1(f) are the light field distribution diagrams of heterogeneous core structure sensing probe which consists of two sections of multimode fibers and a section of single mode fiber. The cladding mode of the sensing probe changes after bending, and the cladding light intensity at the maximum bending curvature is mainly concentrated on one side, and the light intensity of the fiber core is greater than that of fiber cladding during the whole transmission process.

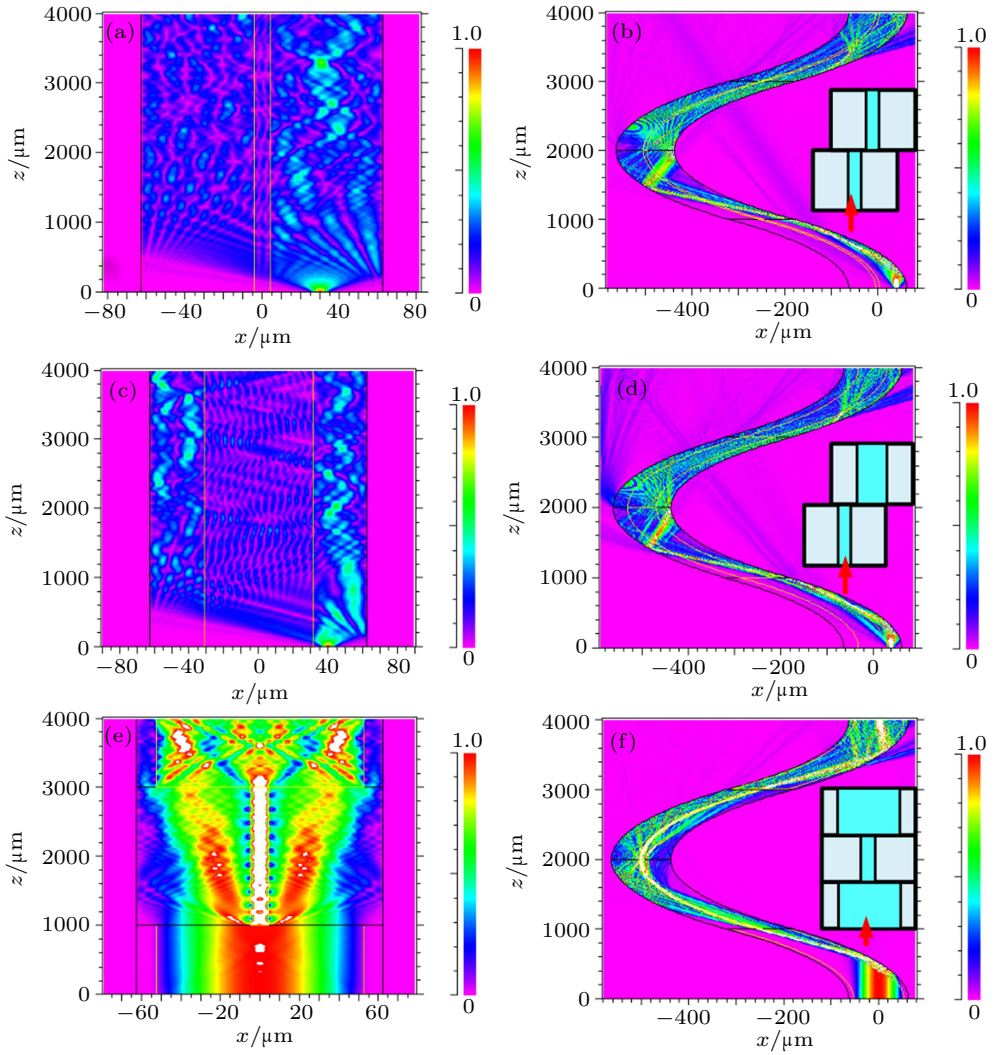


Fig. 1. Beam propagation method simulation results for the proposed (a) straight single mode sensing probe, (b) bending single mode sensing probe, (c) straight multimode sensing probe, (d) bending multimode sensing probe, (e) straight heterogeneous core sensing probe, (f) bending heterogeneous core sensing probe.

