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Analytical Study of Planar Waveguide Sensor With a Metamaterial Guiding Layer

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Abstract: Sensitivities of three-layer and four-layer planar waveguide sensors having metamaterial as guiding layer are analyzed for p-polarization of incident light and compared with existing results. Proposed sensors show improved cover layer sensitivity for each case of the cover layer refractive index. Also, proposed sensors demonstrate improved adlayer sensitivity for different values of adlayer thickness and adlayer refractive indices. It is observed that metamaterial has increased the evanescent field due to the unconventional nature of it, by which values of cover layer sensitivity as well as adlayer sensitivity are enhanced.

Keywords: Metamaterials; sensitivity; three-layer planar waveguides; four-layer planar waveguides

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1. Introduction

Optical waveguide sensors are cause of prime attention for its suitability to detect airborne pathogens and water borne pathogens, due to properties like faster response time for pathogen detection, high accuracy, and online pathogen monitoring. Waveguide sensors also have other remarkable features such as resistance to electromagnetic interference, compact size, light weight, and ability to engraft with other structures. Environmental monitoring, pharmaceutical industries, and food industries are the other possible fields of applications for waveguide sensors. Moreover, waveguide sensors are used in chemical sensing, biosensing, and biochemical sensing [1–3]. Detecting small changes in refractive index of sensing within proximity of sensing layer is the basic precept of optical waveguide sensors.

Tienfenthalar and Lukosz introduced waveguide sensors in their research paper for the application of gas and humidity sensing by changing the refractive index of sensing medium [4]. Tiefenthalar and Lukosz made certain assumptions about adlayer for deriving sensitivity of three-layer waveguide sensor in order to simplify calculations. In this case, Tienfenthalar assumed that the adlayer thickness did not play any role in the sensitivity calculation. Here an adlayer can be simply defined as an additional layer of analyte formed due to homogenous adsorption of analyte over the guiding layer. However, the adlayer thickness in the rigorous sensitivity calculation not only affected but also enhanced the sensitivity of waveguide sensor [5]. In 2015, Upadhyay *et al.* [6] clearly proved that for transverse electric (TE) mode, the adlayer thickness

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played decisive role in the sensitivity calculation by using metamaterial as the guiding layer. Grating coupler is a surface with many parallel grooves in a periodical manner, and it affects sensitivity in immunosensing applications of waveguide sensor [7]. Other potential sensing based applications of grating coupler are anti-reflector [8], bio-sensors [9], and beam expanders [10]. In planar waveguide sensor penetration depth of the evanescent field in cover medium is limited to 150 nm–200 nm, which is sufficient for the detection of lipids bilayer, protein adsorption, and affinity binding [11, 12]. Therefore, the evanescent field penetration in sensing medium is a deciding factor for sensitivity of waveguide sensors. According to Quing and Cheng [13], the application of metamaterial could enhance the evanescent field of waveguide sensor for TE and transverse magnetic (TM) polarization of incident light. Recently, in 2016, Anurag *et al.* [14] verified that introducing metamaterial as the guiding layer improved the cover layer as well as the adlayer sensitivity of metal clad waveguide sensor. Metamaterial is an artificial manmade structure that posseses unconventional behavior, coined by Vesselego in 1968 [15]. The concept of super resolution imaging can be achieved by using metamaterial, which shows the amplification of evanescent fields [16]. The better immunosensing result is achieved by using metamaterial in the reverse waveguide sensor [17]. Refractometry detection limit of peak type metal clad waveguide sensor could also be enhanced by using metamaterial as the guiding layer [18]. Metamaterial as the guiding layer is able to enhance the sensitivity in the metal clad waveguide sensor as well as in planar waveguide sensor for TE mode polarization of the input light [19, 20]. Enhanced resolution limit is a result of using metamaterial in surface plasmon resonance (SPR) sensor having bi-metallic layer [21]. Complex permittivity and permeability of these materials are written as [22]

$$\varepsilon_i = 1 - \frac{\omega_p^2 l}{\omega^2 + \mathrm{i}\gamma\omega} \tag{1}$$

$$\mu_i = 1 - \frac{l\omega^2}{\omega^2 - \omega_r^2 + \mathrm{i}\gamma\omega} \tag{2}$$

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

The cover layer sensitivity and adlayer sensitivity are calculated for the three-layer and four-layer waveguide sensors having metamaterial as the guiding layer. An additional layer of analyte named as adlayer will form due to homogenous adsorption of analyte over the guiding layer. Hence, due to the adsorption of analyte over the guiding layer, the three-layer waveguide sensor is actually converted into the four-layer waveguide sensor.

