

Transmission-type SPR sensor based on coupling of surface plasmons to radiation modes using a dielectric grating

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Abstract A transmission-type surface plasmon resonance (SPR) sensor is presented. In the transmission-type SPR structure, surface plasmon waves are outcoupled to radiation modes by the use of dielectric grating on a thin-film layer of Ag. Compared with the traditional reflection-type SPR sensor, the new method provides larger detectable range, which might be useful to investigate thick targets such as in cell analysis. Theoretical simulations show that the structures provide high transmission efficiency for surface plasmon resonance and the devices present extremely linear sensing characteristics. Furthermore, it is found that the transmission efficiency and the refractive index detection sensitivity of the SPR sensor can be improved by the use of a lower refractive index glass prism.

Keywords surface plasmon resonance (SPR), optical sensors, glass prism, rigorous coupled wave analysis

1 Introduction

Surface plasmon resonance (SPR) results from a coherent fluctuation of free electrons on the surface of a thin-film metal layer [1]. Light with a transverse magnetic (TM) polarization meeting the matching conditions of the surface plasmon waves (SPWs) is absorbed and creates a resonance absorption feature in the reflected angular or wavelength spectrum. Since the resonance condition is highly sensitive to the variations of the medium surrounding the metal surface, a small change in refractive index on the metal surface can be quantitatively analyzed by measuring the spectral shift of the resonance dip. This effect is widely used in highly sensitive sensors [2–4].

Most SPR-based sensors work as reflection types in the sense that a photodetector measures reflected light from the sensor surface by use of a standard Kretschmann

configuration [5]. Such a setup uses a photodetector on the same side of a light source with respect to the metal film, which allows an extremely compact sensing scheme. However, the detectable range of the reflection-type SPR sensor is limited to a penetration depth in the 100–200 nm range because the surface plasmon waves propagate along the metal surface and decay exponentially into both media. So a transmission-type SPR structure might be useful to investigate thick targets such as in cell analysis, in contrast to a traditional reflection-type structure [6]. In a transmission-type SPR sensor, surface plasmons are outcoupled into radiation modes by use of a waveguide layer in which the permittivity of the waveguide layer is periodically modulated. The change of the target environment can be investigated by measuring the resonance shift of the transmittance peak.

The coupling of surface plasmons with a diffraction grating has been reported in several other studies [7–9]. Most of these studies consider a corrugated thin-film metal to generate surface plasmons and for outcoupling in radiation modes. As mentioned by Park et al. [10], however, converting of surface plasmons into only reflection modes may not have enough to connect the radiation modes from the diffract gratings directly to other external optical devices. To overcome this limitation, they utilized dielectric diffraction gratings for the efficient outcoupling of surface plasmons to transmission modes that propagate in free space. An outcoupling efficiency of 50% was presented and proved experimentally by the use of a conventional Kretschmann configuration and a dielectric grating on a silver film. From the report of Lenaerts et al. [11], transmittance of 68% was obtained for a modified structure in which a waveguide grating was added between a metal surface and air. Such gratings are composed of two kinds of dielectric material, which will intent the complexity of the fabrication process. Moreover, enhanced transmittance of up to 72% was predicted numerically by Shen et al. [12] through a thin metal slab with dielectric grating.

In this paper, we report the efficient outcoupling of the surface plasmons to transmission modes by the use of a dielectric grating. Numerical investigation results show that the peak transmission efficiency of 72.829% was obtained when the thickness and period of grating were optimized. The configuration discussed in this paper can be used as a gas or biochemical sensor, which presents extremely linear sensing characteristics. Furthermore, the influence of the refractive index of the prism on the sensing characteristics was investigated. The results presented herein have been carried out by the use of an algorithm based on rigorous coupled wave analysis [13–16]. The algorithm has been widely used for the calculation of the optical properties of periodic or aperiodic structures with a dimension less than the wavelength of the incident light.

2 Structure

A schematic diagram of the proposed transmission-type SPR sensor is shown in Fig. 1, where dielectric grating is represented as a one-dimensional array sitting on a 40-nm-thick silver layer ($d_m = 40$ nm). In Fig. 1, d_g represents the height of the dielectric grating and Λ is the period of the dielectric gratings. The permittivity of BK7 glass prism, dielectric gratings and metal layer were determined as $\epsilon_p = 2.2958$, $\epsilon_g = 2.25$ corresponding to polymethyl methacrylate (PMMA), and $\epsilon_m = -18 + 0.5i$ for silver at $\lambda = 633$ nm, respectively.

