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Sensitivity enhancement of metal clad planar waveguide sensor using metamaterial layer as a guiding layer

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ABSTRACT

In the present paper, a comprehensive study of sensitivity and reflectance of metal clad planar waveguide biosensor having metamaterial in guiding layer has been done. The sensitivity and reflectivity of proposed waveguide sensor are calculated using Fresnel's laws. It is observed that the sensitivity of a waveguide is highly affected by the presence of metamaterial layer. The calculated sensitivity has been compared with those reported in the earlier studies. It is observed that the sensitivity increases in the presence of metamaterial.

1. Introduction

Currently, biosensors are paramount tools in the investigation of biological phenomenon and have importance in many areas, such as disease diagnostics, environmental monitoring and food safety [1–11]. Optical fiber based biosensors are the epicenter of an extensive research work in the past few years [6,12–14]. The use of optical waveguide based planar sensors is gaining attention due to their small size, greater robustness and amenable to integration with other optical components, higher compatibility with traditional micro-fabrication techniques, and allows simpler vertical fabrication [15]. The optical planar waveguide sensors are also known as evanescent wave sensors because of the evanescent wave penetrating in to cover region whose refractive index is to be measured. This evanescent field is responsible for the sensing process [16]. For bio-sensing application, the cover region is replaced by aqueous solutions like water, urine or blood that contains the targeted analyte. The sample is injected into a cuvette ensuring contact with either the sensor surface as stagnate or flowing through cuvette. For specific detection, the surface is coated with a biological affinity layer. The surface of affinity can be coated by biological molecules including antibodies, antigens, dextran layer, etc.

Recently, the bio-sensing technologies based on metamaterial have attracted significant attention toward optical biosensor because of their cost efficient and level free biomolecule detection. Qing and Chen [17] found that metamaterials, which are artificially constructed materials, could enhance the intensity of the evanescent waves in the cladding without altering the propagation constant of the waveguide for both transverse electric (TE) mode and transverse magnetic (TM) mode. The enhancement of intensity of the evanescent waves can improve the performance of such type of optical sensor devices [18,19]. Taya et al. [20] and Wenwei et al. [21] have reported the enhancement of sensitivity in optical TE mode of waveguide sensor using metamaterials of different layers. Very recently, Kullab et al. [22] proposed a four-layer waveguide structure using metamaterial layer as a guiding layer and metal clad as a cladding layer, which is known as metal clad waveguide (MCWG) sensor. They found that the position and shape of the reflectance dip change drastically with the thickness of metal layer. They also found that the presence of metamaterial is more advantageous to have a similar structure with a dielectric guiding layer due to its larger angular shift in the reflectance dip.

It is clear from the above discussion that the introduction of metamaterial enhances the sensitivity of the planar waveguide sensor. Therefore, in contemporary communication, we propose a

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five-layer metal-clad planar waveguide biosensor using metamaterial layer as a guiding layer for the detection of bacteria. The main objective of this paper is to see the effect of affinity layer and affinity thickness on the sensitivity of such waveguides. In addition, the numerical results presented in this article are compared with those of metal clad planar waveguide biosensors having four layers and five layers [22,23]. The brief outline of the paper is as follows: in Section 2 we outline the derivation of the characteristic equations from Helmholtz's wave equation, which helps in the derivation of necessary formula. In Section 3, numerical results and discussion are considered. Finally, the paper ends with some remarks in the conclusion given in Section 4.

2. Theory

Fig. 1 shows a schematic structure of the proposed five layer planar waveguide. The guiding layer is a metamaterial layer with permittivity ε_3, permeability μ_3, and thickness *df*, sandwiched between a metal clad with permittivity ε_2, permeability μ_2, and thickness *dm* and an adlayer with permittivity ε_4, permeability μ_4, and thickness *dA*. In most sensor applications, the supporting metallic material is gold or silver and it has shown that the reflectance dip of gold MCWG sensor is broader than that of silver MCWG based sensor [22,23]. In addition, the cover refractive index of proposed sensor is n_c and substrate refractive index is n_s. The Eigen modes of the proposed waveguide sensor can be obtained by solving Maxwell's equations. The Helmholtz equation can be written as

$$\frac{\partial^2 \Psi(z)}{\partial z^2} + \omega^2 \varepsilon(z)\mu(z)\Psi(z) - \beta^2 \Psi(z) = 0$$

where ψ represents the electric field for TE-polarized light and the magnetic field for TM-polarized light; ω is the angular frequency of the field and β is the propagation constant in *x*-direction, which can be written as $\beta = k_0 N_{eff}$, where k_0 is the free space wave number, and N_{eff} is the modal effective index. Hence, the solutions of the proposed waveguide for different regions can be written as

$$\psi(z) = \left\{ \begin{array}{ll} Ac\, e^{(-ik_c z)} e^{i(\omega t - k_x x)} & \text{Cover layer} \\ \{Aa\, e^{(ik_a z)} + Ba\, e^{(-ik_a z)}\} e^{i(\omega t - k_x x)} & \text{Adlayer} \\ \{Af\, e^{(ik_f z)} + Bf\, e^{(-ik_f z)}\} e^{i(\omega t - k_x x)} & \text{Metamaterial layer} \\ \{Am\, e^{(ik_m z)} + Bm\, e^{(-ik_m z)}\} e^{i(\omega t - k_x x)} & \text{Metal layer} \\ As\, e^{(ik_s z)} e^{i(\omega t - k_x x)} & \text{Substrate layer} \end{array} \right\} \quad (1)$$

where

$$k_c = \sqrt{\beta^2 - n_c^2 k_0^2},\ k_a = \sqrt{n_A^2 k_0^2 - \beta^2},\ k_f = \sqrt{\beta^2 - n_f^2 k_0^2},$$
$$k_m = \sqrt{n_m^2 k_0^2 - \beta^2}, \text{ and } k_s = \sqrt{\beta^2 - n_s^2 k_0^2}$$

