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SENSITIVITY MODULATION OF SURFACE PLASMON RESONANCE SENSOR CONFIGURATIONS IN OPTICAL FIBER WAVEGUIDE

Sushil Kumar, Gaurav Sharma, and Vivek Singh*

Department of Physics, Faculty of Science, Banaras Hindu University,
Varanasi, UP 221005, India

Abstract—The reflectivity of three layer and four layer optical fiber based surface plasmon resonance sensors having silica material substrate and chalcogenide material substrate is plotted and studied. Using the transfer matrix method, the reflection coefficient for *p*-polarized incident lights at various wavelengths is obtained. It is observed that the sensitivity, detection accuracy and quality parameters of the sensor having silica substrates are much larger than the chalcogenide substrates. These parameters can also be increased by introducing an additional thin layer of silica/chalcogenide material on the metallic surface. Also, these sensor parameters are highly affected by the thickness of the additional thin layer.

1. INTRODUCTION

The high sensitivity detection of biological/chemical molecules and molecular binding event in liquid has become a major area of interest in the past few decades. It has been driven by the demand of medical diagnosis, food quality control, environmental sensors and pharmaceutical industry. At present, the conventional screening used for identification of bio-analyte, discovery of drugs etc. requires labeling (fluorescent or radio) which imposed extra time and cost. Therefore, the label-free detection became popular in last few decades. Presently, the most popular label-free detection techniques found in the market are Surface Plasmon Resonance (SPR) sensors [1]. In the technique of SPR, a transverse magnetic (TM) or *p*-polarized light is used to excite the Surface Plasmon Wave (SPW) at the metal dielectric interface which has exponentially decaying nature at the surface. This surface

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* Corresponding author: Vivek Singh (viveks@bhu.ac.in).

plasmon wave can be excited by attenuated total reflection [2], where a finite gap between the prism base and metal layer occurs. This arrangement is modified by removing the gap between prism base and metal layers by coating the metal layer directly on the prism base and is called Kretschmann-Raether arrangement [3]. Presently, Kretschmann-Raether arrangement is most widely used techniques for excitation of surface plasmon [4–7]. But these prism based sensors are bulky in size and cumbersome to adjust with high precision. So, researchers proposed optical fiber based SPR sensors. There are many advantages of the optical fiber based SPR sensors over prism coupled SPR sensors, such as low cost, flexible design and capability for remote sensing in dangerous environment [8–12]. Optical fiber based SPR is not different from prism based SPR system in terms of sensing principle except coupling of light in the sensor setup.

However, the performance of a sensor is generally discussed in terms of its sensitivity, limit of detection and operating range for the spices to be detected. Silica based glass restricts, SPR sensor to operate in the visible range while plasmon exaction in the infrared (IR) range are very different and lead to advantageous properties of sensing characteristics [13]. Chalcogenide glasses have high refractive index and are a potential material for designing the SPR sensor over IR range. Chalcogenide glasses based prism has much advantage as coupling materials and has been used by a group of researchers [14–16]. In the case of optical fiber, these chalcogenide glasses can be used in core region, cladding region or sensing region, and one can tune the sensitivity and operating range of sensor in desired wavelength region. So, in this paper, we study the chalcogenide glasses based optical fiber sensor and compare the obtained results with those obtained by silica based fiber optical sensor systems. The paper is organized as follows. In Section 2, theory and design consideration of the proposed fiber sensors are given. The other necessary formulas used in this paper are also presented in this section. Section 3 is devoted to result and discussion. A conclusion is drawn in Section 4.

