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Theoretical analysis of highly sensitive prism based surface plasmon resonance sensor with indium tin oxide

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A B S T R A C T

An extremely sensitive silica glass prism based SPR sensor with indium tin oxide (ITO) layer is presented and theoretically analyzed. The sensitivity of the sensor enhances with the increase in the thickness of ITO layer. With optimized values of thickness of ITO layer and incident wavelength to be 50 nm and 1600 nm, respectively, the proposed sensor offers high sensitivity of 164°/RIU.

1. Introduction

Over the past three decades, massive research investigations have been performed on various sensing techniques, which may be employed for rapid and accurate measurement of several physical, chemical and biochemical parameters. Liedberg et al. [1] were the first to reveal the use of surface plasmon resonance (SPR) for gas sensing. Since then, the surface plasmon resonance sensing principle has been studied rigorously [2–4]. Collective resonating oscillation of free electrons may exist on the plasma surface (like metal), which gives rise to a charge density wave propagating along the plasma surface. This transverse electromagnetic wave, propagating parallel to the metal–dielectric interface is identified as the surface plasmon wave. Since surface plasmon wave is transverse in nature, it can be excited by exponentially decaying evanescent field of the incident p-polarized light. When the wave vector and the frequency of the incident p-polarized light matches with those of the surface plasmon wave, this light resonantly excites the surface plasmon wave, propagating along the metal–dielectric interface. The resonance condition depends on the incident angle, wavelength of the incident light and the dielectric constants of both metal as well as dielectric. A sharp dip materializes in the spectrum of output signal at the resonance angle (angular interrogation) or at the resonance wavelength (wavelength interrogation). The angle or the wavelength at which the resonant excitation of surface plasmon happens is very sensitive to variations in the refractive index of the dielectric adjacent to the metal. Consequently, the variations in the refractive index of the sensing (dielectric) medium can be detected by measuring the resonance angle or resonance wavelength. For observing SPR, Kretschmann's configuration is generally used over other SPR sensing structures [5–7]. In the Kretschmann's configuration, a high refractive index prism is coated with a thin metal film touching the sample (sensing medium). Surface plasmon waves are excited by evanescent wave from a high refractive index prism at the total reflection condition.

Gold (Au) and silver (Ag) metals are mostly used for SPR sensor. However, both of these metals have various significant drawbacks such as occurrence of band to band transitions in the visible spectral region for Au films and very thin deposited films of Au and Ag are not continuous but agglomerate as islands [8]. In addition, the SPR sensors with a metallic layer have their SPR wavelengths in the visible range and accordingly not permitting the sensing in the infrared spectral region. Sufficient research work has been carried out on transparent conducting metal oxides. It has become possible to achieve surface plasmon resonance by using transparent conducting metal oxide thin films. Further, highest accessible transmissivity for visible light, lowest electrical resistivity, reflection spectra in infrared region and wide band gap semiconductor, makes indium tin oxide (ITO) as one of the most extensively used transparent conducting metal oxides. Besides, ITO thin films are continuous (i.e. no agglomeration as islands) and no involvement of band to band transitions. In recent times, utilization of ITO thin films in SPR based fiber optic sensing is studied theoretically as well as experimentally in many research explorations [9–12].

In the present work, an extremely sensitive silica glass prism based SPR sensor with ITO layer has been theoretically analyzed. The surface plasmon resonance generated by coupling of evanescent light

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to surface plasmons is used as the sensing scheme. The angular interrogation method is employed for the analysis of prism based SPR sensor. In this method, at a particular incident wavelength, the angle of incidence of the incident light is changed and the corresponding reflected power through the prism is measured. At resonance angle, a sharp dip in reflected power takes place. The resonance angle depends on the refractive index of the sensing medium. The effects of thickness of ITO layer and incident wavelength on the sensitivity of the sensor have been studied. The sensitivity of the proposed SPR sensor is shown to increase with the increase in the thickness of ITO layer. In addition, to achieve the best sensing performance from the sensor, the thickness of ITO layer and incident wavelength are also optimized. The optimized values of thickness of ITO layer and incident wavelength are computed to be 50 nm and 1600 nm respectively. At an incident wavelength of 1600 nm, the 50 nm thick ITO layer based SPR sensor comprises high sensitivity of 164°/RIU.

2. Theory

The SPR sensing is based on the principle of attenuated total reflection (ATR) with Kretschmann's configuration. In the proposed prism based SPR sensor, the sensing system comprising of a prism-ITO-sensing medium is considered as shown in Fig. 1.

The silica prism is coated with a thin ITO layer. This ITO layer is finally surrounded by the sensing medium. The light from the source at a particular incident wavelength is shined at one face of the prism and is detected from the other face with proper optics.

2.1. Silica glass prism

Layer I is made of prism. The prism is assumed to be composed of fused silica. The wavelength dependent refractive index of fused silica glass prism (n_c) is given according to Sellmeier dispersion relation as,

$$n_c(\lambda)=\sqrt{1+\frac{a_1\lambda^2}{\lambda^2-b_1^2}+\frac{a_2\lambda^2}{\lambda^2-b_2^2}+\frac{a_3\lambda^2}{\lambda^2-b_3^2}} \quad (1)$$

where, λ is the wavelength in μm and a_1, a_2, a_3, b_1, b_2 and b_3 are Sellmeier coefficients. The values of these coefficients are given as, $a_1=0.6961663$, $a_2=0.4079426$, $a_3=0.8974794$, $b_1=0.0684043$ μm, $b_2=0.1162414$ μm and $b_3=9.896161$ μm [13].