This article is organized as follows. Section 2 includes theoretical background and essential formulas for investigating the sensor properties. In Section 3, the obtained results are analyzed and compared with existing results. Section 4 draws conclusion.

2. Theoretical background

The proposed structure of planar waveguide is comprised of four layers as shown in Fig. 1. Schematic diagram of a four-layer planar waveguide sensor is comprised of metamaterial guiding layer of guiding layer thickness d_g with two grating surfaces to launch and detach light properly into the waveguide.

The metamaterial with electric permittivity ε_g and permeability μ_g as mentioned in (1) and (2) respectively, is sandwiched between the substrate with refractive index n_s and adlayer with refractive index n_a. The cover layer of the waveguide sensor has refractive index n_c. In order to calculate the performance, the Maxwell's equation of the proposed waveguide is solved, and the obtained Helmholtz equation can be written as follows:

$$\frac{d^2\gamma(z)}{dz^2} + (\omega_0^2\varepsilon(z)\mu(z) - \beta^2)\gamma(z) = 0 \, . \tag{3}$$

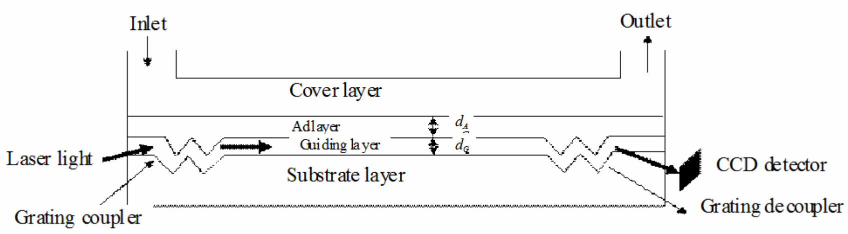

Fig. 1 Schematic diagram of the proposed planar waveguide sensor with an adlayer having refractive index n_a and width d_a. The refractive indices used are: $n_s=1.471$, $n_a=1.45$, 1.50, $n_g=\sqrt{(-4+\mathrm{i}0.001)(-2.4+\mathrm{i}0.001)}$, and $n_c=1.33$ or 1.40.

The solution of Helmholtz equation for each layer gives the following equation

$$\psi(z)=\begin{cases} \left(A_c^+ \exp-\mathrm{i}(k_X x+k_c z)\right)\exp\mathrm{i}(wt) & \text{Cover layer} \\ \begin{pmatrix} A_a^+ \exp-\mathrm{i}(k_X x+k_a z)+ \\ A_a^- \exp-\mathrm{i}(k_X x-k_a z) \end{pmatrix}\exp\mathrm{i}(wt) & \text{Adlayer} \\ \begin{pmatrix} A_g^+ \exp-\mathrm{i}(k_X x+k_g z)+ \\ A_g^- \exp-\mathrm{i}(k_X x-k_g z) \end{pmatrix}\exp\mathrm{i}(wt) & \text{Guiding layer} \\ \left(A_s^+ \exp-\mathrm{i}(k_X x+k_s z)\right)\exp\mathrm{i}(wt) & \text{Substrate layer} \end{cases} \quad (4)$$

assumed initially. Boundary condition for TM mode is $\Psi(z)$ and its derivatives $\frac{1}{n^2}\cdot\frac{d\psi(z)}{dz}$ are continuous across boundary. Six equations are obtained for TM mode because there are six values of amplitude in the four-layer waveguide Helmholtz equation solution. These six equations can be constituted as