2. THEORY AND DESIGN CONSIDERATION

In the SPR generation which is also known as excitation of the electron density oscillation, there are two properties of surface acting media must be satisfied: first the real part of complex dielectric constant should be negative, and second the momentum/energy of the excitation light and surface plasmon should be matched. The first property is the unique characteristics of metals but only some of them such as gold, silver, copper, aluminium etc. satisfy this condition in visible and infrared regions. On the interface of metal and dielectric media, the SPR is generated and decays exponentially in the surrounding. By solving the Maxwell's equations at the metal and dielectric interface, the propagation constant of the SPW can be written as

$$k_{sp} = \frac{\omega}{c}\sqrt{\frac{\varepsilon_m \varepsilon_s}{\varepsilon_m + \varepsilon_s}} \tag{1}$$

where, ε_m and ε_s are the respective metal and dielectric constant. ω is the frequency of the incident light and c the free space velocity of the light. At same polarization state and frequency, the propagation constant of surface plasmon is greater than the light wave in dielectric media. Therefore, direct light cannot be used to excite the surface plasmon. The excitation of surface plasmon can be achieved by matching the momentum of excitation light with surface plasmon. This is the second essential property to excitation of plasmon. For this, there are several methods used for exciting the SPR such as prism coupling, fiber optic coupling, grating coupling. By using these methods, the light beam having a particular angle θ coupled and, when the propagation constant is matches, a resonance occurs. Since the energy of incident light is transferred to the surface plasmon, the intensity of the reflected light will be reduced. A particular angle of incidence, the θ_{res} resonance condition, occurs and is given as

$$\frac{\omega}{c}\sqrt{\varepsilon_s}\sin\theta_{res} = \frac{\omega}{c}\sqrt{\frac{\varepsilon_m \varepsilon_s}{\varepsilon_m + \varepsilon_s}} \tag{2}$$

The schematics diagrams of the proposed sensors are shown in Fig. 1 and Fig. 2. First layer in the figures is the core of the optical fiber waveguides coated by metal, and the upper surface of this metal layer is directly exposed by aqueous media in three-layer waveguide sensors or by coating a thin layer of dielectric materials (silica/chalcogenide) and then exposed by aqueous media in four-layer waveguide sensors. The reflectivity of the waveguide is calculated by using matrix method of K-layer systems. In this method, the tangential fields at first boundary are related to those at the last boundary and then find a characteristic 2×2 matrix for each thin layers. After combining these matrices with some straightforward steps, we find a final matrix which is written as

$$M = \sum_{k=2}^{N-1} M_k = \begin{bmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{bmatrix} \tag{3}$$

with

$$M_k = \begin{bmatrix} \cos\delta_k & -i\sin\delta_k/\eta_k \\ -i\eta_k\sin\delta_k & \cos\delta_k \end{bmatrix} \tag{4}$$

where η_k is the optically admittance and δ_k the phase factor, which is the function of dielectric constant, thickness, incident angle, wavelength and given by

$$\delta_k = \frac{2\pi d_k}{\lambda}\left(\varepsilon_k - n_1^2 \sin^2\theta_1\right)^{1/2} \tag{5}$$

and

$$\eta_k = \frac{\left(\varepsilon_k - n_1^2 \sin^2\theta_1\right)^{1/2}}{\varepsilon_k} \tag{6}$$

Since the proposed waveguide sensor consists of various materials such as silica glass, chalcogenide glass and silver materials and their corresponding refractive indices are the function of wavelength, it is necessary to examine the refractive indices of these materials in various wavelength ranges. The index variation of these materials with wavelength [7, 12, 17] is represented as

$$n(\lambda) = 1 - \frac{\lambda^2\lambda_c}{\lambda_p^2\left(\lambda_c + i\lambda\right)} \quad \text{(Silver materials)} \tag{7}$$

where $\lambda_p = 1.4541 \times 10^{-7}\,\mathrm{m}$ is plasma wavelength and $\lambda_c = 1.7614 \times 10^{-5}\,\mathrm{m}$ collision wavelength.

$$n(\lambda) = \sqrt{A_0 + \frac{A_1}{\lambda^{-2}} + \frac{A_2}{\lambda^2}} \quad \text{(Silica glass)} \tag{8}$$

where $A_0 = 2.09888$, $A_1 = -0.00935\,\mu\mathrm{m}^{-2}$, $A_2 = 0.01141\,\mu\mathrm{m}^2$.