According to the theoretical analysis mentioned above, we employ three sensing structures to fabricate three different sensing probes respectively, and it is only necessary to coat the sensing film on one side of the bent fiber as shown in Fig. 2. A 50-nm gold film is coated on the outer side of the fiber cladding, and a coating film with refractive index of 1.34 is coated on the whole sensing zone to provide the sensing refractive index environment for the sensing probe and protect the sensing probe. According to Figs. 2(a) and 2(b), after the bending, the light propagating in fiber cladding is strengthened, and the evanescent field at the interface between the cladding and the gold film is also strengthened. When the evanescent wave and the surface plasma wave of the gold film transmit at the same frequency, the surface plasma resonance phenomenon occurs. We employ the step multimode fiber with the core diameter of 110 μm to receive the light, an obvious resonance peak which can change with the bending curvature of the sensor probe is observed in the output spectrum. For the heterogeneous core structure, the pre-existing cladding mode is strengthened after bending, we employ the cladding mode to stimulate SPR phenomenon at the interface between the cladding and the sensing film as shown in Fig. 2(c).

Based on the analysis above, the cladding modes of different fiber structures are different, which affects the final SPR resonance spectrum. Therefore, we choose several optical fiber structures for comparative test. The experimental setup is shown in Fig. 3. A light source (HL-1000, Ocean optics) is launched into the sensing probe, and the transmitted beam is received by an optical spectrum analyzer (USB2000+) waiting for follow-up data processing. The sensor probe is fixed by clamps, and the distance D between the two clamps is 30 mm. By employing a micrometer screw, the sensing probe deviates from the center position, and the deviation distance d changes from 1 mm to 7 mm. By the formula $\rho = 8d/(D^2+4d^2)$, the curvature is obtained.

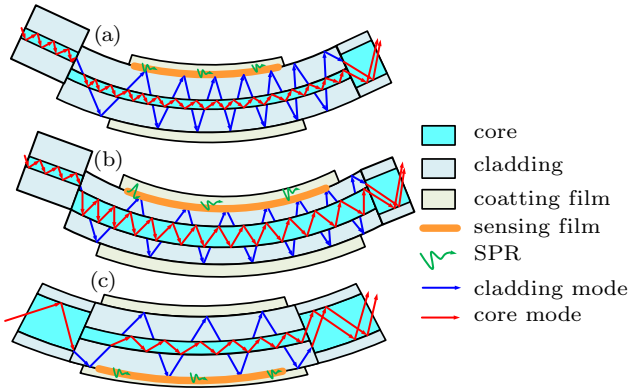


Fig. 2. Schematics of sensing probe fabricated with (a) single mode fiber, (b) graded index multimode fiber, (c) hetero core fiber.

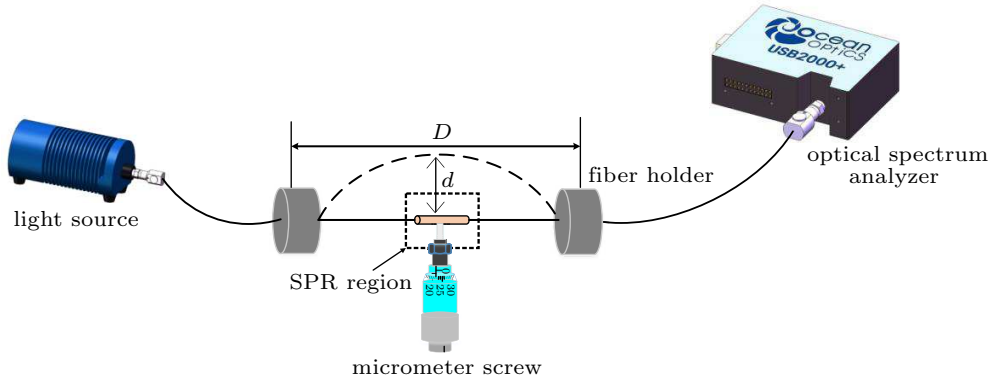


Fig. 3. The experiment setup sketch diagram of the fiber cladding SPR bending sensor.