$$A\,\gamma(z)=0 \quad (5)$$

where $\gamma(z)=\{A_s^-,\ A_g^+,\ A_g^-,\ A_a^+,\ A_a^-,\ A_c^+\}$, and A can be represented as

$$A=\begin{bmatrix} 1 & -1 & -1 & 0 & 0 & 0 \\ \frac{-K_s}{n_s^2} & \frac{-K_g}{n_g^2} & \frac{-K_g}{n_g^2} & 0 & 0 & 0 \\ 0 & e(\mathrm{i}k_g d_g) & e(-\mathrm{i}k_g d_g) & -e(\mathrm{i}k_a d_g) & -e(-\mathrm{i}k_a d_g) & 0 \\ 0 & \frac{K_g}{n_g^2}e(\mathrm{i}k_g d_g) & \frac{-K_g}{n_g^2}e(-\mathrm{i}k_g d_g) & \frac{-K_a}{n_a^2}e(\mathrm{i}k_a d_g) & \frac{-K_a}{n_a^2}e(-\mathrm{i}k_a d_g) & 0 \\ 0 & 0 & 0 & e\left[\mathrm{i}k_a(d_g+d_a)\right] & e\left[-\mathrm{i}k_a(d_g+d_a)\right] & -e\left[\mathrm{i}k_c(d_g+d_a)\right] \\ 0 & 0 & 0 & \frac{-K_a}{n_a^2}e\left[\mathrm{i}k_a(d_g+d_a)\right] & -\frac{-K_a}{n_a^2}e\left[-\mathrm{i}k_a(d_g+d_a)\right] & -k_c e\left[\mathrm{i}k_c(d_g+d_a)\right] \end{bmatrix} \quad (6)$$

where d_g and d_a are the thicknesses of the guiding layer and adlayer, respectively.

In order to get the nontrivial solution of (5), its determinant must be equal to zero, resultant of which gives the dispersion relation of the proposed waveguide sensor. The equations are as follows:

$$\phi_{\text{Total}}=2\,k_g\,d_g+\phi_{\text{gac}}+\phi_{\text{gs}}-2m\pi \quad (7)$$

$$\phi_{\text{gs}}=2\tan^{-1}\left(\mathrm{i}\,\frac{k_s}{k_g}\right) \quad (8)$$

$$\phi_{\text{gac}}=2\tan^{-1}\left[\mathrm{i}\left(\frac{1-r_{\text{ga}}}{1+r_{\text{ga}}}\right)\times\left(\frac{1-r_{\text{ac}}\exp(2k_a d_a)}{1+r_{\text{ac}}\exp(2k_a d_a)}\right)\right] \quad (9)$$

$$k_j=\sqrt{n_j-n_{\text{eff}}^2}\,. \quad (10)$$

Here phase shift at the guiding layer-substrate layer interface is denoted by ϕ_{gs}, and ϕ_{gac} describes the phase shift at the guiding layer-adlayer-cover layer interface. Further, d_g is the metal layer width, m signifies the mode number of propagating waves in the waveguide sensor, r_{IJ} is the reflection coefficients at I, J interface, k is the wave number, and $J=(c,\ g,\ a,\ s)$ [4]. In the four-layer structure, if we assume adlayer thickness $d_a=0$, then the four-layer sensor turns into a three-layer sensor:

$$r_{\text{gac}}=r_{\text{gc}}\,. \tag{11}$$

With the help of implicit characteristics, mode equations for Tienfenthalar [4], four-layer waveguide sensor, and the proposed model are written as

$$\alpha\left[x,n_{\text{eff}}(x)\right]=2\pi m \tag{12}$$

where $x=[n_s,\ n_g,\ n_a,\ n_c,\ d_g,\ d_a]$ for the proposed model and partially differentiating (12). The result of partial differentiation of the above equation is as follows:

$$\frac{d_\alpha}{d_x}+\frac{d_\alpha}{d_{\text{neff}}}\cdot\frac{d_{\text{neff}}}{d_x}=0\,. \tag{13}$$

Hence,

$$\frac{d_{\text{neff}}}{d_x}=-\frac{d_\alpha}{d_x}\bigg/\frac{d_\alpha}{d_{\text{neff}}}\,. \tag{14}$$

The effective refractive index of the guiding layer is affected by the polarization of incident light i.e. TE/TM thickness of guiding layer, refractive index of the substrate, metamaterial guiding layer, thickness of adlayer, and mode number. Sensitivity of sensor may change due to either variation in the refractive index of cover medium or variation in the surface absorption above the film layer. Hence, with the help of (14), the cover layer and adlayer sensitivities are analyzed for Tienfenthalar [4], the four-layer waveguide sensor (the dielectric guiding layer), and proposed models.

