Improving the sensitivity of fiber-optic SPR sensor via radially polarized beam excitation

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We study the sensing properties of an intensity-modulated fiber-optic surface plasmon resonance (SPR) sensor using radially polarized beam (RPB). Because of the rotational symmetry of fiber and RPB, surface plasmon can be excited more efficiently at the sensor surface, which results in an obvious improvement of the sensitivity. Our experiments demonstrate that the sensitivity in the case of RPB illumination is three times higher than that of linearly polarized beam illumination.

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Since the surface plasmon resonance (SPR) technology was firstly used for sensing[1], SPR sensing has been studied intensively because of its unique advantages such as high accuracy, quick analysis, and no need for labeling. SPR sensors are normally made by bulky couplers, for example, in some well-known prism configurations[2−4]. Recently, fiber-optic SPR sensor has been studied because it has some particular advantages such as flexibility, low cost, small size, and possibility in remote sensing. In 1990, the first fiber-optic SPR sensor was reported by Villuendas *et al.*[5]. After that, various fiber-optic SPR sensors have been developed, such as SPR sensing on the tip of a single-mode fiber (SMF)[6], multi-mode SPR fiber-optic sensor using white light source[7], side polished SMF SPR sensor[8], uniform waist single-mode tapered fiber SPR sensor[9], and fiber-optic SPR conical microsensor[10]. Because the configuration characteristics of fiber, the depth of SPR dip is shallow.

Considering the rotational symmetry of fiber, the fiber-optic SPR will be excited more efficiently by using a symmetric configuration of radially polarized beam. Unlike conventional polarization, radially polarized beam is the light with polarizations ordered on the optical axis. In the past decades, radially polarized beam has been obtained by many methods like interferometric systems[11], computer generated holograms[12], space variant liquid crystal cell[13], radial analyzer with a spiral phase element[14], and few-mode optical fiber method[15].

In this letter, we study the sensing properties of fiber-optic SPR sensor using radially polarized beam. A fiber-optic sensor based on SPR is fabricated by depositing silver on the silica core of fiber after removing the cladding. The radially polarized beam, which is obtained by selecting the TM_{01} mode from a few-mode optical fiber, is injected into the sensing fiber with index matching liquid. The transmitted light intensity of fiber optic sensor changes with the different refractive indices of analytes. Comparing the result with that obtained by using linear polarized beam, we find that the fiber-optic SPR with radially polarized beam has higher sensitivity.

The fiber-optic sensor uses a multi-mode fiber, which consists of a silica core (refractive index n_c=1.457), surrounded by a polymer cladding and Tefzel jacket. The diameter of silica core is D=200 μm and the numerical aperture NA = 0.36. The configuration of sensing multi-mode fiber is shown in Fig. 1. We took off the Tefzel jacket and immersed the multi-mode optical fiber into acetone solution for several minutes. Then the softened polymer cladding was removed with blade. The length of the exposed core was L = 10 mm. Then silver film was deposited on the bare core region by vacuum thermal evaporation. In the vacuum thermal evaporation process, we kept the fiber rotating. So the thickness of silver film around the fiber was uniform with a thickness of about 50 nm.

The radially polarized beam was obtained from a few-mode optical fiber based on mode selection. The few-mode optical fiber with a cutoff wavelength (for the fundamental mode) of 780 nm was used. The fundamental mode and the three annular modes will be transmitted under the working wavelength of 532.8 nm. The three annular modes were TM_{01} mode with radial polarization, TE_{01} mode with azimuthal polarization, and HE_{21} mode with hybrid polarization. The setup is shown in Fig. 2(a). The light from a 532.8-nm semiconductor laser with linear polarization was focused by a 10× objective and injected into the few-mode fiber. The length of the fiber was about 2 m. When the fiber was placed on the focus