3. Results and discussion

We perform the comparison test of the three sensing probes. The deviation distance changes from 1 mm to 7 mm, and the curvature is 8.85, 17.467, 25.641, 33.195, 40, 45.977, and 51.095 respectively. The testing results are shown in Fig. 4, where figures 4(a), 4(c), and 4(e) are the transmission spectra of three more clearly, we normalize the testing results and align the resonance peaks to get the calculation results as shown in Figs. 4(b), 4(d), and 4(f). It can be seen from the figure that with the increases of the curvature, the SPR resonance light intensity increases, and the resonance peaks move to the long wavelength direction. In addition, the FWHM of the resonance peaks also change with the curvature of the sensor probe.

We take the curvature as abscissa and resonance wavelength as ordinate, and make appropriate polynomial fitting according to the data trend to get the calculation results as shown in Figs. 5(a), 5(c), and 5(e), respectively. It can be seen from the figure that with the increases of bending curvature, the SPR resonance peaks of the three sensing probes move to the long wavelength direction, and the average wavelength sensitivities are 0.2908 nm/m^{-1}, 0.3243 nm/m^{-1}, and 0.2163 nm/m^{-1}, respectively. The wavelength resolution of the spectrometer we used is 1.5 nm, hence we calculate the resolution of the sensing probes are 5.16 m^{-1}, 4.63 m^{-1}, and 6.93 m^{-1}, respectively.

