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Research Article

Designing a sensitive plasmonic-based 1D photonic crystal biosensor with graphene and two metal layers

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Abstract

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In the present paper, we propose a surface plasmon resonance biosensor in combination with a photonic crystal that works based on changing the refractive index of the biomaterial using the transfer matrix method to diagnose blood components. The proposed biosensor structure is (TiO_2/ SiO_2)^2/ silver/ gold/ graphene, which gives a narrow angular reflectivity resonance. The performance parameters of biosensors such as sensitivity, and detection accuracy reported. Our results show that the sensitivity of the proposed configuration is 150 deg/RIU, which is acceptable compared to the values reported in previous studies and shows better performance of the proposed biosensor.

Keywords

biosensor, graphene, photonic crystal, surface plasmon resonance, sensitivity.

I. Introduction

Optical biosensors are extensively used devices with prominent applications such as health care, medicine, food quality control, environmental analysis, security, and monitoring of industrial and chemical processes [1-3]. Optical biosensors have numerous benefits over other biosensors due to their outstanding characteristics such as high sensitivity and accuracy detection, compact size and low cost, and ability to detect various biological molecules directly and realistically [4,5]. Many unlabeled biosensors, for instance, monitor the changes in refractive index (RI) resulting from molecular interactions on a sensitive surface. This change is directly proportional to the concentration or density of the analyte surface and, unlike fluorescence-based assay settings, could be identified by simple assay processes without any modification or labeling approach that disrupts the molecular interactions. Surface plasmon resonance biosensors are a type of optical biosensors in which a change in the sensor region results in a change in the resonant wavelength or resonant angle [6]. They are distinguished by their high sensitivity, ultra-compact size, and ease of integration with various electro-optical circuits on the chip, promising improved optical bio-sensing capabilities [7,8]. In the last few decades, photonic crystals (PC) have attracted the interest of many researchers to design different types of optical sensors with their simple alternating structure [9]. PCs emerged as fascinating photonic structures in recent decades, and they play a vital role in biomedical sensing and other applications. PCs have a significant influence in designing a variety of photonic sensors due to their compactness, high selectivity, fast responsiveness, high sensitivity, immunity to electromagnetic noise, etc [10,11]. The physical properties of the photonic crystals are modified to generate sensors for a variety of applications such as temperature, pressure, stress, gas, chemical, biomaterials, and so on. PC-based biosensors ensure rapid response, low losses, and good quality factors with excellent accuracy. Several sensing schemes such as surface plasmon resonance, infrared (IR) absorption, and Refractive index (RI) sensing are used and being explored using different PC design structures [12]. Effective RI sensing is the most common sensing mechanism used in biosensors and the optical properties of the sensors are analyzed by comparing the spectral properties of the transmitted and reflected power. Graphene and plasmonic research are two rich and exciting disciplines of study that strongly overlap [13]. Not only does graphene have internal plasmons that are adjustable, and relatively low loss, but also the combination of graphene with noble metal nanostructures promises a variety of exciting applications for ordinary plasmonic. Graphene adaptability means that graphene-based plasmonic can enable the construction of new frameworks based on a two-dimensional layer of carbon atoms arranged in a honeycomb network.

Graphene possesses exceptional mechanical, electrical, and thermal properties. Many research programs explored by academia and industry appreciate graphene's unique properties such as nanoscale size, high hardness and mechanical strength, high optical transparency, adjustability, extremely high electrical and thermal conductivity, flexibility acceptance, and surface-to-volume ratio [14]. Interestingly, graphene has shown its true nature in optics and is the first commercial use of graphene. Graphene has extremely high quantum efficiency for material interactions and strong optical nonlinearity, it contains unusual plasmons. So far, much research in the field of optics and photonics has been done concerning graphene [15]. Gold is chemically stable in many environments (aquatic environments, etc.) and shows a lot of resonance. However, it has a large spectrum width that reduces the accuracy of the diagnosis. Conversely, silver has a sharper peak resonance than other plasmonic materials. However, silver is not chemically stable and oxidizes easily. Silver film with graphene coating can solve the oxidation problem [16]. In this article we proposed a biosensor sensitive to change of refractive index with high sensitivity for detecting blood components, (refractive index of blood components varies based on its chemical, physical, and biological properties). The proposed biosensor is a surface plasmon resonance sensor in the presence of a photonic crystal.