$$n(\lambda) = 2.24047 + \frac{2.693\times 10^{-2}}{\lambda^2} + \frac{8.08 \times 10^{-3}}{\lambda^4} \quad \text{(Chalcogenide glass)} \tag{9}$$

From Equation (3), we calculate the reflection coefficient of the p-polarized incident light which is given by

$$r_p = \frac{\left(M_{11} + M_{12}\eta_k\right)\eta_1 - \left(M_{21} + M_{22}\eta_k\right)}{\left(M_{11} + M_{12}\eta_k\right)\eta_1 + \left(M_{21} + M_{22}\eta_k\right)} \tag{10}$$

Finally, the reflectivity of a given multilayer structure becomes $R_p = |r_p|^2$. The sensitivity of this waveguide is measured as the small change in refractive index of the sensing layer δn_s with the change in resonance condition $\delta\lambda_{res}$ in the reflectance curve; therefore the sensitivity is given as $S_n = \frac{\delta\lambda_{res}}{\delta n_s}$. The detection accuracy, also known as the signal to noise ratio (SNR ratio), can be determined by the reflectivity curve and given by SNR $= \frac{\delta\lambda_{res}}{\delta\lambda_{0.5}}$, where, $\delta\lambda_{0.5}$ is the spectral width of the SPR curve corresponding to 50% reflectivity. The quality parameter of the sensor depends upon the sensitivity and spectral width of the SPR curve and is given by $Q = \frac{S_n}{\delta\lambda_{0.5}}$.

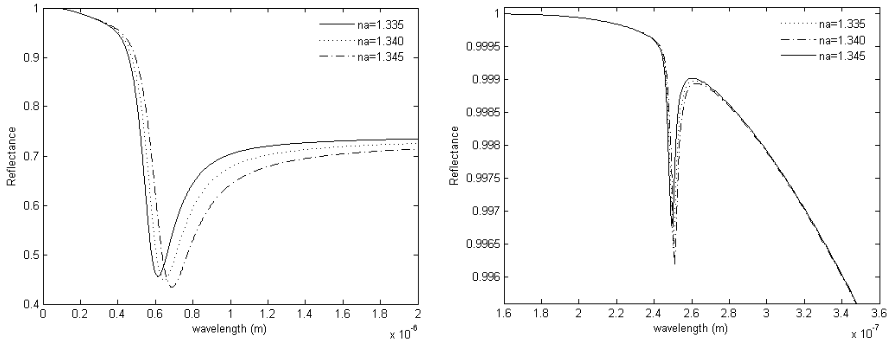
Figure 1. Schematic configuration for three layer SMA sensor.

Figure 2. Schematic configuration for four layer SMChA, SMSA, ChMChA and ChMSA sensors.

3. RESULTS AND DISCUSSION

Schematic configurations of the proposed fiber sensors are shown in Fig. 1 and Fig. 2, and their performance is analysed by three main parameters: sensitivity, detection accuracy and quality parameter. Fig. 1 is devoted to three-layer fiber waveguide sensors which consist of a silica glass substrate (S), a metal layer (M) and an aqueous media (A) denoted as SMA sensor or chalcogenide glass substrate (Ch), and a metal layer (M) and aqueous media (A) denoted as ChMA sensor. A thin metallic layer with permittivity ε_M, permeability μ_M, and thickness dM is sandwiched between a semi-infinite silica/chalcogenide glass layer with permittivity ε_S, permeability μ_S, and aqueous media with permittivity ε_C, permeability μ_C. A typical four-layer fiber waveguide is shown in Fig. 2 which consists of silica glass layer as a silica substrate (S), metal layer (M), chalcogenide glass thin layer (Ch) and aqueous media (A) denoted as SMChA sensor. The other possible combinations of these layers are also studied and denoted as SMSA, ChMChA and ChMSA sensors. Here we choose the angle of incident 75° and 81° for silica substrata and chalcogenide substrate, respectively. The reflectivity of these sensors are computed by putting the values of core diameter 600 μm, metallic layer thickness $d_M = 50\,\text{nm}$ in Equation (10).