3. Results and discussions

The proposed structure is analyzed by using the He-Ne laser beam with the wavelength 632.8 nm for p-polarization. The proposed structure is comprised of semi-infinite substrate of refractive index 1.471, an adlayer of thickness d_a and refractive indices 1.50 and 1.45 are used, while the cover layer has an aqueous medium of refractive indices 1.33 and 1.40. The proposed structure has a metamaterial guiding layer of thickness d_g which has permittivity (ε_g) and permeability (μ_g) equal to $-4.0+\text{i}\ 0.001$ and $-2.4+\text{i}\ 0.001$ respectively and refractive index of the metamaterial guiding layer can be calculated by $-\sqrt{(\varepsilon_g\times\mu_g)}$. Lossless metamaterial is an ideal hypothesis, but for achieving approximate ideal behavior metamaterial having minimal absorption coefficient is generally preferred. The effect of metamaterial on cover layer and adlayer sensitivities is analyzed by using (7) and (14).

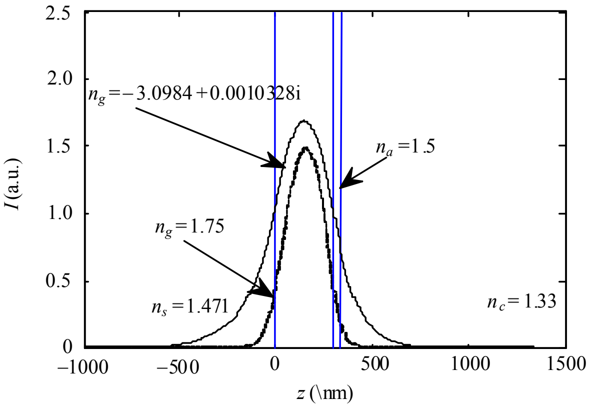

Fig. 2 Calculated TM mode profile of electromagnetic field for the proposed and conventional waveguide structures. The mode profile is shown for guiding layer thickness (d_g) = 300 nm and adlayer thickness (d_a). The refractive indices used in the simulation are: $n_s=1.471$, $n_a=1.50$, and $n_c=1.33$.

From Fig. 2, it is seen that TM mode profile ($m=0$) for the configuration is asymmetric with the evanescent field extending into cover and substrate. The evanescent field in the cover medium is lesser than the evanescent field in the substrate region due to a large refractive index of substrate layer. The evanescent field lasts hundreds of nanometers in the cover layer for the proposed four-layer structure and four-layer dielectric sensors. However, magnetic field strength of the proposed sensor is much larger compared with the four-layer dielectric sensor, because metamaterial enhances the evanescent field which is clearly shown in Fig. 2. Henceforth, sensitivity enhancement could be obtained by using the metamaterial guiding layer. Figure 3 shows a plot of $\delta_{\text{neff}}/\delta_{nc}$ against metamaterial guiding layer thickness for three-layer and four-layer waveguide sensors for the cover layer refractive index value equal to 1.33.

From Fig. 3, it is seen that the proposed three-layer sensor attains peak value equal to 0.3531 (solid line) at 80 nm, while the three-layer Tienfenthalar model [4] achieves peak value equal to 0.162 (circular dot) at 140 nm. On the other hand, the proposed four-layer waveguide sensor attains the peak value equal to 0.2938 (dash) at 140 nm, while the four-layer waveguide sensor attains its peak value equal to 0.2272 (square) at 200 nm.

