Improvement of the Sensivity of Nano Biosensors By Multilayered Structures

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Abstract—**This paper presents a multilayer surface plasmon resonance biosensor (SPRB). The aim of the proposed multilayer structure is to improve the sensitivity of the SPRB through monitoring of the biomolecular interactions of DNA hybridization. For this purpose, the sensing surface is immobilized with the ssDNA specific to the corresponding cDNA to allow the hybridization reactions. The binding of the target DNA (cDNA) to its receptor counterpart produces a RI change which is gradually increased during the course of the DNA hybridization reaction. Our numerical results show that the proposed SPR substrate with a dielectric grating can provide a better sensitivity due to the field distribution at the binding region .This paper presented the design of a multilayer SPRB with theoretically and computationally developed frameworks for analysis of its performance. A comprehensive numerical analysis was carried out to investigate the effect of the design parameters including grating configurations, grating height and grating period on the performance of this biosensor.**

Keywords-: Biosensor; sensitivity enhancement; grating; surface plasmon resonance

I. INTRODUCTION

Many optical biosensors are based on the phenomenon of surface plasmon resonance (SPR) techniques. In other words SPR is an optical sensing technique based on electromagnetic phenomenon in which surface plasmon polaritrons (SPP) waves are used to probe the interactions between target biomolecules and receptor molecules [1].

Since the SPR condition is modified based on the refractive index change, the method becomes an important tool for studying bimolecular interactions in pharmaceutical and biomedical research [2]. During the sensing operation, the adsorption of biomolecules to the receptor molecules will produce a local change in the refractive index (RI) at the metal-dielectric interface. The RI change will then further affect the propagation constant of the SPPs [3].

One of the issues with the conventional SPRBs is insufficiency of the detection sensitivity faced with low concentration analytes.

A multilayer SPRB is one of the newly introduced approaches for improving sensitivity and accuracy of biosensing [4]. Nano grating structure is one of the best ways to improve sensitivity that recently which has recently attracted the attention of researchers. It was demonstrated that the field distribution at the binding region due to the presence of grating improves sensitivity [5].

The proposed SPR biosensor consists of gold layer that is covered with periodic dielectric grating. The use of nano grating allows strong optical coupling of incident light (through surface plasmon polaritons (SPPs) excited on a thin metallic film) to localized resonances in nano grating, (localized surface plasmons (LSPs)). The strong interaction between SPPs and LSPs and between LSPs can present different resonance properties, resulting in an additional shift of resonance angle.

This proposed multilayer biosensor, modelled, and simulated using the finite element method (FEM) and the finite difference frequency domain (FDFD) methods. In this paper sensitivity enhancement as regards to varying S-parameters will be studied. In this way some parameters as changes of refractive index (RI) resulted during the course of DNA hybridization reaction, grating configurations, grating height, grating period will be applied.

II. MATERIALS AND METHOD

A schematic of the proposed SPR biosensor is shown in Fig.1. To excite the surface Plasmon to match the evanescent wave, the laser beam is coupled with a prism (flint glass prism). The base of the prism is covered by a thin gold film. The thicknesses of the gold layer fixed at 50 nm. One dimensional rectangular grating with a period of (p_g) width (w_g) and height (h_g), patterned on gold/flint glass prism that supporting the SP waves. The initial value of p_g, w_g and h_g selected at 35 nm, 60 nm and 200 nm, respectively.

TM-polarized plane wave light of fixed wavelength 632.8 nm to excite SPs illuminates the prism.