The variation in reflectance with the wavelengths for three-layer sensor systems at constant angle of incidence and thickness of constituent material layers are shown in Fig. 3. Fig. 3(a) shows the SPR reflectance curve for three-layer silica substrate SMA sensor, as the refractive index of the sensing media changing from 1.335 to 1.345 in step of 0.005. It is observed that the corresponding resonance curve shifts from 0.614 μm to 0.690 μm. Fig. 3(b) shows the SPR reflectance curve for three-layer chalcogenide substrate ChMA sensor, as the refractive index of the sensing media changing from 1.335 to 1.345 in step of 0.005. Here the corresponding resonance curve shifts



(a) (b)

Figure 3. Calculated Fresnell reflectance for p-polarized light for proposed three layer fiber waveguide sensors on (a) silica substrate, (b) chalcogenide substrate.

Table 1. Comparison between the performances of three layer optical fiber based SPR sensors having silica substrate and chalcogenide substrate.

Parameters	**SMA sensor**	**ChMA sensor**
Sensitivity (μm/RIU)	8	0.16
Detection accuracy	0.2	0.242
Quality parameter (RIU^{-1})	40	48

from 0.249 μm to 0.251 μm. The comparisons of these two waveguides are shown in Table 1. It is observed that the sensitivity of the silica substrate waveguide based sensor is much larger than the sensitivity of chalcogenide substrate based waveguide while the detection accuracy and quality parameter of the lateral sensor are higher. This shows that by taking suitable combination of silica and chalcogenide materials, one can increase these parameters simultaneously. Therefore, we introduce an additional thin chalcogenide material or silica material layer on the metallic surface of a three-layer waveguide sensor. There are two possibilities to introduce these materials in the waveguide sensor, first the substrate/core of sensor waveguide made by chalcogenide or silica materials, second a very thin layer of these materials are coated on the metal layer.

The variation of reflectivity with the wavelength in four-layer chalcogenide substrate waveguide sensor for two different coatings, one for chalcogenide thin material on metal surface and the other