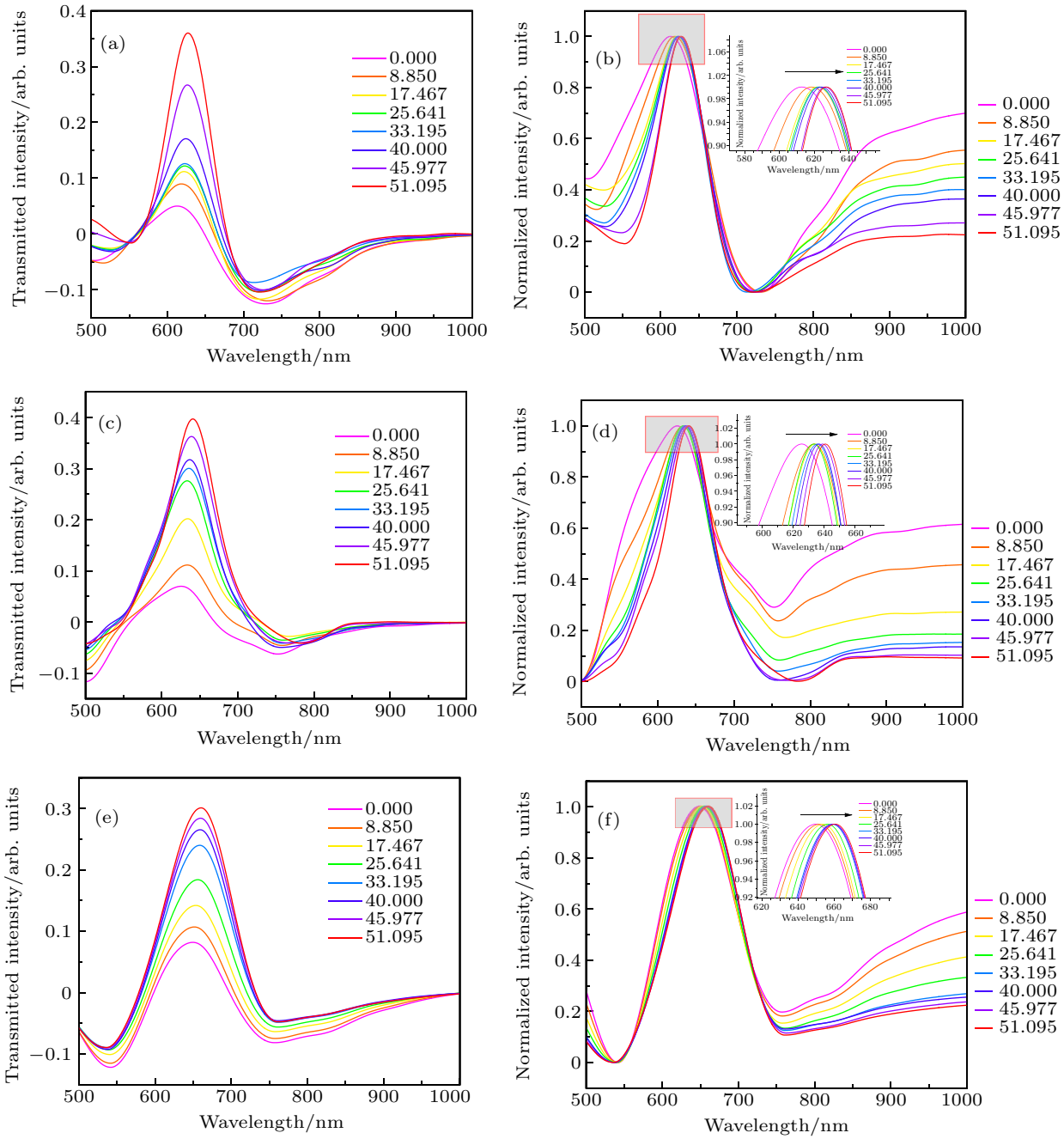


Fig. 4. The transmission spectrum of fiber SPR bending sensor (a) the sensing area is single-mode optical fiber, (b) the normalization results of panel (a), (c) the sensing area is graded index multimode fiber, (d) the normalization results of panel (c), (e) the sensing area is heterogeneous core fiber, (f) the normalization results of panel (e).

Similarly, the curvature is taken as abscissa, and the resonance peak value is taken as ordinate, the polynomial fitting is carried out to obtain the calculation results as shown in Figs. 5(b), 5(d), and 5(f). With the increases of the bending curvature, the resonance light intensities of the three sensors increase, and the average light intensity sensitivities are 0.006 a.u./m^{-1}, 0.0064 a.u./m^{-1}, and 0.0043 a.u./m^{-1}, respectively.

According to the above experimental results, the wavelength sensitivity, the light intensity sensitivity and resolution of the eccentric spliced sensing probes are better than those of the heterogeneous core sensing probe. While the FWHM of the graded index multimode sensing probe is smaller than that of the heterogeneous core structure, and the variation range is small and basically stable. However, the eccentric spliced sensing structure is easy to be damaged which has a relatively poor practical value. The hetero core structure is stable and easy to package because of its connecting mode of coaxial butting.

In order to obtain the sensor with good performance and stable structure, we try to improve the hetero core sensing probe. In the selection of metal sensing film, due to the largest ratio of the real part to the virtual part of the dielectric constant, silver has the strongest local electric field enhancement effect in theory.[19] Therefore, we choose silver film instead of gold film as the sensing film, and the experimental results are

shown in Fig. 7, where figure 7(a) is the transmission spectrum and figure 7(b) is normalized results of Fig. 7(a). It can be seen from the figure that as the bending curvature increases, the resonance wavelength moves to the long wavelength direction, and the resonance intensity increases with it.

In addition, the full width at half maximum (FWHM) of the resonance peak is also a very important parameter. Take the curvature as the abscissa and FWHM as the ordinate, and make a polynomial fitting for them to get the calculation results as shown in Fig. 6.