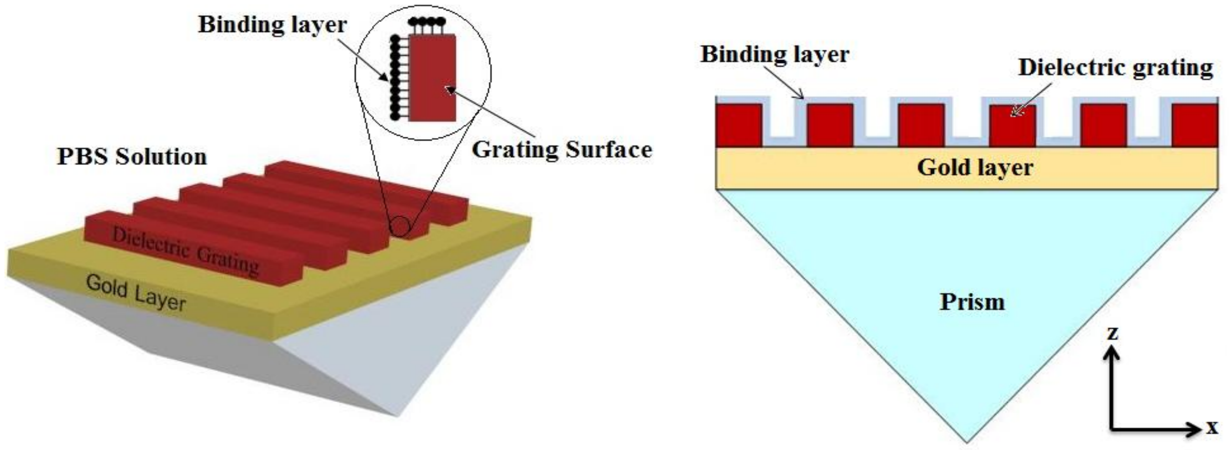

Figure 1. Schematic of the proposed SPR biosensor

Materials used in this simulation are defined using introduced articles and related dispersive theory. For example RI of gold is defined from the Drude model [25]. The RI of the fused silica glass prism is described by the Sellmeier dispersion formula [26]. And, the optical constants $\varepsilon(n,k)$ of dielectric grating selected (1.50, 0) [e.g., polymethyl methacrylate (PMMA)].

III. Results and Discussion

The base of proposed biosensor performance is DNA self assembly characteristics. the result indicated that due to the hybridization between single-stranded DNA (ssDNA) and complementary DNA (csDNA) (based on the self assembly property in DNA) to from a double stranded DNA (dsDNA) on the surface of biosensors, the RI of surrounding medium changes which leads to changes in the characteristics of SPR and change in the output of the sensor (e.g., change of reflectance and transmittance intensity, far field and magnetic field, etc.). In other words the refractive indexes resulted from the DNA hybridization will then further affect the propagation constant of the SPPs and shift of the optical characteristics like S-parameter. The changes of S-parameter caused by biomolecular interactions onto the sensing surface considered as detection of target biomolecules [8].

With the attachment of the ssDNA, the initial refractive index of the immobilized ssDNA is assumed to be 1.452 for a density of 0.028 g/cm^3 obtained from the ellipsometry measurements [6]. This amount of RI During the course of DNA hybridization reaction increases and Refractive index of dsDNA in the end reported to be 1.52 [7]. As a quantitative measure of the biosensor performance a quantities may be introduced. Sensitivity enhancement factor (SEF), a ratio of S-parameter shift due to target analyte binding on a grating based biosensor to that of a conventional SPR structure using a thin gold film with equal thickness is defined as:

$$SEF = \frac{\Delta S_{NGSPR}}{\Delta S_{SPR}} \quad (1)$$

$$SEF = \left| \frac{S_{NGSPR}(with\ analyte) - S_{NGSPR}(without\ analyte)}{S_{SPR}(with\ analyte) - S_{SPR}(without\ analyte)} \right| \quad (2)$$

The following condition must be maintained to excite the SPs on the metal- dielectric interface [8]:

$$K_{sp} = K_{ev} = \frac{2\pi}{\lambda}\sqrt{\frac{\varepsilon_M \varepsilon_{D,eff}}{\varepsilon_M + \varepsilon_{D,eff}}} = \frac{2\pi}{\lambda}\sqrt{\varepsilon_P}\, sin\theta_{res} \quad (3)$$

where k_{sp} and k_{ev} are the wave vectors of the propagation constant of the surface plasmon and the evanescent wave, respectively, and c is the speed of light. ε_M and ε_D are the dielectric constants of metal and dielectric layer, respectively and $\varepsilon_{D,eff}$ is the effective permittivity of grating layer and surrounding dielectric analytes.

Mth-order momentum matching between an incident photon and a surface plasmon, In the presence of the grating is given by:

$$k_{SP}^{(m)} = k_{x,photon} sin\theta_i \pm m k_{grating} = \frac{2\pi}{\lambda} n_P sin\theta_i \pm m\frac{2\pi}{P} \quad (4)$$

where $k_{x,photon}$ and $k_{grating}$ are the wave vectors of an incident photon and grating respectively, $k_{SP}^{(m)}$ is the wave vector of surface plasmon polariton mode excited by the mth order of diffraction, m (=0,1,2…) is the diffraction order, P is the diffraction grating period [8].

A. *Effect of Grating period*

Reduction of a grating period P is another effective way to increase the surface reaction area. For the subewavelength grating-mediated interactions between LSP and target bioanalytes, the following momentum matching relation is preserved:

$$k_{SP}^{(m)} = \frac{2\pi}{\lambda} n_P sin\theta_{res} \pm m\frac{2\pi}{P} = \frac{2\pi}{\lambda}\sqrt{\frac{\varepsilon_M \varepsilon_{D,eff}}{\varepsilon_M + \varepsilon_{D,eff}}} \qquad (5)$$

According to equation (5) if $\lambda \gg P$, meaning that no higher order diffraction is excited. On the other hand by increase in P above a certain limit the effect of radiation damping, which indicates that the incident light is interfered by the diffracted beam can affect the sensitivity of the sensor. Hence, the optimized diffraction grating period can be fashioned to obtain the required SPR condition [8].

