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Experimental demonstration of high sensitivity for silver rectangular grating-coupled surface plasmon resonance (SPR) sensing

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A B S T R A C T

We experimentally demonstrated a high sensitivity of surface plasmon resonance (SPR) sensor with silver rectangular grating coupling. The reflection spectra of the silver gratings indicated that surface plasmon resonance can be excited by either positive or negative order diffraction of the grating, depending on the period of the gratings. Comparing to prism-coupled SPR sensor, the sensitivities are higher for negative order diffraction coupling in bigger coupling angle, but much smaller for positive order diffraction coupling of the gratings. High sensitivity of 254.13 degree/RIU is experimentally realized by grating-based SPR sensor in the negative diffraction excitation mode. Our work paves the way for compact and sensitive SPR sensor in the applications of biochemical and gas sensing.

1. Introduction

Since the use of surface plasmon resonance (SPR) for gas detection and biosensing in 1982 by Nylander and Liedberg [1], sensors based on SPR have been extensively studied for their potential applications in the fields of chemistry, biology and environment monitoring [2]. Because the propagation constant of surface plasmon wave is greater than the wavenumber of propagating wave in free space, SPR sensors are generally built in configuration of the attenuation total reflection (ATR) in prism couplers [3], optical waveguide [4] or diffraction at the surface of diffraction grating [5]. Prism-based ATR configuration is widely used in commercial bio-chemical SPR sensing system because of its high sensitivity and resolution [3]. Grating-based surface plasmon sensor provided attractive features for compact sensing system, especially for gas sensing [6]. However, it is commonly believed that grating-based SPR sensor is not as sensitive as the prism-based SPR sensor [7]. Our previous work proved theoretically that sensitivity of grating-based SPR sensor was low only when the forward surface plasmon wave was excited through the positive diffraction of grating, but could be very high if the backward surface plasmon wave was excited by the negative diffraction of grating [8]. Even more sensitive SPR sensors can be designed with double-dips method [9], which uses the opposite movement of positive and negative resonant dips to enhance the sensing to the refractive index alteration of the analytes.

We also noted there are a lot of theoretical researches on surface plasmon resonance sensing [8–14] and experimental works are heavily lacked to testify the performance of the designed sensors especially for grating-based SPR sensors [15,16] because the high sensitivity of theoretical prediction is generally hard to achieve in practices. In this letter, grating-based SPR sensor with angular interrogation sensitivity higher than that of prism-based SPR sensor was demonstrated in experiment for the first time. Grating-based SPR sensors are fabricated by interference lithography technology and then coated with 80 nm-thick silver film. Lamellar gratings with different periods are prepared to make sure that SPR dips corresponding to both positive-order and negative-order diffraction could be measured in the reflection curves. The sensitivities of grating-based SPR sensor were measured at different incident angles for both positive-order and negative-order diffraction excitation, and compared with the theoretical predictions.

2. Theoretical calculation

Surface plasmon polariton (SPP) is a hybrid mode of collective conductance electron oscillation and the electromagnetic field existing at the boundary between metal and dielectric. According to the electromagnetic boundary conditions analysis, dispersion relation of SPP is given as following:

$$k_{sp} = k_0 \sqrt{\frac{\varepsilon_a \varepsilon_m}{\varepsilon_a + \varepsilon_m}} \quad (1)$$

where k_0 is the free space wave vector of optical wave, ε_a and ε_m the permittivities of analyte and metal respectively. Since the SPP momentum

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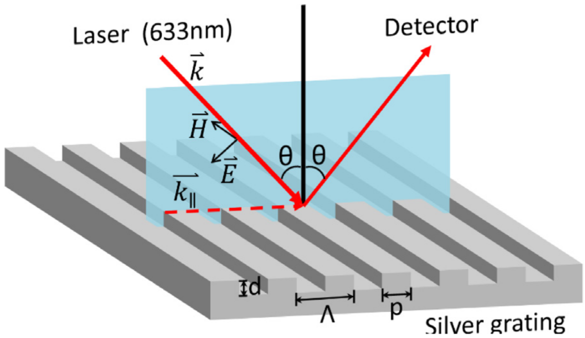

Fig. 1. Schematic diagram of rectangular silver grating surface plasmon resonance (SPR) sensor.

is always greater than that of the same-energy freely propagating wave, efficient coupling between them must involve an additional momentum compensation to meet the requirement of momentum conversation. Gratings are traditionally used to introduce additional momentum because of the optical diffraction.

As shown in Fig. 1, the incident plane of TM-polarization wave is perpendicular to the grooves of rectangle silver grating. The momentum conservation law for an optical wave exciting SPP via diffraction grating is

$$\pm k_{sp} = k_0 n_a \sin\theta_{res} + m\frac{2\pi}{\Lambda}. \tag{2}$$

Substituting Eq. (1) into Eq. (2), we gain a new expression below,

$$\pm k_0\sqrt{\frac{\varepsilon_a\varepsilon_m}{\varepsilon_a+\varepsilon_m}} = k_0 n_a \sin\theta_{res} + m\frac{2\pi}{\Lambda} \tag{3}$$

where $n_a = \sqrt{\varepsilon_a}$ is the refractive index of analyte, θ_{res} the resonant incidence angle of SPPs, m an integer representing the diffraction order of the grating to compensate the momentum mismatch between SPP and incident light, Λ period of grating, p the width of grating ridges, and d the height of grating. Sign "+" on the left side of Eq. (3) represents the forward propagating surface plasmon wave excited only in the case of $m > 0$, and sign "−" represents the backward propagating surface plasmon wave excited only in the case of $m < 0$. As an example, silver rectangular grating with a period of 520 nm, duty cycle of 0.6 and grating depth of 20 nm is simulated by rigorous coupled-wave analysis (RCWA) method. The localized electromagnetic field intensity and energy flux maps of $m = +1$ ($\theta_{res} = 10.2°$) and $m = -2$ ($\theta_{res} = 47.4°$) clearly indicate that forward SPP is inspired by $m = +1$ diffraction (Fig. 2(a)) and backward SPP by $m = -2$ diffraction (Fig. 2(b)).