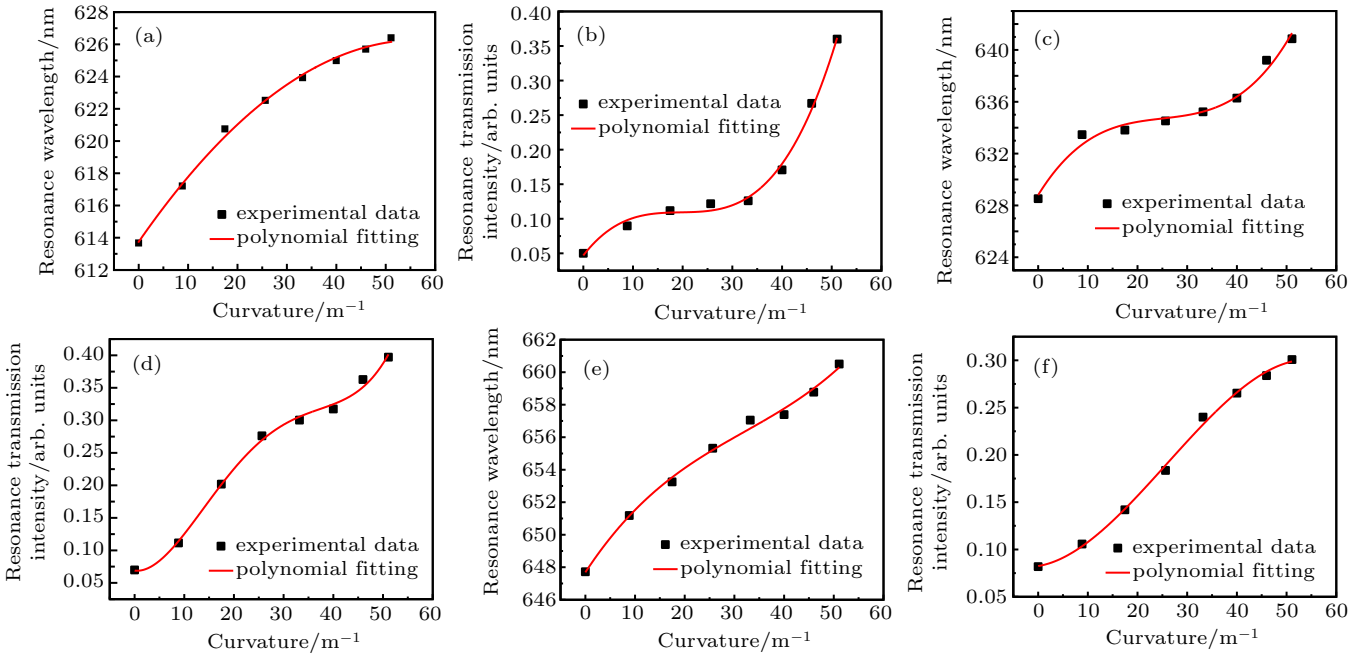


Fig. 5. The relationship between the bending curvature and resonance wavelength with the sensing zone of (a) single mode fiber, (c) graded index multimode fiber, (e) heterogeneous core fiber. The relationship between the bending curvature and resonance intensity with the sensing zone of (b) single mode fiber, (d) graded index multimode fiber, (f) heterogeneous core fiber.