TABLE I. SENSITIVITY ENHANCEMENT FACTOR FOR DIFFERENT GRATING PERIODS

SEF	Period, P (nm)
5.616219951	150
4.263583955	200
3.22256317	250
3.06025472	300
2.99687415	350

As shown in Table 1, the SEF decreases almost exponentially with P.

Fig. 2 shows the SEF versus the grating period. It is demonstrated that the SEF decreases almost with P.

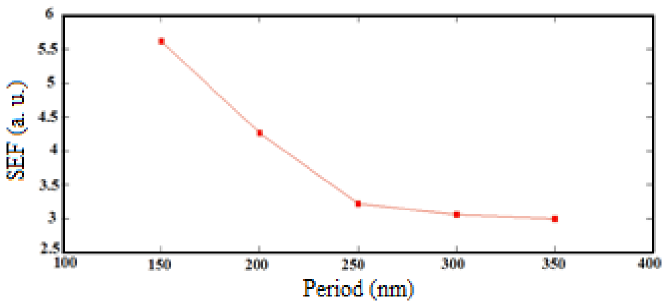

Figure 2. SEF versus the nano grating period

B. *Effect of Grating Configurations*

As shown in the Fig. 3 sensitivity enhancement increased with the increase of RI. Based on the results the best SEF for proposed structure obtained for sinusoidal gratings.

C. *Effect of Grating Thickness*

As shown in the Fig. 4 as a grating thickness h_g increases from 5 to 100 nm, at initial stage sensitivity increased with the grating thickness. However, when h_g exceeds 35 nm, sensitivity becomes decreased.

In general, if LSPs are dominated by SPPs, local field enhancement and sensitivity improvement over conventional SPR structure is rather weak. On the other hand, if LSPs dominate SPPs in thick nano gratings, resonance characteristics tend to be so broad that resonance can effectively disappear.

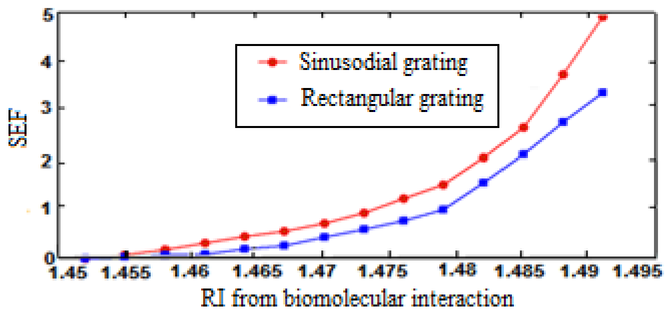

Figure 3. Sensitivity enhancement factor in response to the refractive index changes

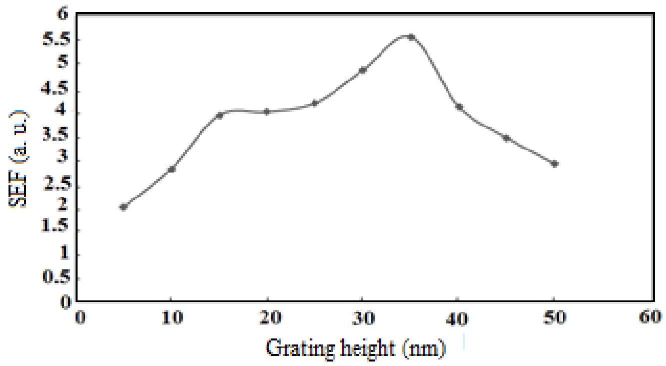

Figure 4. SEF versus the nano grating height

In Fig. 5 show that the field amplitude reaches a maximum at the metal surface and then falls exponentially along the z-axis. The peak amplitude of E_x increased with the grating thickness until h_g=35 nm, with a larger increase in thickness the E_x become weak.

On the bottom a summary of the investigations of the SPDM for the proposed SPRB is shown in Fig. 6. As is clear from Fig. 6 the proposed structure can enhance sensitivity compared to the conventional SPRB. It was found that a periodic grating of comparatively narrow width, lower VF, lower period, and moderate depth can lead to a higher SEF of up to five.

IV. CONCLUSION

We have presented in this paper the design and analysis of a multilayer SPR biosensor using the FDFD method. A numerical analysis was carried out to investigate the effect of the design parameters including grating configurations, grating height, grating angle, VF, and grating period on the performance of the SPRB.