According to Eq. (3), the momentum conservation diagrams of grating-coupled SPP excitation for both $m > 0$ and $m < 0$ are illustrated in Fig. 2(c) and (d). Wave vectors of SPP k_{sp} and incident laser $k_{inc} = k_0 n_a \sin\theta_{res}$ are in the same direction for $m > 0$, but in the counter direction for $m < 0$. Supposing that the sensor works at the resonant condition of $m > 0$, variation of n_a induces subtractive wave vector alteration of SPP $\Delta k_{sp} = k_0\left(\frac{\varepsilon_m}{\varepsilon_a+\varepsilon_m}\right)^{\frac{3}{2}}\cdot\Delta n_a$ and incident laser $\Delta k_{inc} = k_0 \sin\theta_{res}\cdot\Delta n_a$, which are compensated by the additional wave vector from the shift of resonant angle $\delta k_{inc} = k_0 n_a cos\theta_{res}\cdot\delta\theta_{res}$, that is, $\delta k_{inc} = \Delta k_{sp} - \Delta k_{inc}$. In the case of $m < 0$, the vector alteration of SPP Δk_{sp} and incident laser Δk_{inc} are additive, which results in greatly enlarged wave vector mismatch to be compensated as $|\delta k_{inc}| = \Delta k_{sp} + \Delta k_{inc}$, implies higher sensitivity for SPR sensor. Following this momentum conservation diagrams, sensitivity of grating-based SPR sensor in angular interrogation can be easily derived as,

$$S_G = \left|\frac{d\theta_{res}}{dn_a}\right| = \left|\frac{1}{n_a\cos\theta_{res}}\left[\pm\left(\frac{\varepsilon_m}{\varepsilon_m+\varepsilon_a}\right)^{\frac{3}{2}} - \sin\theta_{res}\right]\right|. \tag{4}$$

The plus and minus "±" in the formula correspond to the positive ($m > 0$) and negative ($m < 0$) order diffraction, respectively. As we have proved with numerical simulation, (i) the sensitivity is an explicit function of the resonant angle; (ii) sensitivity is much larger in the case of $m < 0$ than that of $m > 0$; (iii) the resonant dips move oppositely with the refractive index of the analyte which yield the sensitive scheme of double-dips method [9]. All the predictions above will be demonstrated experimentally by measuring the sensing characteristics of metallic lamellar gratings with different periods.

3. Experimental results and discussions

In order to excite surface plasmon resonance by diverse diffraction of grating, the lamellar gratings are fabricated by double-beam interference lithography on photoresist, then depositing 80 nm-thick silver film. A typical AFM picture of the metallic lamellar grating is presented in the top-left corner of Fig. 3. The depth of grating is around 25 nm and the duty cycle is about 0.65. In our experiments, we fabricated and measured six metallic lamellar gratings with different periods and keeping the depth of grating within 20 nm–30 nm and the duty cycle within 0.6–0.7.

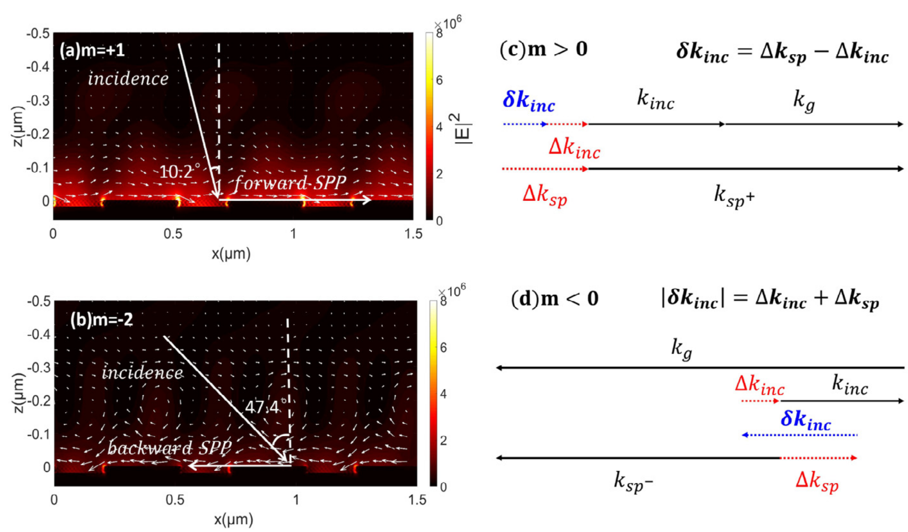

Fig. 2. (a)(b) Localized electromagnetic field intensity and energy flux maps of $m = +1$ and $m = -2$ for metallic grating with period of 520 nm, duty cycle of 0.6 and grating depth of 20 nm. (c)(d) Diagrams to depict the momentum conservation of grating-coupled SPR sensor for $m > 0$ and $m < 0$.