II. Structure

The configuration of the proposed biosensor illustrated in Fig. 1 is made up of the BK-7 prism with a refractive index of 1.51509, alternating layers of TiO_2 and SiO_2 photonic crystals with thicknesses of 40 and 100 nm and refractive index of 2.232 and 1.450, respectively, with periodicity of 2. Gold and silver metal layers with thicknesses of 5 and 40 nm and permittivity of $0.1726 + 3.4218i$ and $0.059 + 4.243i$ are considered on photonic crystal layers. Finally, a monolayer graphene with a thickness of 0.34 nm on the mentioned layers is supposed.

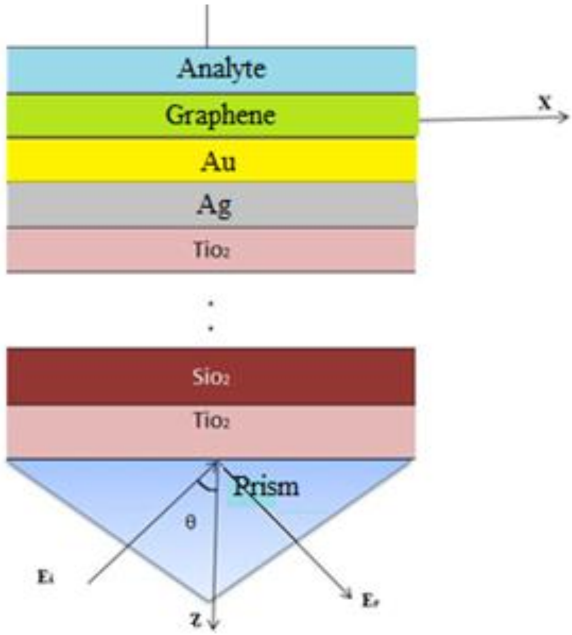


Fig. 1 Schematic view of proposed biosensor

The refractive index of graphene is calculated according to the Eq. 1 at each wavelength [17]:

$$n = 3 + iC\lambda/3 \quad (1)$$

Where the constant value of C is equal to $5.466\mu m^{-1}$

The biological substance is various blood components such as water, krypton, blood plasma, ethanol, and hemoglobin with refractive index of 1.33, 1.34, 1.35, 1.36, 1.38, respectively [18].

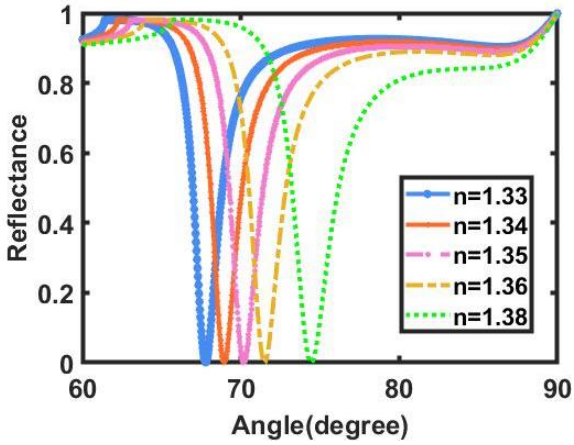
III. Results

Light with TM polarization incident on the prism and the evanescent wave reaches the metal layers, generating surface plasmon resonance at the graphene-analyte interface. The reflection spectrum of the biosensor was studied using the transfer matrix method (TMM) and MATLAB programming. For TM polarization, the transfer matrix of the i_{th} layer is expressed as Eq. 2. [19]

$$M_i = \begin{bmatrix} cos\partial_i & \frac{-i}{\gamma_i} sin\partial_i \\ -i\gamma_i sin\partial_i & cos\partial_i \end{bmatrix} \quad (2)$$

Where $\partial_i = \omega n_i d_i cos\theta_i / c$, $\gamma_i = \frac{n_i}{cos\theta_i}$, in the refractive index of layer i, di, and θi indicates the thickness and the incident angle of layer i, respectively.