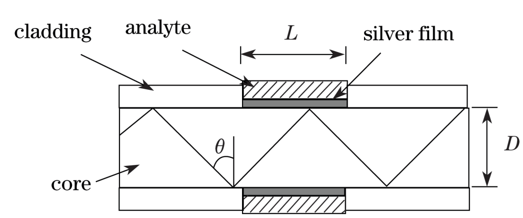

Fig. 1. Configuration of sensing multi-mode fiber.

of objective, the fundamental mode could be visualized. TM_{01} mode or other modes could be selected by shifting

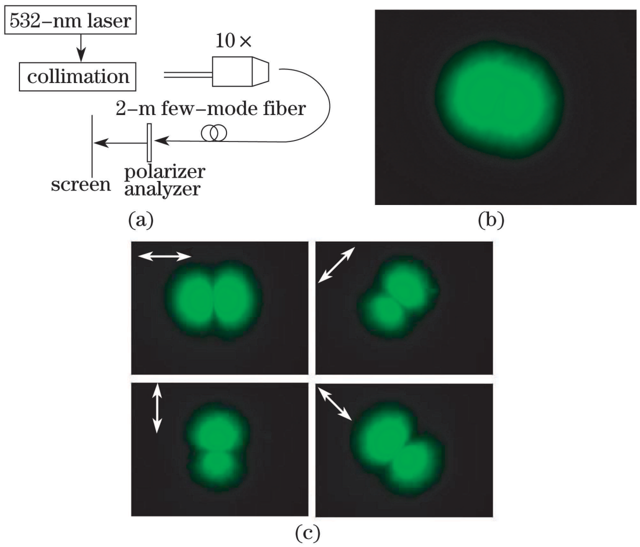

Fig. 2. (a) Setup of generating radially polarized beam; (b) field intensity distribution of radially polarized beam; (c) intensity distributions after crossing different polarizers with the axes oriented along the arrows.

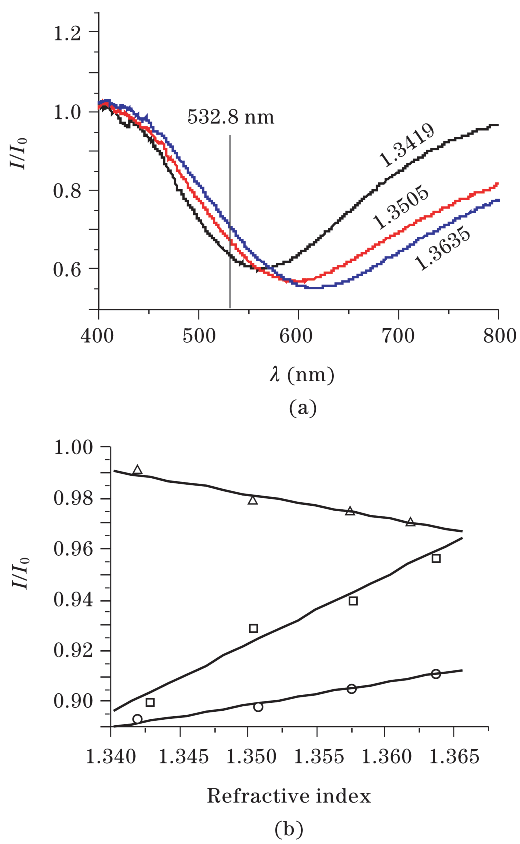

Fig. 3. (a) Transmission SPR spectrum passing through the sensing fiber for different analytes with the refractive indices of 1.3419, 1.3505, and 1.3635; (b) normalized transmitted light intensity versus refractive index, triangles are the results on bare multi-mode fiber, circles are the results on silver coated multi-mode fiber with linearly polarized beam, and squares are the results on silver coated multi-mode fiber with radially polarized beam.

the few-mode fiber in the incident beam direction or in the perpendicular direction to filter the unwanted modes. The field intensity distribution of the radially polarized beam is shown in Fig. 2(b). And the intensity distribution after crossing a polarizer is shown in Fig. 2(c). The result indicates the generation of radially polarized beam.

