Sensitivity Enhancement of Metamaterial Based Five Layered SPR Sensor

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Abstract- *This paper deals with a numerical analysis of Surafce Plasmon resonance (SPR) sensor using metamaterial for three layers, four layers and five layered structure. This calculation shows that the proposed SPR sensor structure has a preference over the conventional SPR sensors and bimetallic SPR sensors since it gives a much sharper reflectance dip. The effect of the Metamaterial permittivity, permeability, and thickness on the reflectance curve for three layers, four layers and five layers are calculated. It is also, seen that metamaterial layers improves the field of proposed SPR structure, which may provide novel tools to significantly enhance the sensitivity and resolution of the sensors.*

Keywords**-** Surface Plasmon resonance (SPR), Metamaterials, Fresnel equations, Reflectance.

I. INTRODUCTION

The phenomenon of surface Plasmon resonance has been known for a long time and has been used for chemical sensors and remote sensing [1]. It makes use of a prism and a thin metal layer deposited upon the prism. Traditionally, SPR is measured using the kretschman configuration, with a prism and a thin highly reflecting metal layer (silver or gold) deposited upon the prism base [2]. The reflection spectrum (reflected light intensity versus angle of incidence with respect to the normal of the metal) is measured by coupling transverse magnetically (TM) polarized monochromatic light in to the prism and measuring the reflected light intensity of the ray exciting the prism versus the angle of incidence. Fresnel equations [3] are used to predict reflected and transmitted light intensity from multilayered structures.Resonance condition is established when the frequency of light photons matches the natural frequency of surface electrons oscillating against the restoring force of positive nuclei. This paper explores the use metamaterials to produce the surface Plasmon resonance at microwave frequencies. Metamaterials are materials with negative permittivity and permeability. Metamaterials have attracted considerable attention in recent years [4-8]. These are artificial materials engineered to provide properties which may not be readily available in Nature. These materials usually gain their properties from structure rather than composition, using the inclusion of small inhomogeneties to enact effective macroscopic behavior [9]. Apart from sensing field metamaterial can be used in other applications such as perfect lens, various filter applications, phase shifter, and MRI .By using metamaterial in surface Plasmon resonance (SPR) sensor, it increases refractive index sensitivity by generating the resonance condition at longer wavelength and reduces the value of reflectance.

II. FORMULATIONS FOR A GENERALIZED SURFACE PLASMON RESONANCE SENSOR

Considering the layered structure shown in Fig.1

A Plane wave is incident from the medium 1 with ε_1 and μ_1 on the layer with ε_2 and μ_2 bounded by the medium 3 with ε_3 and μ_3.Here ε and μ are relative permittivity and relative permeability normalized to free space ε_0 and μ_0.The reflection coefficient R is well know [10].

$$R = \frac{A+\frac{B}{Z_3}-Z_1\left(C+\frac{D}{Z_3}\right)}{A+\frac{B}{Z_3}+Z_1\left(C+\frac{D}{Z_3}\right)} \tag{1}$$

Where

$A = D = \mathrm{Cos}k_{z2}d$, $B = jZ_2\mathrm{Sin}k_{z2}d$, $C = \frac{j\mathrm{Sin}k_{z2}d}{Z_2}$

$k_{zi} = \sqrt{k_i^2-(k_i\mathrm{Sin}\theta_1)^2}$,i = 1,2,3, $k_i = k_0 n_i$

$k_0 = \frac{\omega}{c}$ is the free space wave number

$$Z_i = \begin{cases} \frac{k_{zi}}{\omega\varepsilon_0 i} \text{ for } p-\text{polarization } (E_x, E_z, H_y) \\ \frac{\omega\mu_0\mu_i}{k_{zi}} \text{ for } s-\text{polarization } (H_x, H_z, E_y) \end{cases}$$

In this formulation, both ε_i and μ_i are complex. However for a passive medium , we require, using exp($j\omega t$) time dependence,

$$\mathrm{Im}(\varepsilon_i) < 0$$
$$\mathrm{Im}(\mu_i) < 0$$

Im (n_i) < 0
Im (k_{zi}) < 0
Re $\sqrt{\frac{\mu_i}{\varepsilon_i}}$ > 0

Figure 1.