When the wave vector of the incident TM-polarized electromagnetic wave parallel to the prism-metal interface matches with that of the surface plasmon, a strong SPW is generated at the metal-dielectric interface. This resonance phenomenon can be mathematically expressed by equating the x -component of the input wave vector, k_x , with the real

part of the wave vector of the SPW, k_{sp} , as shown in the following equations [1]:

$$k_x = k_0 \sqrt{\epsilon_p} \sin \theta_1, \quad (1)$$

$$k_{sp} = k_0 \sqrt{\frac{\epsilon_m \epsilon_s}{\epsilon_m + \epsilon_s}}. \quad (2)$$

At the resonance,

$$k_{SPR} = k_0 \sqrt{\epsilon_p} \sin \theta_{SPR} = \text{Re} \left\{ k_0 \sqrt{\frac{\epsilon_m \epsilon_s}{\epsilon_m + \epsilon_s}} \right\}, \quad (3)$$

where k_{SPR} and k_0 denote the wave vectors of the surface plasmon and the incident light, and ϵ_s is the dielectric constant of the medium on top of a metal film. At a particular angle of incidence, θ_1 , when the value is equal to the resonance angle, θ_{SPR} , the resonance condition of Eq. (3) is satisfied and SPR is observed. The surface plasmon is then diffracted strongly by the dielectric gratings to airspace. The diffracted angle, θ_r , is given by

$$k \sin \theta_r = k_{SPR} + qK, \quad q = 0, \pm 1, \pm 2, \dots, \quad (4)$$

where k is the magnitude of the wave vector of diffracted light, q is the diffraction order, and $K (= 2\pi/\Lambda)$ is the grating vector. The grating period, Λ , is designed to be small enough that only the low diffraction orders can propagate in airspace.

Using rigorous coupled wave analysis we numerically estimate the diffraction efficiency of the radiation mode in the proposed structure considering an incident TM wave with a wavelength of 633 nm. The period Λ is defined as 600 nm when the line width is 300 nm ($VF = 0.5$). This is almost equal to the wavelength of an incident light, so that only the low diffraction orders can transmit into air. The calculated reflection and transmission curves for the case of $d_g = 110$ nm are shown in Fig. 2. It is obvious that

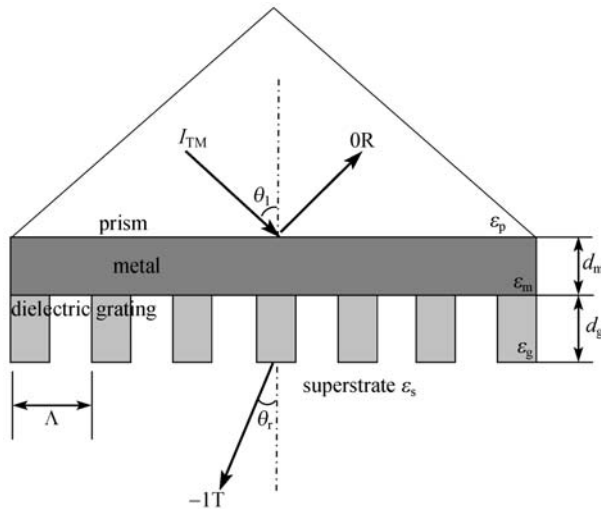


Fig. 1 Schematic of studied setup that consists of Kretschmann configuration in which a dielectric grating is placed on the top of metal layer