The sensing multi-mode fiber was mounted on a V-shaped groove. And the few-mode fiber was precisely controlled to inject the radially or linearly polarized beam into the sensing multi-mode fiber with index matching liquid. The output light intensity at the end surface of sensing fiber was measured by an optical power meter.

To test the capability of sensing, different analytes with the refractive indices ranging from 1.3419 to 1.3635 were used. The experimental results are shown in Fig. 3. The transmission SPR spectra passing through the sensing fiber are shown in Fig. 3(a). The SPR wavelength red-shifts with the increase of refractive index. Figure 3(b) shows the change of light intensity at 532.8 nm passing through the sensing fiber. The three lines are both normalized by the intensity without analyte, respectively. The triangles are the results of light intensity changing with different analytes on a bare multi-mode fiber. The light intensity decreases as the refractive index increases because of the leakage loss. The circles and squares are the experimental results using linearly and radially polarized beams, respectively. The light intensity increases when the refractive index increases. The working wavelength of 532.8 nm is at the left side of SPR peak with the analyte. Because of the red-shift of the resonant peak, the transmitted light intensity increases with the increase of refractive index of the analyte. As the rotational symmetry of sensing multi-mode fiber, a SPR excitation efficiency of about 2.997 times higher than that of linearly polarized beam is obtained by using the rotational symmetry light of radially polarized beam.

The experimental results can be analyzed by three-layer sensing system[16] with the configuration shown in Fig. 1. The three layers are silica core, silver film, and analyte, respectively. The normalized transmitted power of the fiber with white light source can be expressed as

$$T = \frac{\int_{\theta_{\rm cr}}^{\pi/2} R^N \cdot P(\theta)\,{\rm d}\theta}{2\int_{\theta_{\rm cr}}^{\pi/2} P(\theta)\,{\rm d}\theta}, \qquad (1)$$

where $R = \left|\dfrac{r_{21} + r_{10}\exp(-2a_1 d)}{1 + r_{10}r_{21}\exp(-2a_1 d)}\right|^2$ is the reflection coefficient for TM polarized light in meridian plane with $r_{21} = \dfrac{\varepsilon_1 a_c - \varepsilon_c a_1}{\varepsilon_1 a_c + \varepsilon_c a_1}$ and $r_{10} = \dfrac{\varepsilon_1 a_2 - \varepsilon_2 a_1}{\varepsilon_1 a_2 + \varepsilon_2 a_1}$ being the reflection coefficients of fiber core to silver film and silver film to analyte, respectively; d is the thickness of silver film; $\varepsilon_{\rm c}$, ε_1, and ε_2 are the permittivities of fiber core, silver, and analyte; $a_{\rm c}$, a_1, and a_2 are the propagation constants in fiber core, silver film, and analyte, respectively; $N = \frac{L}{D\tan\theta}$ is the number of light reflections with incident angle of θ and silica core diameter of D; $P(\theta) \propto \frac{n_{\rm c}^2 \sin\theta\cos\theta}{(1-n_{\rm c}^2\cos^2\theta)^2}$ is the modal power for a corresponding incident angle of θ, and $n_{\rm c}$ is the refractive index of fiber core; $\theta_{\rm cr}$ is the critical angle of reflection in few-mode fiber whose numerical aperture NA=0.13.

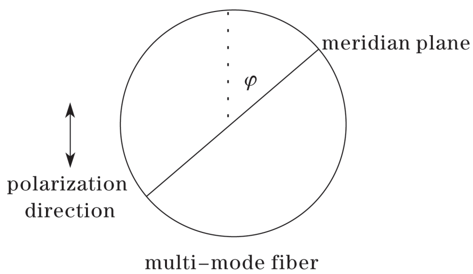

Fig. 4. Geometry configuration in multi-mode fiber.