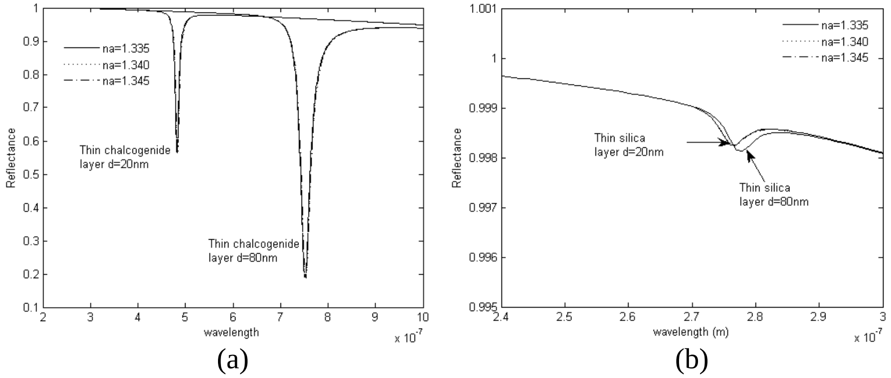


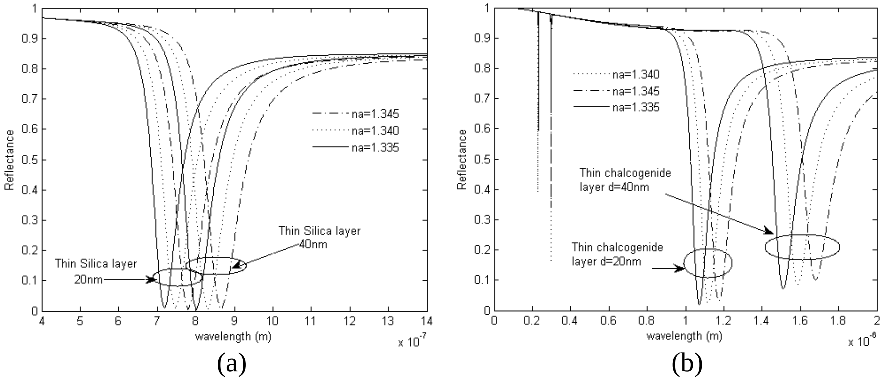
Figure 4. Calculated Fresnell reflectance for *p*-polarized light for proposed four layer fiber waveguide sensors on chalcogenide substrate with (a) chalcogenide thin layer on metal surface, (b) silica thin layer on metal surface.

Table 2. The performances of four layer optical fiber based SPR sensors having chalcogenide substrate with the variation of thickness of thin layer on the metal surface.

Parameters	**ChMChA sensor**		**ChMSA sensor**	
	20 nm	80 nm	20 nm	80 nm
Sensitivity (µm/RIU)	0.12	0.14	Negligible	Negligible
Detection accuracy	0.068	0.027	Negligible	Negligible
Quality parameter (RIU^{-1})	13.79	5.55	Negligible	Negligible

for silica thin material on metal surface, are shown in Fig. 4(a) and Fig. 4(b), respectively. From the comparison point of view, the various parameters of these waveguides are listed in Table 2. We observe that the overall performance of chalcogenide substrate waveguide sensor becomes poorer than the previously studied three-layer waveguide. This may be due to the region that the chalcogenide substrate has higher refractive index therefore most of the light confined in the substrate region.

The variation of reflectivity with the wavelength in four-layer silica substrate waveguide sensor for two different coatings, one for silica thin material on metal surface and the other for chalcogenide thin material on metal surface, are shown in Fig. 5(a) and Fig. 5(b), respectively. Here it is observed that the sensitivity, detection accuracy and quality parameter of SMSA sensor are much higher than the previously studied waveguide sensors. If we compare the results obtained for SMSA



(a) (b)

Figure 5. Calculated Fresnell reflectance for p-polarized light for proposed four layer fiber waveguide sensors on silica substrate with (a) silica thin layer on metal surface, (b) chalcogenide thin layer on metal surface.

Table 3. The performances of four layer optical fiber based SPR sensors having silica substrate with the variation of thickness of thin layer on the metal surface.

Parameters	SMSA sensor		SMChA sensor	
	20 nm	40 nm	20 nm	40 nm
Sensitivity (μm/RIU)	6.6	6.88	11	18.8
Detection accuracy	0.428	0.329	0.514	0.614
Quality parameter (RIU^{-1})	85.71	65.96	102	122.2

sensor with the SMChA sensor as shown in Table 3, we found that the above parameters for SMChA sensor are significantly improved. This improvement may be observed because most of the light is confined near the sensing region, which means within the high refractive index chalcogenide material. From Table 3 it is also observed that the increment of thickness of silica materials in SMSA sensor improved the sensitivity, but at the same time, the detection accuracy and quality parameter decreased while this increment in chalcogenide materials in SMChA sensor improved all parameters significantly.

4. CONCLUSIONS

The wavelength interrogation methods for resonance condition are used to study the three- and four-layer waveguide sensors. The reflected light is measured as the function of wavelength with fixed value of angle of incidence and thickness of constituent material layers, then a sharp dip of the reflected light is observed at resonance angle due to an efficient transfer of energy to the surface plasmon. The sensitivity, detection accuracy and quality parameter of these waveguide sensors are studied and compared. It is observed that the chalcogenide substrate waveguide based sensors give poorer result than the silica substrate waveguide based sensors because most of the light is confined within the chalcogenide substrate. But in the silica substrate waveguide based sensors with thin coating of chalcogenide materials, all the above defined parameters improvised because most of the light is confined within the chalcogenide thin layer near the sensing region.

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