All-optical sensor based on surface plasmon polaritons in multi-layers metal-dielectric structure

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We study all-optical sensing characteristics based on long-range surface plasmon resonance in a four-layered metal-dielectric structure immersed in the liquid to be measured. The resonance peaks in the reflection angle spectra depend on different refractive indices from 1.30 to 1.38, which are calculated and compared in three typical wavelengths of 532, 632.8 and 780 nm, respectively. Compared with 532 nm, the incident light of 780 nm results in an unstable sensing stability, but the resolution enhances two times. The sensitivity of this refractive index sensor at an incident angle of 45° is about 236.7 nm/RIU which uses 532-nm laser as the light source.

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Surface plasmon resonance (SPR) is a free electron longitudinal wave oscillation, which is obtained by coupling resonance between the incident photons and free electrons of metal at the metal–dielectric interface[1]. With the development of materials technology and nanofabrication technology, SPR has been widely studied in the field of optical biochemical sensors[2], optical microscopy[3], optical measurement[4] and optical memory[5] due to its excellent characteristics, such as high sensitivity, minute structure and high integration[6–8]. The metal film of thickness of nanometers is very sensitive to its surrounding refractive index (RI) changes[9]. Studying the optical-sensing properties of SPR-based multilayered metal-dielectric structure is very important for practical devices[10–12]. In order to obtain a planar metal-dielectric structure without nanoarrays, the prism is needed to compensate the difference between the wave vector of SPR and the wave vector in vacuum[13,14]. The measured liquid is also equivalent to the liquid prism to sense the RI change, resulting in different attenuation total reflectivity (ATR) spectra[15].

In this paper, we will study the RI-sensing properties of a four-layered metal structure immersed in the liquid to be measured. This structure can be used as an RI sensor without relying on a prism or other nanostructures.

Figure 1 illustrates the four-layered metal-dielectric structure immersed in the liquid with the dielectric constant of ε_1, RI of n_1 and the thickness of d_1. These three parameters for the below four layers are $\varepsilon_{2r(i)}$, $n_{2r(i)}$, d_2, ε_3, n_3, d_3, ε_4, n_4, d_4, and ε_5, n_5, d_5, respectively; the incident angle is θ.

The four-layered structure includes the silver film, polymethylmethacrylate (PMMA) film, SiO_2 substrate and surrounding air. The thickness of the liquid and the surrounding air are assumed to be infinite (∞). The dielectric constant $\varepsilon_{2r(i)}$ and the RI $n_{2r(i)}$ for silver are complex, $\varepsilon_2 = -9.73 + 0.82171i$ and $n_2 = 0.12932 + 3.1932i$ at 532 nm.

The complex wave vector at different types of interfaces can be expressed as[16]

$$k_i = \frac{2\pi}{\lambda}\sqrt{n_i^2 - n_1^2 \sin^2\theta}, i = 1,2,3,4,5, \qquad (1)$$

where $n = n_r + in_i$, n_r and n_i are the real component and imaginary component of the complex RI, respectively, which is analyzed in detail for different materials[17] as well as for different wavelengths. For example, silver, both the curves of the real and imaginary components of the complex wave vector as a function of wavelength are shown in Fig. 2.

The real and imaginary components are related with the resonance wavelength and the intensity attenuation factor of the SPR, respectively.

The surface reflectivity of the asymmetric monolayer metal film can be calculated as[18]

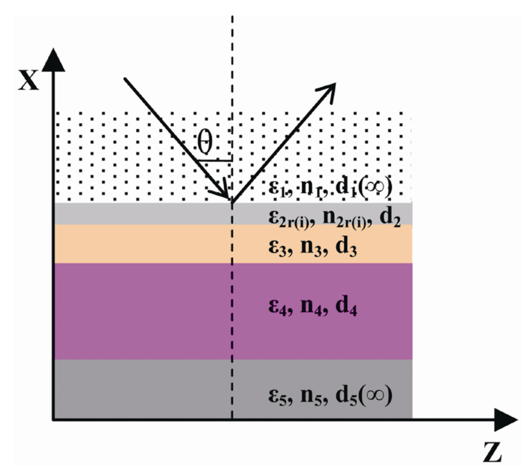

Fig. 1. Illustration of the four-layered metal-dielectric structure.

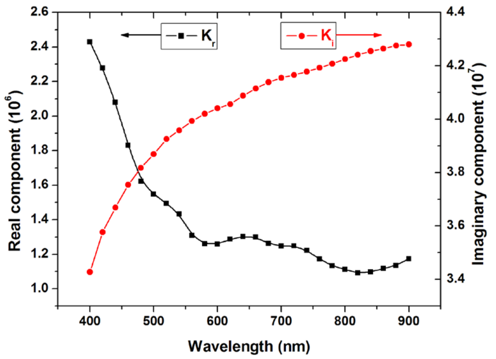

Fig. 2. Real component (black-cube dots) and imaginary component (red-round dots) of wave vector as a function of wavelength.

$$R = \frac{r_{1m} + r_{m2} e^{2i\alpha_m}}{1 + r_{1m} r_{m2} e^{2i\alpha_m}}, \tag{2}$$

where, $\alpha_m = k_m d_m < 0$ (the real part of the dielectric constant for metal $\varepsilon_{mr} < 0$), k_m and d_m are the wave vector and film thickness of the metal, respectively, r_{1m} and r_{m2} are the reflectivity at the interface of metal and dielectric, respectively, which are calculated by Fresnel equation[19]:

$$r_{i(i+1)} = \frac{\varepsilon_i k_{i+1} - \varepsilon_{i+1} k_i}{\varepsilon_i k_{i+1} + \varepsilon_{i+1} k_i}, i = 1,2,3,4. \tag{3}$$