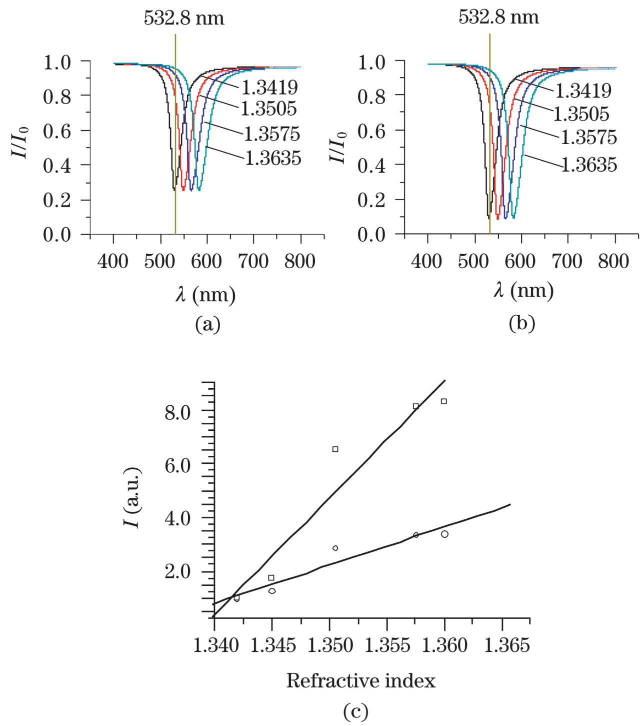

Fig. 5. Calculated results. (a) Transmission SPR spectrum passing through the sensing fiber with linearly polarized beam; (b) transmission SPR spectrum with radially polarized beam; (c) change of light intensity at 532.8 nm, circles are the results on silver coated multi-mode fiber with linearly polarized beam, and squares are the results with radially polarized beam.

In plane bulk system, only TM polarized light can lead to SPR excitation. In our case, we assume that the light from the few-mode fiber is injected into the sensing fiber at the center position and most light is transmitted in meridian plane. For linearly polarized beam, the effective light intensity to the SPR excitation can be described as

$$I_{\mathrm{eff},L} = \frac{1}{2\pi}\int_0^{2\pi} I\cos^2(\varphi)\mathrm{d}\varphi = \alpha I, \qquad (2)$$

where I is the light intensity, φ is the angle between the polarization direction and a meridian plane (as shown in Fig. 4), and α is the proportion of the p-polariztion at the fiber surface in the case of linearly polarized beam illumination. If the light is radially polarized, all the light at the fiber surface can be regarded as p-polarized, that is, α=1. The remaining light intensity is regarded as a direct current (DC) component of the transmitted light power. The normalized transmitted power should be rewritten as

$$T = \frac{\alpha\int_{\theta_{\mathrm{cr}}}^{\pi/2} R^N \cdot P(\theta)\,\mathrm{d}\theta + (1-\alpha)\int_{\theta_{\mathrm{cr}}}^{\pi/2} P(\theta)\,\mathrm{d}\theta}{\int_{\theta_{\mathrm{cr}}}^{\pi/2} P(\theta)\,\mathrm{d}\theta}. \qquad (3)$$

Figures 5(a) and (b) show the calculated transmission SPR spectra passing through the sensing fiber with linearly polarized beam (with Eq. (1)) and radially polarized beam (with Eq. (3)), respectively. The SPR wavelength red-shifts with the increase of refractive index. Figure 5(c) shows the calculated capability of sensing under the intensity modulation at 532.8 nm. The sensitivity of using radially polarized beam is 3.056 times higher than that of using linearly polarized beam. The calculation result is similar to the experimental result of 2.997 times improvement.

In conclusion, we study the sensing properties of fiber-optic SPR sensor using radially polarized beams. Because of the rotational symmetry of sensing fiber, radially polarized beams have high efficiency to excite surface plasmon and exhibit high sensitivity. Both the experiment and simulation results show that the sensitivity of radially polarized beams is about three times higher than that of linearly polarized beam. This work shows the advantages of radially polarized beam to excite SPR in axisymmetric systems.

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