III. CONVENTIONAL SURFACE PLASMON RESONANCE SENSOR

Before we discuss metamaterial Surface Plasmon Resonance (SPR), firstly we see the conventional optical sensor making use of the surface Plasmon resonance. Fig. 2 illustrates the model geometry of the three layered surface Plasmon resonance (SPR) presented here. The model structures consist of a high index prism (SF10 with refractive index n = 1.723), Ag metal layer, and a water buffer (n = 1.332) for a p-polarized incident light of 632.8 nm to have sharp resonance curves and minimum reflectivity dips.

Figure 2.

IV. MODELLING OF SURFACE PLASMON RESONANCE SENSOR FOR META MATERIALS

A schematic geometry of the proposed SPR sensor is shown in Fig.3. It consists of five layers with Bi-metamatareial layers thickness of d_1 and d_3 respectively. The metamaterial layer is characterized by electric permittivity (ε_m) and maganetic permeability (μ_m). Park et al. [11] introduced the frequency dependent complex permittivity and permeability in the form

$$\varepsilon_m(\omega) = 1 - \frac{\omega_p^2}{\omega^2 + i\gamma\omega} \quad (1)$$

$$\mu_m = 1 - \frac{F\omega^2}{\omega^2 - \omega_0^2 + i\gamma\omega} \quad (2)$$

where ω_p is the plasma frequency, ω_0 is the resonance frequency, γ is the electron scattering rate, and F is the fractional area of the unit cell occupied by the split ring.

The metal gold (Au) and metamaterial layers are sandwiched between cover which is water buffer with refractive index is 1.332 and high index prism with refractive index is 1.723. By using gold (Au), metamaterial layers of d_2 thickness, it is possible to optimize several combinations only for a p-polarized incident light of 632.8 nm to get sharp resonance curves and minimum reflectivity dips because the s-polarized light cannot excite electronic surface plasmons [12]. Among these combinations, four layered and five layered structures are discussed in this paper.

First, we solve Maxwell's equations for four and five layer SPR sensor and get the Helmholtz equations for p-polarized light, which can be written as

$$\frac{\partial^2 H_y}{\partial z^2} + (k_0^2\varepsilon - \beta^2)\, H_y = 0 \quad (3)$$

where H_y represent the magnetic field for p- polarized light and β is the propagation constant in the x-direction.

Hence the solutions of the proposed SPR sensor for different region can be written as

Figure 3. Five Layer Strucure

$$Hy = \begin{cases} Ac\ e^{(-ik_c z)} e^{i(\omega t - k_x x)} & \textit{water buffer} \\ \{Aa\ e^{(ik_{m2} z)} + Ba\ e^{(-ik_{m2} z)}\} e^{i(\omega t - k_x x)} & \textit{outer metamaterial layer} \\ \{Ag\ e^{(ik_g z)} + Bg\ e^{(-ik_g z)}\} e^{i(\omega t - k_x x)} & \textit{gold layer} \\ \{Am\ e^{(ik_{m1} z)} + Bm\ e^{(-ik_{m1} z)}\} e^{i(\omega t - k_x x)} & \textit{inner metamaterial layer} \\ As\ e^{(ik_p z)} e^{i(\omega t - k_x x)} & \textit{prism} \end{cases} \quad (4)$$

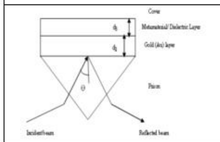
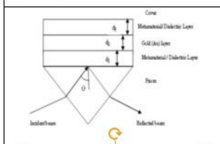
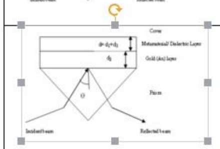
where
$k_c = \sqrt{\beta^2 - n_c^2 k_0^2}$, $k_{m2} = \sqrt{\beta^2 - n_{m2}^2 k_0^2}$, $k_g = \sqrt{n_g^2 k_0^2 - \beta^2}$, $k_{m1} = \sqrt{n_{m1}^2 k_0^2 - \beta^2}$, and $k_p = \sqrt{\beta^2 - n_p^2 k_0^2}$

V. NUMERICAL RESULTS AND DISCUSSION

This paper deals with optical SPR sensors making use of isotropic and homogeneous metamaterials. We have chosen the following parameters an operating wavelength λ_0 = 632.8 nm and d1=300nm, d2=35nm and d3=300nm. Values of negative dielectric and magnetic constants for metamaterial layers are{ε_m ,μ_m }={-0.66-0.001i ,-2} and these sets generate a negative refractive index of n= -(εμ)^(1⁄2) [20]. Refractive indices for Prism, gold (Au), dielectric layer and water buffer (cover) are 1.723, 0.2184 + 3.5113i, 2.198 and 1.332 respectively [13].