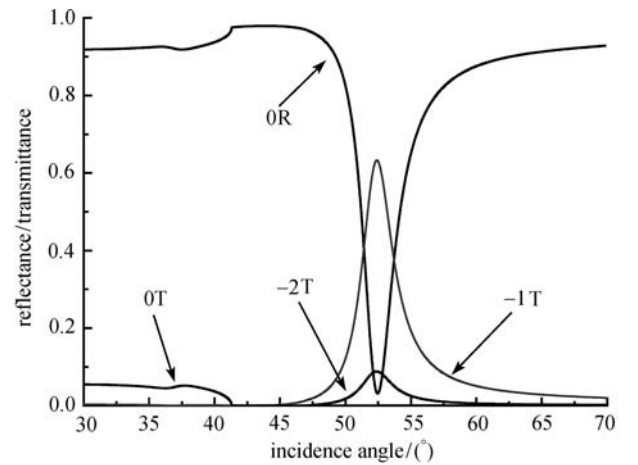


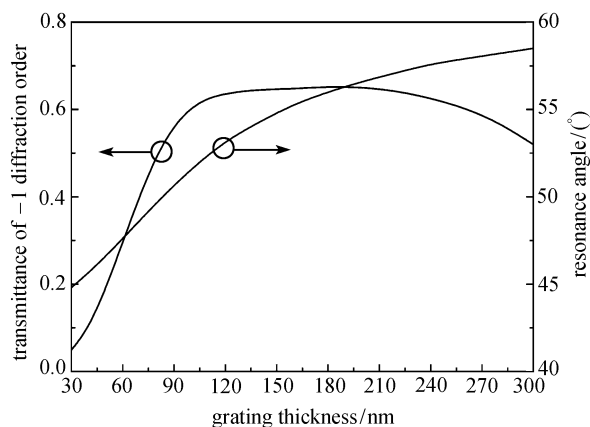
Fig. 2 Reflectance (OR) and transmittance (0T, -1T and -2T) plotted as a function of incidence angle ($\epsilon_s = 1$, $d_g = 110$ nm, $\theta_1 = 54.20^\circ$, and $T_{\max} = 63.264\%$)

the -1 diffraction order ($-1T$) is to be selected as the target under interrogation instead of $0T$, since $-1T$ is the indicator of a radiation mode.

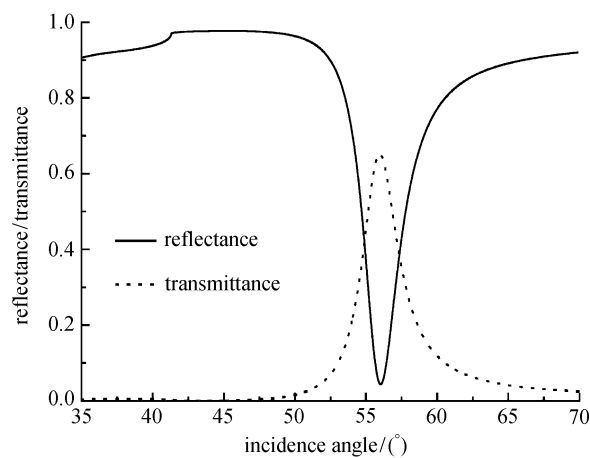
3 Optimization

The intensity of the diffraction modes can be described by the relation $I \propto fQ$, where f is the field-enhancement factor of the surface plasmon and Q is the coupling coefficient of the surface plasmon with the diffraction grating. f and Q depend strongly on the dielectric constant of the grating, but Q is much more sensitive to other grating parameters of the surface-relief profile, such as period, aspect ratio, and modulation depth [10].

Firstly, the height of the grating must now be determined. Figure 3(a) presents the transmittance of the -1 diffraction order ($-1T$) and corresponding resonance



(a)

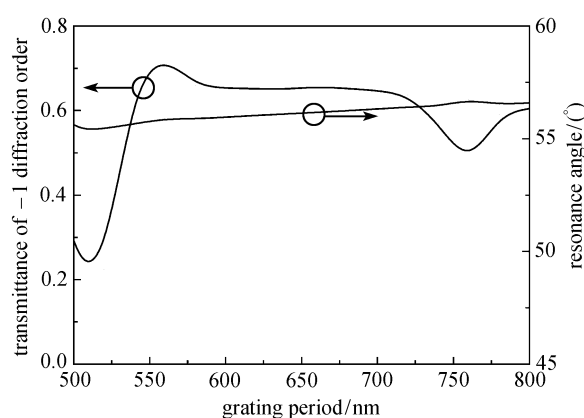


(b)

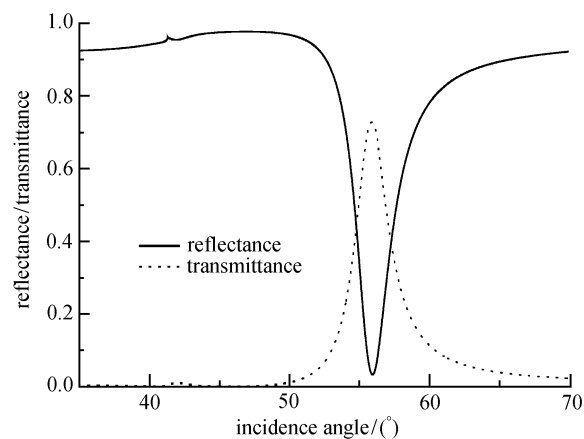
Fig. 3 Influence of thickness of dielectric gratings on resonance characteristics ($\Lambda = 600$ nm, $VF = 0.5$, and $d_m = 40$ nm). (a) Transmittance efficiency ($-1T$) and resonance angle plotted as a function of thickness of dielectric gratings; (b) reflectance ($0R$) and transmittance ($-1T$) plotted as a function of incidence angle for the case of $d_g = 180$ nm at $\theta_1 = 55.96^\circ$ and $T_{\max} = 65.263\%$