2.2. ITO layer

Layer II is made of ITO. The dielectric constant of ITO is written according to the Drude model as,

$$\varepsilon_m(\lambda)=\varepsilon_{mr}+i\varepsilon_{mi}=3.8-\frac{\lambda^2\lambda_c}{\lambda_p^2(\lambda_c+i\lambda)} \quad (2)$$

where, λ_p and λ_c are the plasma wavelength and the collision wavelength of ITO respectively. Where, $\lambda_p=5.649\times10^{-7}$ m and $\lambda_c=11.121\times10^{-6}$ m for ITO, respectively [8].

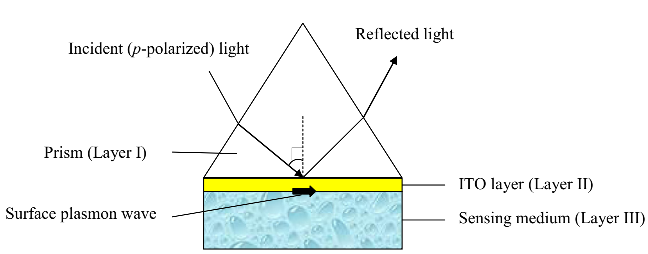

Fig. 1. Schematic diagram of prism based SPR sensor.

2.3. Sensing medium

Layer III is made of sensing medium. The dielectric constant of the sensing medium is ε_s. If n_s is the refractive index of the sensing medium, then $\varepsilon_s=n_s^2$. The resonance condition for excitation of surface plasmon wave is given as,

$$\frac{2\pi}{\lambda}n_c\ \sin\ \theta=\mathrm{Re}\{K_{sp}\} \quad (3)$$

where

$$K_{sp}=\frac{\omega}{c}\sqrt{\frac{\varepsilon_m\varepsilon_s}{\varepsilon_m+\varepsilon_s}}=\frac{2\pi}{\lambda}\sqrt{\frac{\varepsilon_m n_s^2}{\varepsilon_m+n_s^2}}$$

is the propagation constant of the surface plasmon wave and c is the speed of light in vacuum. The left hand side of Eq. (3) denotes the propagation constant of the light incident at an angle θ and the right hand side shows the real part of the propagation constant of the surface plasmon wave. If the refractive index of the sensing medium is changed, the right hand side of Eq. (3) gets modified and therefore the resonance condition will be satisfied at some other value of the angle. By measuring the shift in the resonance angle, a change in the refractive index of the sensing medium can be determined.

2.4. Reflected power

The expression for amplitude reflection coefficient of p-polarized incident light can be obtained by using the matrix method for N-layer model [14]. The matrix method is very simple and accurate due to absence of approximations and can be applied to a system containing any number of layers. The layers are considered to be stacked along the Z-axis. For an arbitrary medium layer, the thickness is d_k; dielectric constant is ε_k; permeability is μ_k and refractive index is n_k. The tangential fields at the first boundary $z=z_1=0$ are related to those at the final boundary $z=z_{N-1}$ by

$$\begin{bmatrix}U_1\\V_1\end{bmatrix}=M\begin{bmatrix}U_{N-1}\\V_{N-1}\end{bmatrix} \quad (4)$$

where, U_1 and V_1 are the tangential components of electric and magnetic fields respectively at the boundary of first layer. U_{N-1} and V_{N-1} are the corresponding fields at the boundary of Nth layer. Also, M is characteristic matrix of the combined structure and is given as,

$$M=\prod_{k=2}^{N-1}M_k=\begin{bmatrix}M_{11} & M_{12}\\M_{21} & M_{22}\end{bmatrix} \quad (5)$$

with,

$$M_k=\begin{bmatrix}\cos\ \beta_k & (-i\ \sin\ \beta_k)/q_k\\-iq_k\ \sin\ \beta_k & \cos\ \beta_k\end{bmatrix} \quad (6)$$

where,

$$q_k=\sqrt{\frac{\mu_k}{\varepsilon_k}}\ \cos\ \theta_k=\frac{\sqrt{(\varepsilon_k-n_1^2\sin^2\theta_1)}}{\varepsilon_k} \quad (7)$$

and,

$$\beta_k=\frac{2\ \pi}{\lambda}n_k\ \cos\ \theta_k(z_k-z_{k-1})=\frac{2\ \pi\ d_k}{\lambda}\sqrt{(\varepsilon_k-n_1^2\sin^2\theta_1)} \quad (8)$$

The amplitude reflection coefficient of p-polarized incident light is given as,

$$r_p=\frac{(M_{11}+M_{12}\ q_N)\ q_1-(M_{21}+M_{22}\ q_N)}{(M_{11}+M_{12}\ q_N)\ q_1+(M_{21}+M_{22}\ q_N)} \quad (9)$$