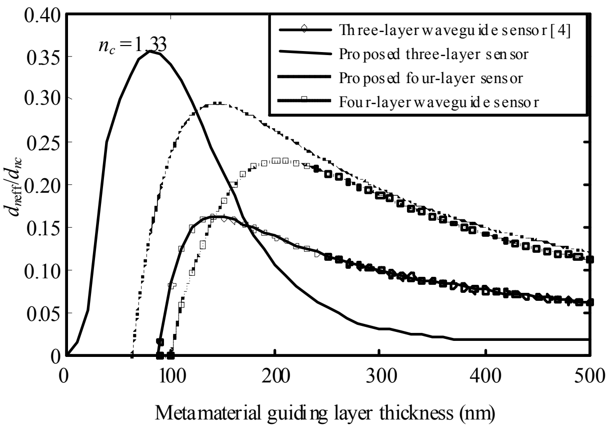

Fig. 3 Plot of cover layer sensitivity variation versus film thickness for the proposed three-layer and four-layer sensors, three-layer waveguide sensor proposed in [4], and four-layer waveguide sensor (dielectric guiding layer). The refractive indices used in the simulation are: $n_s = 1.471$, $n_a = 1.45$, and $n_c = 1.33$.

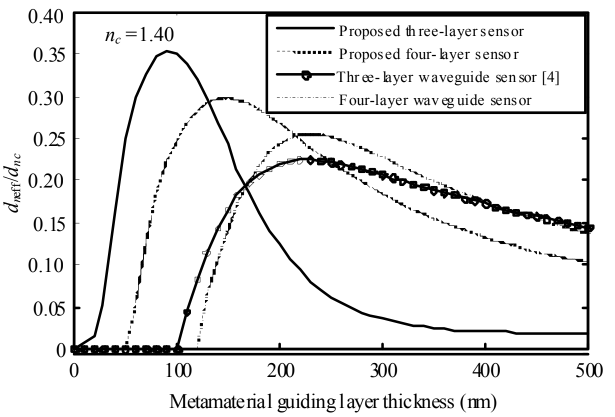

Fig. 4 Plot of cover layer sensitivity variation against film thickness for the proposed three-layer and four-layer sensors, three-layer waveguide sensor proposed in [4], and four-layer waveguide sensor. The refractive indices used in the simulation are: $n_s = 1.471$, $n_a = 1.45$, and $n_c = 1.40$.

Figure 4 demonstrates a graph of $d_{n_{\mathrm{eff}}} / d_{n_c}$ versus metamaterial guiding layer thickness for three-layer and four-layer waveguide sensors for the cover layer refractive index value equal to 1.40. From Fig. 4, it is concluded that the proposed three-layer sensor attains peak value equal to 0.3531 (solid line) 90 nm, while the three-layer Tienfenthalar model [4] achieves peak value equal to 0.2239 (square) at 220 nm. On the other hand, the proposed four-layer waveguide sensor attains peak value equal to 0.298 (dash) at 150 nm, while the four-layer waveguide sensor attains its peak value equal to 0.2553 (dash-dot) at 230 nm.

From Figs. 3 and 4, it is seen that the sensitivity curve is zero upto cut-off thickness of guiding layer while for larger thickness of guiding layer, sensitivity also approaches to zero. The sensitivity curve attains the maximum value in between these points for which most of the mode power flows in the cover layer compared with other points in the graph. The proposed three-layer and four-layer waveguide sensors attain much higher peak value compared with Tienfenthalar [4] and four-layer waveguide sensor at lower values of guiding layer due to the lossy nature of metamaterial, and its adsorption coefficient increases with an increase in thickness [23]. Hence, the proposed sensor can be of compact in size. Therefore, from the above discussion, it can be concluded that the cover layer sensitivity of the proposed three-layer and four-layer waveguide sensors is much larger compared with Tienfenthalar and the four-layer waveguide sensor as shown in Table 1. A rapid decrement in the sensitivity curve is observed with an increase in the value of metamaterial guiding layer thickness for the proposed three-layer sensor, due to the lossy and backward wave propagation [24] nature of metamaterial. However, an adlayer over metamaterial improves the real part of the metamaterial refractive index, which makes metamaterial less lossy in nature, i.e. tends to ideal nature of metamaterial. Therefore, for the proposed four-layer sensor to increase the value of metamaterial guiding layer thickness, the lesser decrement in the curve is observed compared with the proposed three-layer sensor. The four-layer waveguide sensor is more sensitive compaing with the three-layer waveguide sensor for thicker values of guiding layer [23].