The



reflection matrix of the whole structure can be written as:

$$M = \prod_{i=1}^{N} M_i = \begin{pmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{pmatrix} \quad (4)$$

The reflection coefficient r can be given as:

$$r = \frac{(M_{11}+M_{12}\gamma_0)\gamma_0-(M_{21}-M_{22}\gamma_0)}{(M_{11}+M_{12}\gamma_0)\gamma_0+(M_{21}+M_{22}\gamma_0)} \quad (5)$$

The reflectance equal to $R(\omega)=|r^2|$.
So, the reflection spectrum of the biosensor is shown in Fig. 2.

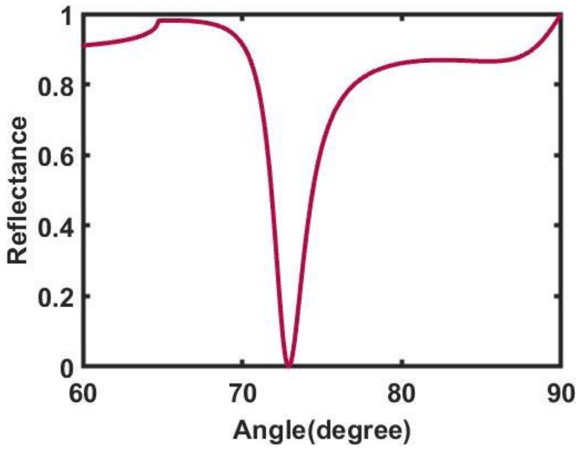


Fig. **2** The reflection spectrum of the biosensor

The resonance angle at which the value of reflection in the reflection spectrum, decreases sharply ($5.18*10^{-5}$) is 73.27.

whit the refractive index of the biomaterial changes, the resonant angle shifts (see Fig. 3). It shows that even very small changes in the refractive index of biomaterials (in the range of 0.01) cause significant displacements in the plasmon resonance angle. This indicates that the designed biosensor is very sensitive to refractive index changes, and since changes in the refractive index of biomaterials are not very severe, this biosensor can be one of the most efficient devices in biomaterials detection.

Fig. **3** The reflection spectrum of the biosensor with different analytes

The sensitivity of the biosensor is defined as the ratio of the change in the resonant angle to the change in the refractive index of biomaterial. So, to obtain the sensitivity of the mentioned biosensor is plotted the changes in the resonant angle of the surface plasmon versus changes in the refractive index of the biomaterial, and the slope of the curve is calculated. Therefore, according to Fig. 4, the slope of the curve, the sensitivity of this biosensor is 1.5 degrees per 0.01 of the RI of biological material, in other words, $150\frac{\boldsymbol{deg}}{\boldsymbol{RIU}}$, which is a high sensitivity compared to the previous work [20]. In the previous work and in the case where there is no graphene in the structure, the sensitivity of 110 was calculated. By adding the graphene layer, the sensitivity of the biosensor has increased due to the increase in the absorption and excitation of plasmons.

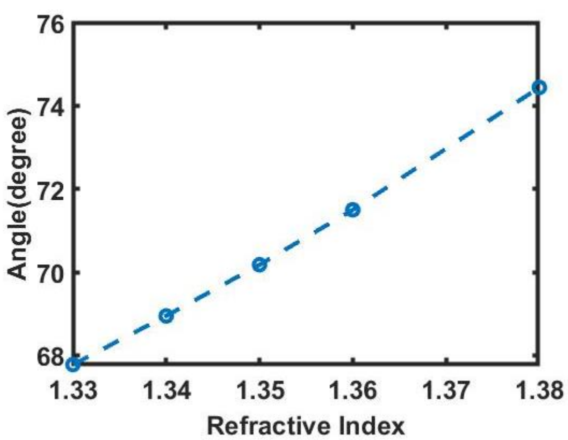


Fig. **4** The curve of biomaterial refractive index changes according to resonance angle.