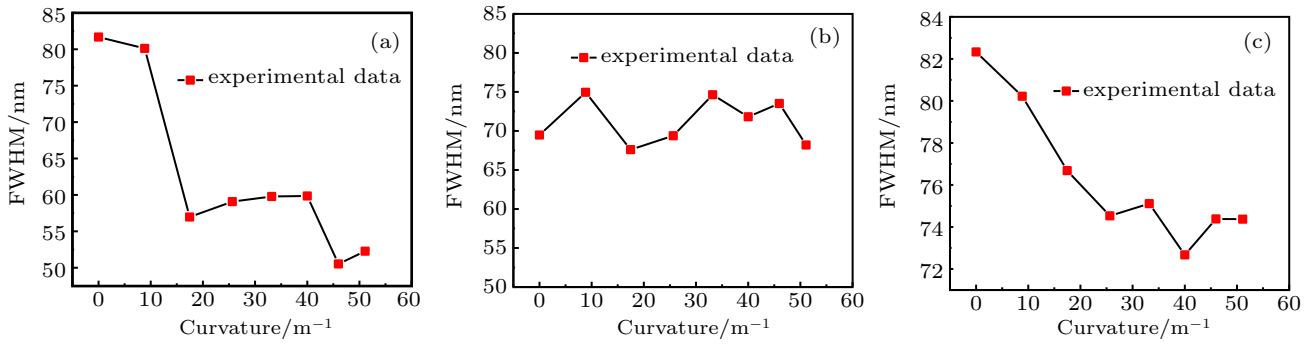


Fig. 6. The relationship between bending curvature and FWHM with the sensing zone of (a) single mode fiber, (b) graded index multimode fiber, (c) heterogeneous core fiber.

We take the bending curvature as the abscissa, the resonance wavelength, the resonance light intensity and the FWHM of the resonance peak as the ordinate respectively, and employ the appropriate fitting method to get the calculation results as shown in Fig. 8. It can be seen from the figure that with the increases of the bending curvature, the resonance wavelength, the resonance intensity and FWHM of the resonance peak all increase. The average wavelength sensitivity is 0.5736 nm/m^{-1}, and the resolution is 2.62 m^{-1}. The resonance light intensity is linear with the bending curvature, its average sensitivity is 0.00596 a.u./m^{-1}. The FWHM of the resonant peak increases with the curvature, which can also be used as a sensing parameter.

In terms of the above results, when the probe is bent with different curvatures, the SPR incident angle changes. Liu and Wei employed single mode fiber to investigate the relationship between grinding angle (SPR incident angle) of the fiber taper and resonance wavelength in 2015.[20] They proposed that with the decreased of the incident angle of SPR, the working range of SPR resonance wavelength moved to long wavelength. When the sensing probe is fabricated with different fibers, the transmission property of the optical fiber is different, hence the sensitivity has differences. According to the testing results, the two-parameter performances of sin-

gle mode sensing probe and graded index multimode sensing probe are better than that of hetero core sensing probe, but their structures are unstable and easy to damage because of the fabricate method of eccentric spliced. And the hetero core sensing probe is stable and easy to package. By employing silver film instead of gold film, the two-parameter performance of hetero core sensing probe is improved, and FWHM of the resonant peak increases with the curvature, which can also be used as a sensing parameter. In addition, we employ the coating film to provide sensing refractive index environment, except protecting the sensing probe from mechanical damage, it also prevents the oxidation of the sensing film. It is possible to choose the coating film with different refractive index to realize distributed fiber SPR curvature sensor.

