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Improved polarization contrast method for surface plasmon resonance imaging sensors by inert background gold film extinction

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ABSTRACT

To improve the performance of high-throughput surface plasmon resonance (SPR) imaging sensors, the imperfections of the conventional gold film polarization contrast method and the bare prism polarization contrast method are discussed, and a background extinction method is proposed. Thick gold film is coated as the background area, surrounding gold sensing spots, to form a “gold microwell array”. By blocking the light reflected from the background area with appropriate parameters, an opposite-oriented SPR curve is obtained, which can be exploited to achieve a high signal-to-noise ratio in trace amount detection. The contrast between the sensing spots and the background is effectively improved, and the background is inert to the change of solution. Influences of parameter errors on the SPR curve are also investigated, and results show that extinction adjustment in this method is easy to be realized. The practicability of the background extinction method is proved by an experiment using a home-built SPR imaging sensor.

1. Introduction

The demand for rapid high-throughput chemical sensor and biosensor technologies is increasing in many important areas such as life science, medical diagnostics, environment monitoring, and food safety [1,2]. Due to the ability of label-free multi-analyte interrogation and the potential for realizing high-throughput applications, surface plasmon resonance imaging (SPRi) has gained considerable interest in these areas [3,4]. A simple implementation for SPRi is based on analysis of the distribution of light intensity reflected from an SPR surface containing multiple sensing arrays. The main limitation of SPRi is its poor refractive index resolution, which is lower than conventional angular or spectroscopic SPR systems [5,6]. In addition, the operating range of conventional SPRi systems is typically restricted to 0.002–0.005 RIU [7], which cannot satisfy the demand for detecting varieties of analytes. An angular scanning method for SPRi [8] has the same refractive index resolution and dynamic range as conventional SPR sensors, but it needs a complicated angle scanning system. A phase modulation SPRi method [9] has high sensitivity, but the system contains extra expensive devices and the dynamic range is also limited. In recent years, a polarization contrast method for high-throughput SPR sensing has been developed [10]. It converts changes of light polarization (phase and amplitude) into changes of light intensity that is measured directly and thus it gains the same level of sensitivity as the phase modulation method [6]. The SPRi sensor based on this method is capable of measuring changes in small surface coverage simultaneously in more than one hundred sensing channels, which has been applied to detect short sequences of nucleic acids, hormones and other small bio-molecules [11]. Different from the conventional intensity-modulated SPRi, this method exhibits an improved refractive index resolution of $<10^{-6}$ RIU within a large operating range (~0.012 RIU) [6]. However, gold film in sensing spots is always used to realize light extinction, in which the sensing signal will be easily affected by fabrication or regulation errors [12]. The performance in practice can hardly reach the similar level of the theoretical calculation.

In this paper, we first evaluate the imperfections of using sensing gold film as the extinction area and then introduce a new extinction method, which uses the thick gold film as the background for light extinction. This method will improve the performance of a SPRi sensor working in the polarization contrast fashion. Simulations are validated experimentally with a home-built SPRi system.

2. Theory and analysis

2.1. Polarization contrast theory

The polarization contrast theory was first proposed in 1998 [13]. In this method, a selected elliptical polarization state of

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reflected light is extinguished using a set of $\lambda/4$ waveplate and analyzer and thus a high-contrast image between SPR sensing area and the "background" is achieved. The scheme is illustrated in Fig. 1(a). A narrow-band collimated light is first linear-polarized using a polarizer, which has an acute angle ψ_{polar} between the polarization axis and transverse-electric (TE) wave. The linear light E_0 contains both TE and transverse-magnetic (TM) waves. When the light launches into a right-angle prism at a fixed incident angle and is total-internal-reflected at the gold film interface, the polarization of the reflected light is elliptical because the amplitude and phase of TM and TE waves change in different manner. The reflected light can be expressed as:

$$E_1 = \begin{pmatrix} \cos\psi_{polar} r_s \\ sin\psi_{polar} r_p \end{pmatrix} \tag{1}$$

where r_s and r_p are reflectivity of TE and TM waves, respectively. They can be calculated from multiple beam interference in a three-layer (prism–metal–dielectric) model in Fig. 1(b):

$$r_{s|p} = \frac{r_{12} + r_{23}\exp(i\delta)}{1 + r_{12}r_{23}\exp(i\delta)} \tag{2}$$

where r_{ij} is the reflectance of different interface, which can be calculated by using Fresnel equations. Subscripts i and j are 1 for prism, 2 for gold film, and 3 for solution. δ is the phase difference between two adjacent reflection in multiple beam interference, which is:

$$\delta = 2k_{z2}d = \frac{4\pi}{\lambda} n_2 d\cos\theta_2 \tag{3}$$

As the reflected light $\boldsymbol{E}_1$ is elliptical, the azimuth angle of its long axis can be calculated as:

$$\psi_{ellip} = \frac{1}{2}\tan^{-1}\left(\frac{2|sin\psi_{polar} r_p||\cos\psi_{polar} r_s|cos\delta_{ref}}{|\cos\psi_{polar} r_s|^2 - |sin\psi_{polar} r_p|^2}\right) \tag{4}$$