Now, applying the boundary conditions stating from Eq. (1) that ψ and $d_z\psi$ are continuous across the two boundaries for TE modes, ψ and $(n^{-2})\, d_z\psi$ are continuous across the two boundaries for TM modes. After applying boundary conditions, we get eight equations that can be written as

$$\Delta y = 0 \quad (2)$$

where

$$\Delta = \begin{bmatrix} A_{11} & A_{12} & A_{13} & A_{14} & A_{15} & A_{16} & A_{17} & A_{18} \\ A_{21} & A_{22} & A_{23} & A_{24} & A_{25} & A_{26} & A_{27} & A_{28} \\ A_{31} & A_{32} & A_{33} & A_{34} & A_{35} & A_{36} & A_{37} & A_{38} \\ A_{41} & A_{42} & A_{43} & A_{44} & A_{45} & A_{46} & A_{47} & A_{48} \\ A_{51} & A_{52} & A_{53} & A_{54} & A_{55} & A_{56} & A_{57} & A_{58} \\ A_{61} & A_{62} & A_{63} & A_{64} & A_{65} & A_{66} & A_{67} & A_{68} \\ A_{71} & A_{72} & A_{73} & A_{74} & A_{75} & A_{76} & A_{77} & A_{78} \\ A_{81} & A_{82} & A_{83} & A_{84} & A_{85} & A_{86} & A_{87} & A_{88} \end{bmatrix}$$

with

$$A_{11} = \exp(-k_s d_m),\quad A_{12} = -\exp(-ik_m d_m),\quad A_{13} = -\exp(ik_m d_m),$$
$$A_{14} = 0,\quad A_{15} = 0,\quad A_{16} = 0,\quad A_{17} = 0,\quad A_{18} = 0;$$

$$A_{21} = -k_s \exp(-ik_s d_m),\quad A_{22} = ik_m \exp(-ik_m d_m),$$
$$A_{23} = -ik_m \exp(ik_m d_m),\quad A_{24} = 0,\quad A_{25} = 0,$$
$$A_{26} = 0,\quad A_{27} = 0,\quad A_{28} = 0;$$

$$A_{31} = 0,\quad A_{32} = 1,\quad A_{33} = 1,\quad A_{34} = -1,\quad A_{35} = -1,\quad A_{36} = 0,$$
$$A_{37} = 0,\quad A_{38} = 0;$$

$$A_{41} = 0,\quad A_{42} = ik_m,\quad A_{43} = -ik_m,\quad A_{44} = -ik_f,\quad A_{45} = ik_f,$$
$$A_{46} = 0,\quad A_{47} = 0,\quad A_{48} = 0;$$

$$A_{51} = 0,\quad A_{52} = 0,\quad A_{53} = 0,\quad A_{54} = \exp(ik_f d_f),$$
$$A_{55} = \exp(-ik_f d_f),\quad A_{56} = -\exp(ik_a d_f),\quad A_{57} = -\exp(-ik_a d_f),$$
$$A_{58} = 0;$$

$$A_{61} = 0,\quad A_{62} = 0,\quad A_{63} = 0,\quad A_{64} = ik_f \exp(ik_f d_f),$$
$$A_{65} = -ik_f \exp(-ik_f d_f),\quad A_{66} = -ik_a \exp(-ik_a d_f),$$
$$A_{67} = ik_a \exp(-ik_a d_f),\quad A_{68} = 0;$$

$$A_{71} = 0,\quad A_{72} = 0,\quad A_{73} = 0,\quad A_{74} = 0,\quad A_{75} = 0,$$
$$A_{76} = \exp(ik_a(d_f + d_A)),\quad A_{77} = -\exp(-ik_a(d_f + d_A)),$$
$$A_{78} = -\exp(-ik_c(d_f + d_A));$$

$$A_{81} = 0,\quad A_{82} = 0,\quad A_{83} = 0,\quad A_{84} = 0,\quad A_{85} = 0,$$
$$A_{86} = ik_a \exp(ik_a(d_f + d_A)),\quad A_{87} = -ik_a \exp(-ik_a(d_f + d_A)),$$
$$A_{88} = k_c \exp(-ik_c(d_f + d_A)).$$

In order to get non-trivial solutions the determinant (Δ) would be zero, which leads to an equation identical to the mode equation found from the ray-tracing technique. The field distribution of proposed sensor is obtained by calculating the effective refractive index N_{eff} from Eq. (2) with an assumption that one of the field

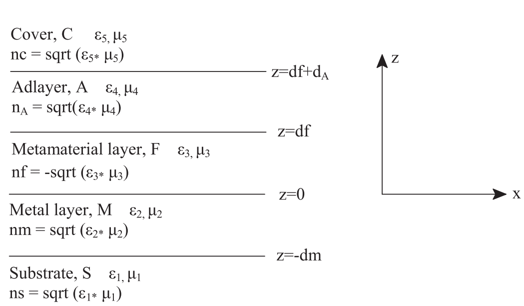

Fig. 1. Schematic diagram of a five layered structure with their thickness and refractive indices.