The presence of a photonic crystal in the biosensor structure increases the sensitivity of the surface plasmon. To use the photonic crystal in the structure, the number of optimal alternating layers of the photonic crystal for which the reflectivity reaches zero should be determined. Fig. 5 shows the periodicity changes of the photonic crystal. As can be seen, the largest drop in reflectance is related to the photonic crystal consisting of 2 pairs of layers. This value is the most optimal in terms of half-width, reflectivity, and buildability.

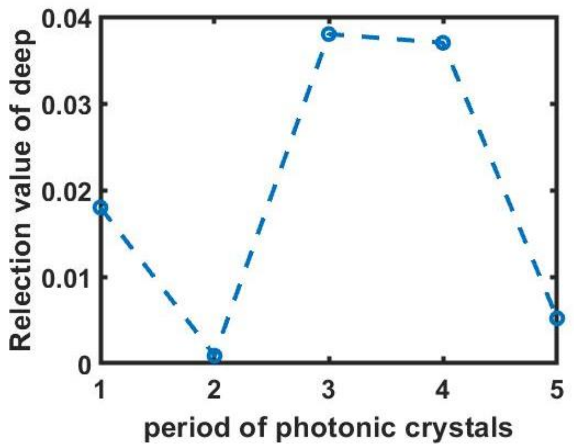


Fig. **5** the number of photonic crystal layers and the deep reflection value

Silver is not chemically stable and oxidizes easily in contact with biomaterials. To prevent the oxidation of silver, we considered gold, which is chemically stable in many environments. Also, a monolayer of graphene has been considered for the high absorption of biological material. To investigate the necessity for graphene, the reflection spectrum (Fig. 6) was drawn for the state with and without graphene. The result indicates that the presence of graphene is necessary to increase the absorption and excitation of plasmons in the structure.

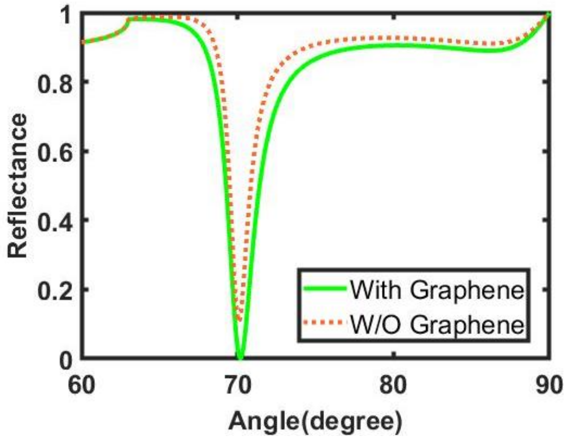


Fig. **6** The reflection spectrum of the biosensor with/without the graphene layer

Despite the graphene in the structure, the question may arise that the presence of the gold layer is not necessary, but the result as shown in Fig. 7 shows presence of gold is necessary to reduce the FWHM and increase the adsorption in the structure. Fig. 7a shows the reflection spectrum with and without (w/o) gold. For a better view, Fig. 7b shows the diagram around the resonance point with greater magnification, which in the structure with gold shows that the amount of reflection has reached almost zero.