where δ_{ref} is the phase difference between the TM and TE waves of the reflected light. Waveplate is adjusted to ensure that the fast axis coincides with the long axis of the elliptical light ($\psi_{waveplate} = \psi_{ellip}$) in order to turn it back into a linear light E_2, which is

$$E_2 = \begin{bmatrix} \cos\psi_{waveplate} & -\sin\psi_{waveplate} \\ \sin\psi_{waveplate} & \cos\psi_{waveplate} \end{bmatrix} \begin{pmatrix} 1 & 0 \\ 0 & i \end{pmatrix} \times \begin{bmatrix} \cos\psi_{waveplate} & \sin\psi_{waveplate} \\ -\sin\psi_{waveplate} & \cos\psi_{waveplate} \end{bmatrix} E_1 = \begin{pmatrix} E_{2s} \\ E_{2p} \end{pmatrix} \tag{5}$$

Then, this linear light can be blocked by an analyzer with a cross angle:

$$\psi_{ana} = \tan^{-1}\left(\frac{E_{2p}}{E_{2s}}\right) + \frac{\pi}{2} \tag{6}$$

This process is called light extinction. We can set a solution (e.g. water) to be blocked by adjusting both the waveplate and the analyzer with a fixed incident angle and a fixed ψ_{polar}. When the refractive index of the solution changes, light extinction is no longer complete. Therefore, the light intensity (E_3^2) caused by changes of refractive index will be detected.

2.2. Choice of extinction area

Sensing arrays are always designed on the SPR chip to achieve high-throughput detection. The gold film array in Fig. 1(a) is one of the most popular structures, which is constructed by depositing an array of thin gold film on the surface of a bare prism [14,15]. The gold film arrays work as sensing spots while the bare prism parts around them form the "background". Since approximately 90% of the noise measured in SPR imaging originates from light intensity fluctuations [6] and intensity distribution in large sensing area can hardly be uniform, a real-time referencing approach should be applied to reduce the noise of SPR images. It is usually carried out by the normalization formula:

$$I_{norm} = \frac{I_s - I_{dark}}{I_{ref} - I_{dark}} \tag{7}$$

where I_s, I_{dark}, and I_{ref} are the intensity of sensing spot, non-imaging area, and the background reference close to the sensing spot, respectively. I_{dark} represents the dark current noise of the CCD detector, and I_{ref} represents the light intensity fluctuations, which should be free from the influence of the sample. Additionally, we

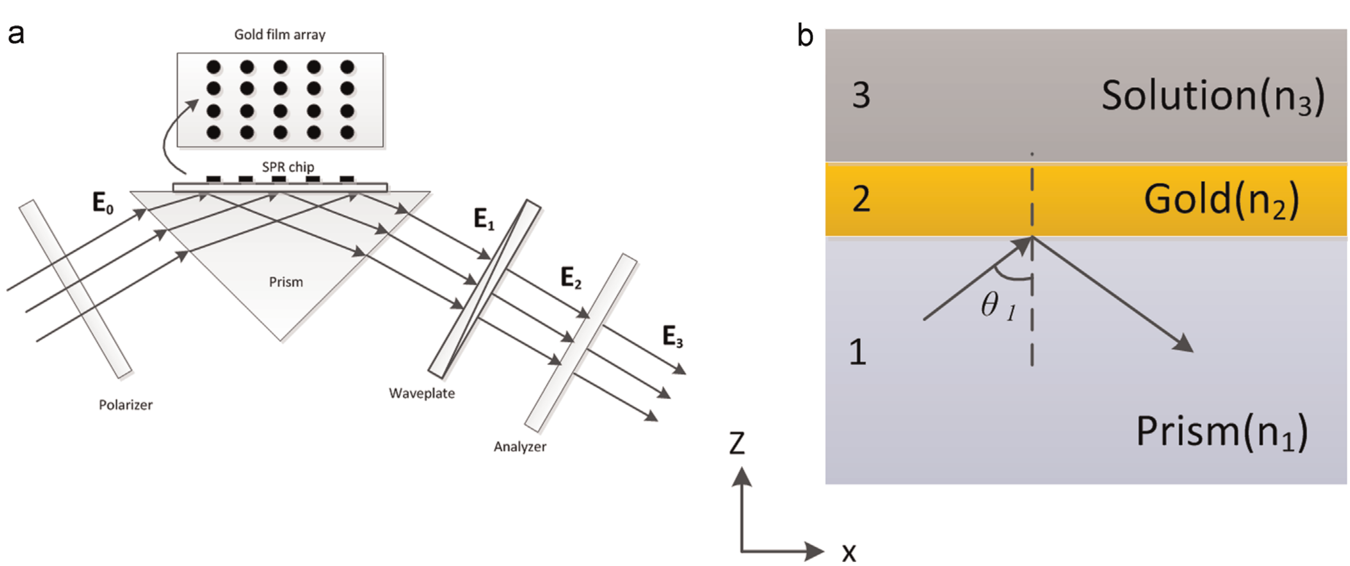

Fig. 1. Schematic of the SPR polarization contrast method (a) and the three-layer model (b).