Table 1 Variation in cover layer sensitivity versus metamaterial guiding layer thickness. Other parameters are: n_s= 1.471, n_a=1.45, n_c=1.33, and 1.40.

Type of sensor (model)	Refractive index (n_c)	Maximum sensitivity ($\delta_{\mathrm{neff}}/\delta_{nc}$)	Film thickness (nm)
Proposed Three-layer model	1.33	0.3531	80
	1.40	0.3531	90
Three-layer model proposed in [4]	1.33	0.1620	140
	1.40	0.2239	220
Proposed four-layer model	1.33	0.2938	140
	1.40	0.298	150
Four-layer waveguide sensor	1.33	0.2272	200
	1.40	0.2553	230

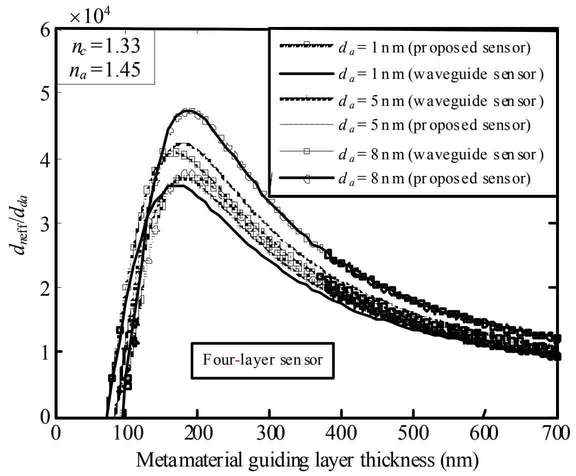

Fig. 5 Plot of adlayer sensitivity variation against film thickness of proposed and conventional four-layer sensors for adlayer refractive index n_a=1.45, in which the refractive indices used are: n_s=1.471 and n_c=1.33.

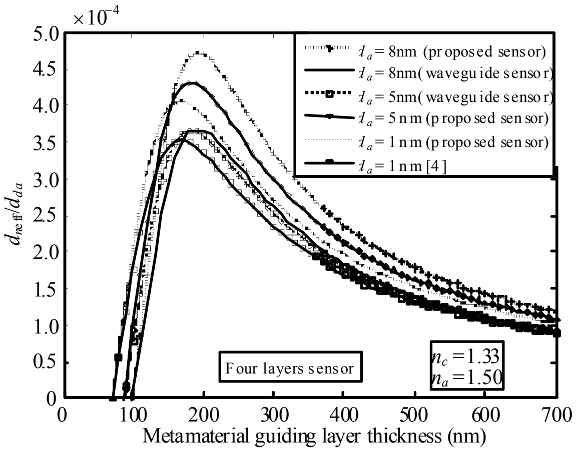

Fig. 6 Plot of adlayer sensitivity variation against film thickness of proposed and conventional four-layer sensors for adlayer refractive index n_a=1.50, in which the refractive indices used are: n_s=1.471 and n_c=1.33.

Figures 5 and 6 demonstrate sensitivity variation ($\delta_{\mathrm{neff}}/\delta_{da}$) against guiding layer thickness for adlayer refractive indices values equal to 1.45 and 1.50, respectively. Figure 5 shows change in adlayer sensitivity versus metamaterial guiding layer thickness for different adlayer thicknesses at adlayer refractive index 1.45. Peak values observed for THE proposed sensor at adlayer thickness 1 nm, 5 nm, and 8 nm are 4.08×10^{-4} nm^{-1} (square line), 4.23×10^{-4} nm^{-1} (dash line), and 4.73×10^{-4} nm^{-1} (circular dot-solid line) while for four-layer waveguide sensor the values for 1 nm, 5 nm, and 8 nm thicknesses are 3.57×10^{-4} nm^{-1} (square line), 3.69×10^{-4} nm^{-1} (plus line), and 3.76×10^{-4} nm^{-1} (circular dot-dash line), respectively. Therefore, increasing adlayer thickness d_a, adlayer sensitivity increases despite the thickness being far smaller compared with the incident wavelength. Therefore, sensitivity is the function of adlayer thickness.