angles, as the grating thickness d_g varies from 30 to 300 nm. The transmittance and resonance characteristics exhibit strong dependence on the grating thickness. The transmittance of -1 diffraction order rapidly increases first to 61.46% until d_g reaches 100 nm, and then it becomes nearly constant. As the thickness exceeds 260 nm, a slight decrease in transmittance appears since other diffraction orders become significant. The peak efficiency obtained was $T_{\max} = 65.263\%$ at a thickness of $d_g = 180$ nm. Figure 3(b) shows the resonance characteristics for the case of $d_g = 180$ nm. Also, the resonance angle increases monotonically with grating thickness as the change in d_g causes the local effective index to increase effectively. Results of approximately 68% of transmittance can be found in the literature for similar systems [11].

A new study has been carried out to optimize the device to reach at least the results published in the literature. Thus, the period of the dielectric gratings is still to be determined. Figure 4(a) presents the transmittance of the -1 diffraction



(a)



(b)

Fig. 4 Influence of period of dielectric gratings on resonance characteristics ($d_g = 180$ nm, $VF = 0.5$, and $d_m = 40$ nm). (a) Transmittance efficiency ($-1T$) and resonance angle plotted as a function of period of dielectric gratings; (b) reflectance ($0R$) and transmittance ($-1T$) plotted as a function of incidence angle for the case of $\Lambda = 560$ nm at $\theta_1 = 55.88^\circ$ and $T_{\max} = 72.829\%$

order ($-1T$) and corresponding resonance angles, as the grating period Λ varies from 500 to 800 nm. The outcoupling of the electromagnetic energy toward the air space is maximum if the period of grating is $\Lambda = 560$ nm. With the period of grating, a transitivity of 72.829% is obtained at the $\theta_1 = 55.88^\circ$. Figure 4(b) shows the resonance characteristics for the case of $\Lambda = 560$ nm.

4 Sensing application

The proposed transmission-type SPR structure based on optimal dielectric gratings designed to provide maximum transmittance is now applied as a gas or biochemical sensor, the working principle of which is to use the sample medium as the superstrate. The resonance angle is sensitive to the local change in the environmental supersrate on the grating-metal film. By measuring the diffraction characteristics in an enhanced transmission mode, real-time monitoring can easily be achieved.

Figure 5 shows that transmittance spectra of -1 diffraction order for varying refractive indices of superstrate (increasing from 1.00 to 1.05 in steps of 0.01) with three different prism materials. The transmittance peak of -1 diffraction order can be found fine tuned by scanning of the incidence angle. With $\varepsilon_p = 3.19$ (LaSFN21), the resonance angle shifts from 44.67° to 46.35° as the refractive index of the superstrate varies from 1.00 to 1.05 [Fig. 5(a)]. With $\varepsilon_p = 2.2958$ (BK7 glass), the resonance angle shifts from 55.88° to 58.43° [Fig. 5(b)]. With $\varepsilon_p = 2.1199$ (synthesized quartz), the resonance angle shifts from 59.43° to 62.38° [Fig. 5(c)], and the peak transmission efficiencies of -1 diffraction order are all larger than 0.7 for three prisms.

The resonance of each curve was obtained and plotted as a function of n_s as shown in Fig. 6. The shifts of the resonance angle are almost linear over the range of refractive indices for each prism; the slopes of the straight lines denote the angular sensitivity. From linear fit analysis, the slopes of the lines were found to be $33.71^\circ/\text{RIU}$ ($R = 0.99989$), $51.2^\circ/\text{RIU}$ ($R = 0.99982$), and $59.09^\circ/\text{RIU}$ ($R = 0.99978$) with permittivity values of 3.19, 2.2958, and 2.1199, respectively, where RIU is refractive index unit and R is the correlation coefficient that denotes the linearity obtainable in the sensor performance. It can be seen that the angular sensitivity increases with the decrease in ε_p , which indicates that the choice of prism material proves to be a vital design parameter for optimizing the sensor's performance.