Now we plot the reflectance curve for the proposed SPR sensor using a very simple approach using Fresnel's equations and compute the reflectance for various values of incident angle θ and plot the curves between reflectivity and incident angle for four and five layered structure as illustrated in Fig. 4, Fig.5 and Fig.6. These curves show SPR sensors with metamaterial layer providing minimum reflectance that can be seen by table 1.

Table 1

Structure	Metamaterial layer based SPR		Dielectric layer based SPR	
	Incident Angle	Reflectance value	Incident Angle	Reflectance value
	45.6962	0.03544	49.755	0.52346
	42.2682	0.00009	49.7814	0.53153
	45.3072	0.05312	60.9002	0.13134

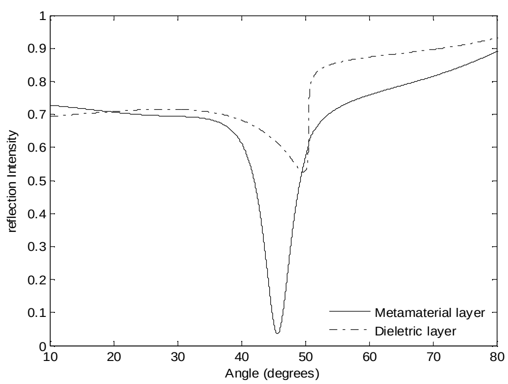


Figure 4. Three layered structure

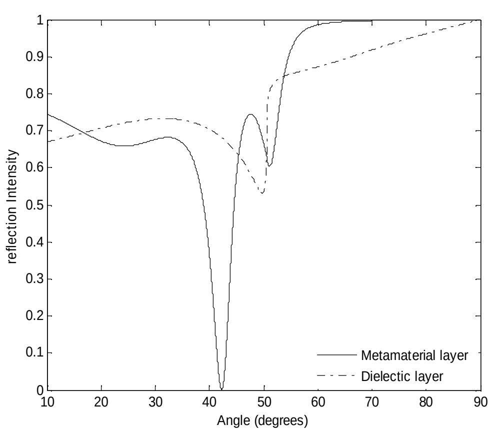


Figure 5. four layered structure

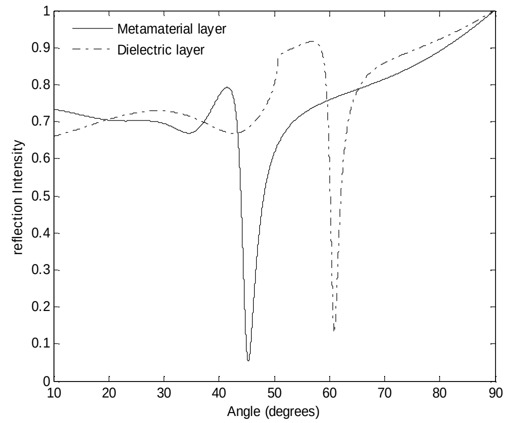


Figure 6. Five layered structure

VI. CONCLUSION

This paper has presented the use of metamaterials for Plasmon resonance sensors (SPR) at microwave frequencies. sensor (SPR) reflectance curve for the conventional surface Plasmon sensor (SPR) sensor as a function of incident angle θ, in the incident medium of the SF10 prism.

From the above discussion, it can be said that on the same thickness of the layer, metamaterial SPR gets the lower value of reflectance for the five layers structure.

It can be clearly seen by the graphs which are done by the MATLAB, the dip of reflectance is quite sharp in case of five layered structure. The use of metamaterial layers is confirmed to have an advantage in increasing the reflectance dip of optical SPR sensor, thus improving the sensitivity in term of sensing resolution and dynamic range. This is advantage for sensing applications.

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