Figure 6 illustrates a graph of adlayer sensitivity ($\delta_{\mathrm{neff}}/\delta_{da}$) versus guiding layer thickness for a fixed value of adlayer refractive index 1.50. The peak value observed at adlayer thickness 1 nm, 5 nm, and 8 nm for proposed sensor, are 4.06×10^{-4} nm^{-1} (dot line), 4.32×10^{-4} nm^{-1} (solid line-diamond), and 4.72×10^{-4} nm (dot line- plus) while for four-layer waveguide sensor the peak values for thickness 1 nm [4], 5 nm, and 8 nm are 3.52×10^{-4} nm^{-1} (square dot), 3.65×10^{-4} nm^{-1} (circular dot), and 3.67×10^{-4} nm^{-1} (solid line), respectively. It is observed that adlayer sensitivity increases more rapidly for adlayer refractive index 1.45 with respect to adlayer refractive index 1.50. Cut-off thickness values and optimal peak values are affected by presence of adlayer. It is observed that these values increase by increasing adlayer thickness even in the case of metamaterial guiding layer, i.e. the proposed sensor. Therefore, adlayer sensitivity increases for the proposed sensor compared with that proposed by Tienfenthlar [4] and the four-layer waveguide sensor. Also, the sensitivity can be controlled by film and adlayer thicknesses both. However, an increase in adlayer sensitivity is less prominent than cover layer sensitivity. Also, it is observed that the proposed sensor is better than the dielectric guiding layer based sensor in terms of adlayer sensitivity as shown in Table 2.

Table 2 Variation of adlayer sensitivity with adlayer and metamaterial film thicknesses.

Type of Sensors	Adlayer refractive index	Adlayer thickness (nm)	Film thickness (nm)	Maximum adlayer sensitivity ($\delta_{neff}/\delta_{nc}$) ($10^{-4}$ nm^{-1})
Proposed four-layer sensor	1.45	1	170	4.08
		5	180	4.23
		8	190	4.76
	1.50	1	168	4.06
		5	180	4.32
		8	190	4.72
Four-layer waveguide sensor	1.45	1	172	3.57
		5	183	3.69
		8	190	3.76
	1.50	1 [4]	170	3.52
		5	180	3.65
		8	192	3.67

Refractive index of cover layer changes by changing the refractive index of analyte, and hence the peak of cover layer sensitivity shifts towards higher value of guiding layer thickness. By measuring shifts in peaks, one can predict the refractive index of analyte. Sensitivity peaks are sharper for sensor having a metamaterial guiding layer while for dielectric guiding layer sensor peaks are obtuse in nature. Hence, the signal to noise ratio is low for the metamaterial guiding layer comparing with the dielectric guiding layer. This information can be extracted easily.

4. Conclusions

Present work deals with the sensitivity analysis of three-layer and four-layer waveguide sensors having a guiding layer of metamaterial. Cover layer sensitivity is enhanced for three-layer sensor as well as four-layer waveguide sensor due to unconventional properties of metamaterial. Therefore, change in the cover layer refractive index is effectively detectable, and larger molecule detection as compared with the dielectric sensors, is possible. By changing adlayer thickness, adlayer sensitivity has been increased together with large shift in the peak positions observed. An increase in sensitivity as well as a shift in peak position of the curve shows an increase in the resolution of proposed sensor. Hence, the proposed sensor can be efficiently used for biosensing. Thus adlayer plays an important role in sensitivity calculation. Therefore, adlayer can't be overlooked even if it has much smaller dimension than incident wavelength. By adjusting the size and period of metamaterial, its properties can be tailored further. Hence, sensitivity can be enhanced by adjusting the size of the metamaterial guiding layer.

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