5 Conclusion

We have presented a transmission-type SPR sensor based on resonant coupling surface plasmon to radiation modes

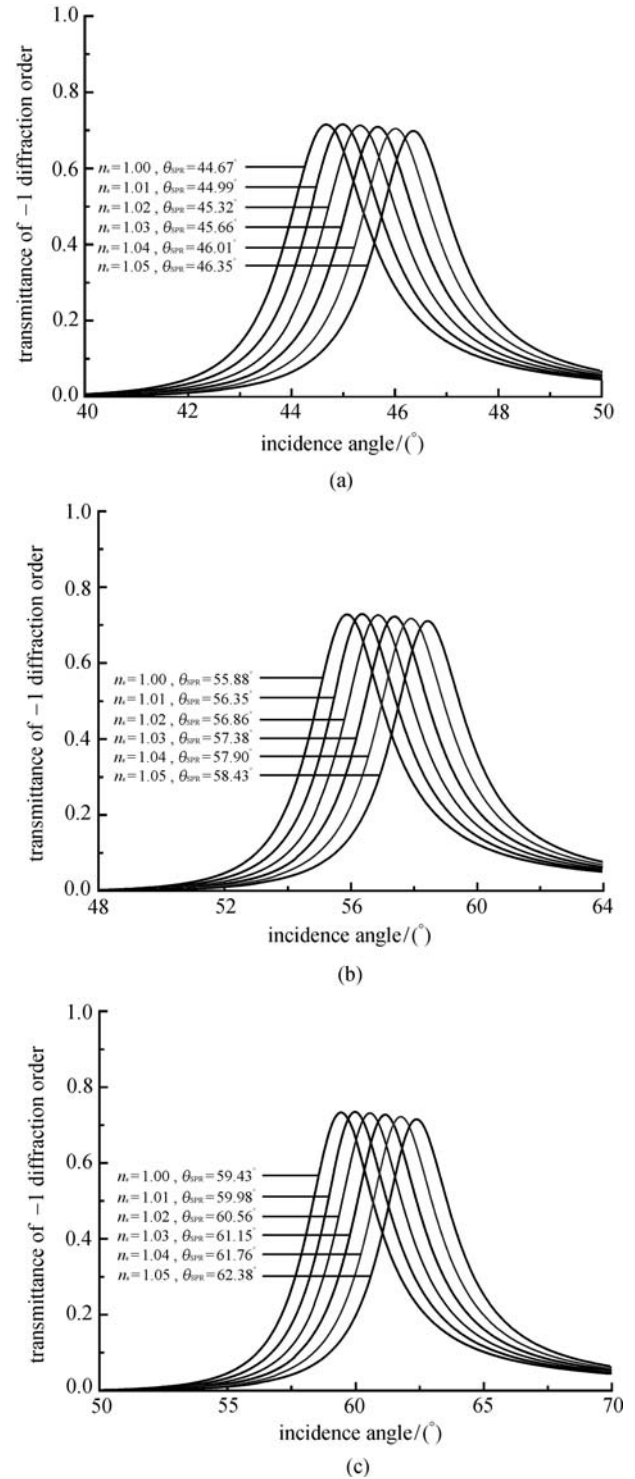


Fig. 5 Transmittance spectra as n_s increases from 1.00 to 1.05 for three different prism materials. (a) $\varepsilon_p = 3.19$ corresponding to LaSFN21; (b) $\varepsilon_p = 2.2958$ corresponding to BK7 glass; (c) $\varepsilon_p = 2.1199$ corresponding to synthesized quartz

by use of a dielectric grating, which might be useful to investigate thick targets compared with conventional reflection-type SPR sensors. Optimal grating thickness

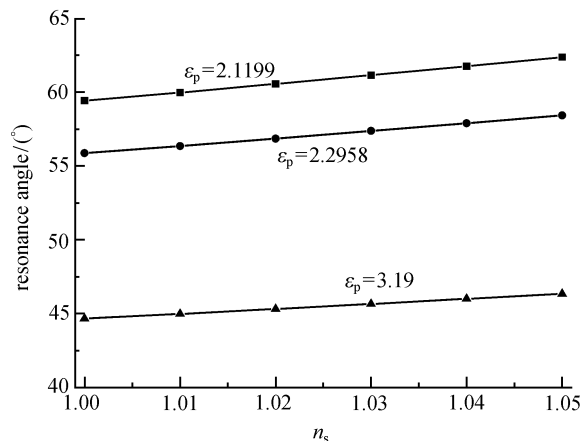


Fig. 6 Plot of resonance angle as function of refractive index of superstrate obtained for three different prism materials (slope of each line indicates the angular sensitivity)

and period were determined in consideration of transmission efficiency by using an algorithm based on the rigorous coupled wave analysis. The results show that peak transmission efficiency of 72.829% was obtained for the configuration. This value is higher than those provided in the literature for this kind of system. For gas or biochemical sensing applications, the devices present extremely linear sensing characteristics with an angular sensitivity of 51.2°/RIU. In addition, the angular sensitivity of the SPR sensor can be improved by use of a lower refractive index glass prism.

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