In this paper by employing the S-parameters-based detection it was demonstrated that proposed structure will improve sensitivity and the speed of detection. The SEF of up to five can be obtained with the h_g=35 nm, p_g =150 nm, while this factor is equal to 4 for conventional biosensors. So it was found that a periodic grating can lead to a higher SEF compared with conventional biosensors.

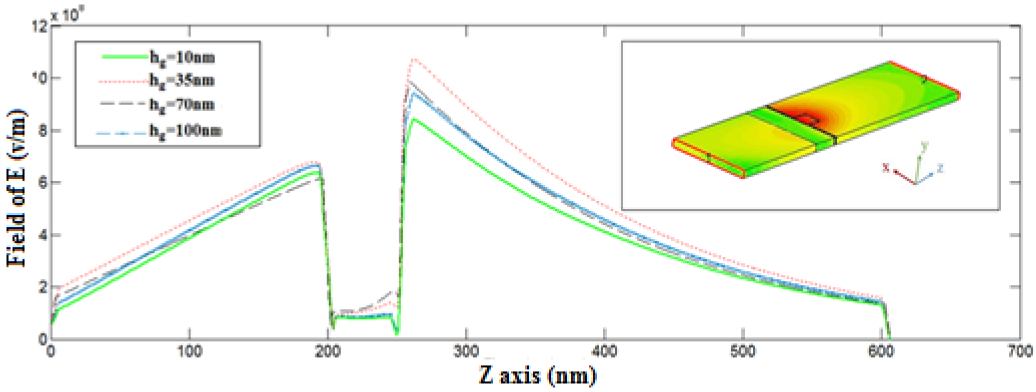

Figure 5. Vertical field of E_x along z axis when the SPR structure process dielectric grating of $h_g = 10, 35, 70, 100$ nm

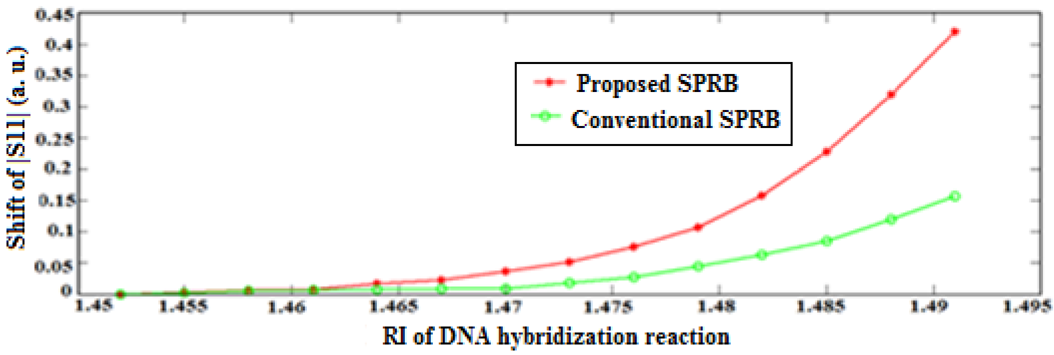

Figure 6. Change of the magnitude of s_{11}in response to the refractive index change

V. References

[1] Homola, J., S.S. Yee, and G. Gauglitz, Surface plasmon resonance sensors: review. Sensors and Actuators B: Chemical, 1999. 54(1): p. 3-15.

[2] Islam, M., et al., Design and analysis of a multilayer localized surface plasmon resonance Graphene biosensor. Journal of biomedical nanotechnology, 2012. 8(3): p. 380-393.

[3] Xinglong, Y., W. Dingxin, and Y. Zibo, Simulation and analysis of surface plasmon resonance biosensor based on phase detection. Sensors and Actuators B: Chemical, 2003. 91(1): p. 285-290.

[4] Wu, L., et al., Highly sensitive graphene biosensors based on surface plasmon resonance. Optics express, 2010. 18(14): p. 14395-14400.

[5] Jung, W.K., N.-H. Kim, and K.M. Byun, Numerical study on an application of subwavelength dielectric gratings for high-sensitivity plasmonic detection. Applied optics, 2012. 51(20): p. 4722-4729.

[6] Choi, S.H., Y.L. Kim, and K.M. Byun, Graphene-on-silver substrates for sensitive surface plasmon resonance imaging biosensors. Optics express, 2011. 19(2): p. 458-466.

[7] Gray, D., et al., Ellipsometric and interferometric characterization of DNA probes immobilized on a combinatorial array. Langmuir, 1997. 13(10): p. 2833-2842.

[8] Islam, M.S. and A.Z. Kouzani, Simulation and Analysis of a Sub-Wavelength Grating Based Multilayer Surface Plasmon Resonance Biosensor. Journal of Lightwave Technology, 2013. 31(9): p. 1388-1398.