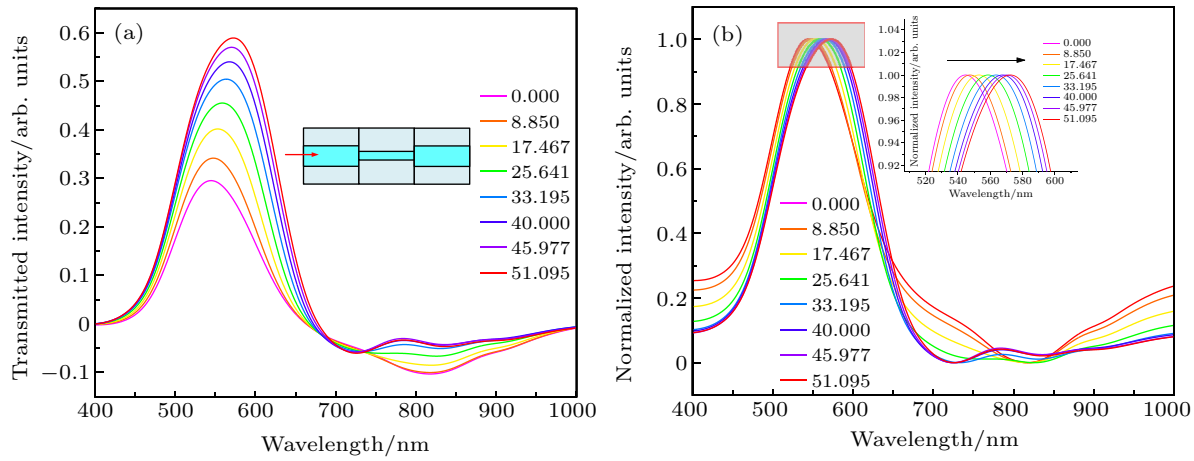


Fig. 7. (a) The transmission spectrum of SPR bending sensing probe based on hetero core fiber coating with silver film, (b) normalized results of panel (a).

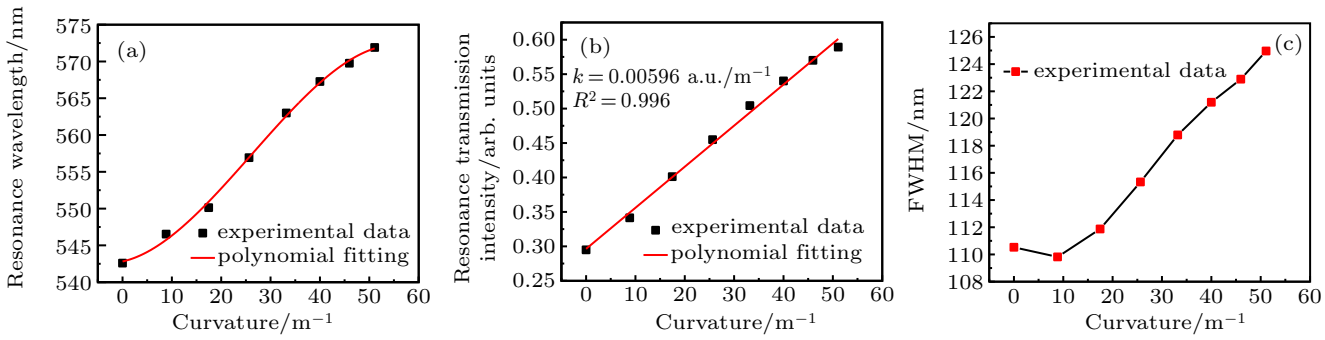


Fig. 8. The relationship between (a) bending curvature and resonance wavelength, (b) bending curvature and resonance light intensity, (c) bending curvature and FWHM of the proposed probe based on hetero core fiber coating with silver film.

4. Conclusions

In this paper, the optical fiber cladding is used as the sensing interface, the metal film is coated on the surface of the fiber cladding, and the coating film with refractive index of 1.34 is coated on the outside of the sensing zone to protect the sensing zone. By a micrometer screw, the bending curvature is changed. We employ single mode eccentric spliced structure, multimode eccentric spliced structure, and hetero core structure to fabricate the sensing probes and perform the two-parameter testing respectively. The testing results indicate that the single mode sensing probe and graded index multimode sensing probe have better two-parameter performances (wavelength sensitivity and light intensity sensitivity) than hetero core sensing probe, and the hetero core sensing probe has a more stable structure and easy to package. By testing the hetero core sensing probe with the silver film, the maximum wavelength sensitivity and average intensity sensitivity is 0.7612 nm/m^{-1} and 0.00596 a.u./m^{-1}, and its FWHM increases with the curvature, which can also be used as a sensing parameter. The proposed research method of fiber cladding SPR bending sensor characterized by two parameters provides a new direction for the research of distributed SPR bending sensor.

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