The reflectivity in more complex structure can be obtained in this way, such as the five-layered metal-dielectric structure (including the liquid) as shown in Fig. 1. The total reflectivity is calculated by adding the reflectivity of different layers on the incident plane[20]:

$$R_5 = \frac{r_{12} + R_4 \exp\left(2id_2k_2\right)}{1 + r_{12} R_4 \exp\left(2id_2k_2\right)}, \tag{4}$$

$$R_4 = \frac{r_{23} + R_3 \exp\left(2id_3k_3\right)}{1 + r_{23} R_3 \exp\left(2id_3k_3\right)}, \tag{5}$$

$$R_3 = \frac{r_{34} + r_{45} \exp\left(2id_4k_4\right)}{1 + r_{32} r_{45} \exp\left(2id_4k_4\right)}. \tag{6}$$

Measuring the concentration of NaCl and sucrose solution is very important in the biochemical research. Generally, the RI of NaCl and sucrose solution with different concentrations distributes near 1.35[21,22]. Therefore, only the RI change from 1.30 to 1.38 is analyzed in this paper.

Here, we have calculated the ATR spectra by changing the RI of the liquid from 1.30 to 1.38 at three wavelengths (532, 632.8 and 780 nm), as shown in Fig. 3.

Figure 3(a) shows that the RI responses at 532 and 632.8 nm have a more excellent linear stability. It can be observed from Fig. 3(b) that the half widths of the resonance peak of 532 nm, 632.8 nm and 780 nm are 2.39 nm, 1.75 nm and 1.20 nm, respectively. It means that higher resolution is obtained using 780 nm incident light than 532 nm or 632.8 nm.

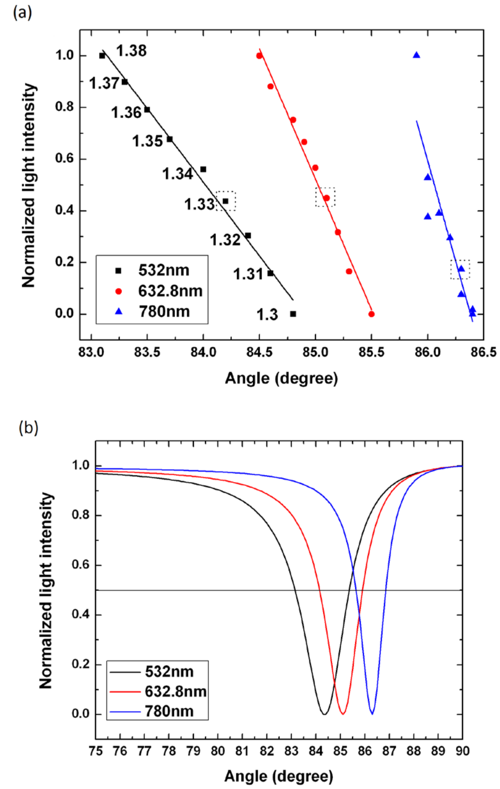

Fig. 3. (a) Resonance angles as functions of light intensity from RI 1.30 to 1.38 at 532, 632.8 and 780 nm. (b) The ATR spectrum of RI is 1.33.

To explore the sensitivity of this metal-dielectric structure, we have calculated the ATR spectra at a single incident angle of 45°. The corresponding RIs of the liquid for these four spectra are 1.31, 1.33 1.35 and 1.37, respectively, as shown in Fig. 4.

Resonance peaks drift to longer wavelength (from 517.3 to 531.5 nm) with an increase in RI (from 1.31 to 1.37). Therefore, the sensitivity of this RI sensor at an incident angle of 45° is about 236.7 nm/RIU using 532 nm light source.

In conclusion, we design and study the ATR spectra of a five-layered metal-dielectric structure by changing the RI of the analytes from 1.30 to 1.38 using

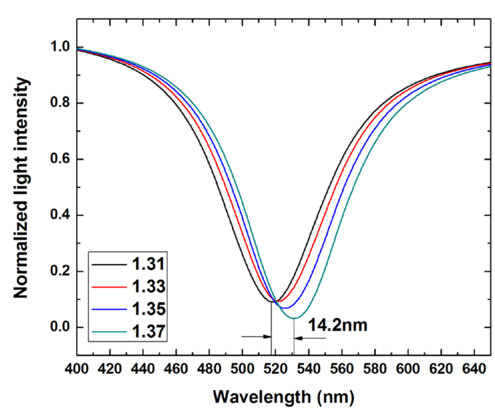

Fig. 4. ATR spectra of RI are 1.31, 1.33, 1.35 and 1.37 at an incident angle of 45°.

different incident light sources of 532, 632.8 and 780 nm. Calculated results support that this structure can be used as an RI sensor to measure the concentration of NaCl or sucrose solution in biochemical research, whose sensitivity is 236.7 nm/RIU at an incident angle of 45°. The sensitivity and resolution are balanced in a practical sensor choosing the proper light source. Although the uniformity and attenuation characteristics of the analytes affect the light intensity, the resonance wavelength is not changed. Therefore, the results are reliable.

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