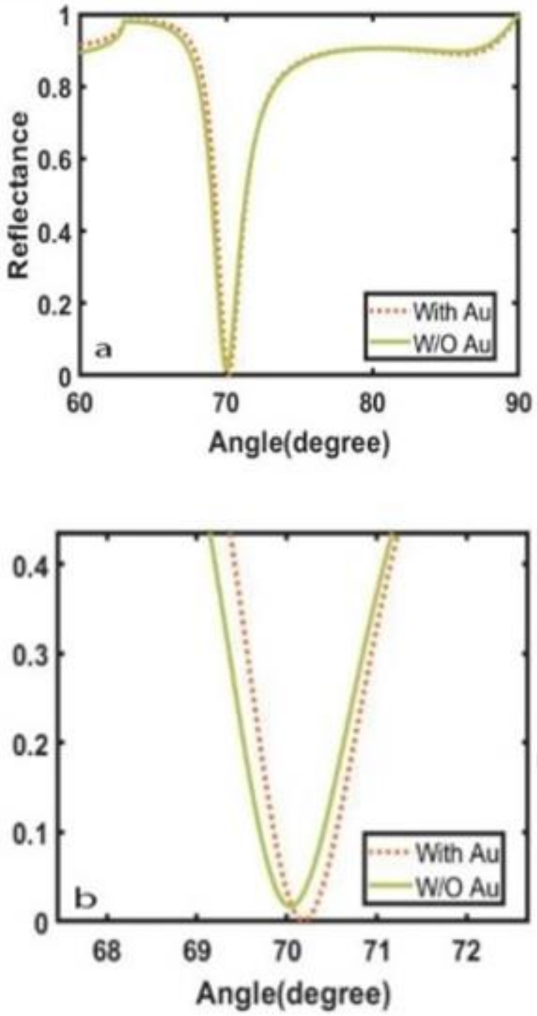


Fig. **7** a) The reflection spectrum of the biosensor with/without gold layer. b) magnification of the dip curve.

As mentioned, in the resonance angle of the surface plasmon, the intensity of the reflected light shows the lowest possible value. In the structure used in this paper, it is necessary to examine the thickness of metal layers to introduce the optimal thickness to achieve the minimum intensity of reflected light at the SPR angle. Accordingly, we calculated the intensity of the reflected light for different thicknesses of gold and silver. According to Fig. 8, the optimal thickness to achieve the minimum light intensity is reflected in a thickness of 5 nm of gold and 40 nm of silver.

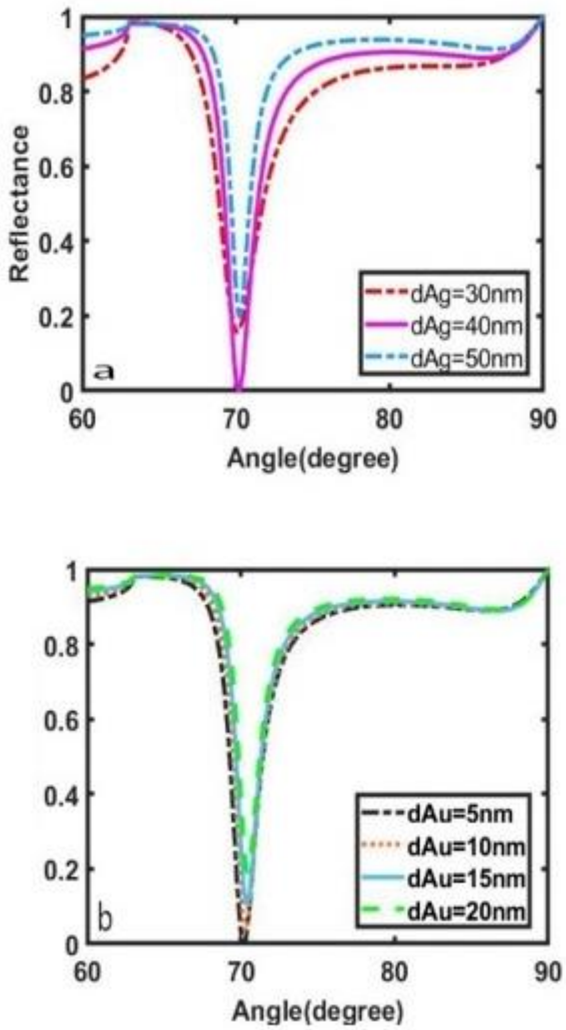


Fig. **8** The reflection spectrum of biosensor a) different thickness layer of Ag, b) different thickness layer of Au.

IV. Conclusion

In this article, a theoretical study of a biosensor based on surface plasmon resonance with two layers of gold and silver as well as graphene in the presence of a photonic crystal was investigated. This biosensor was simulated in angular modulation and MATLAB programming using the transfer matrix method. The gold layer was proposed to prevent the oxidation of silver in contact with biomaterials and graphene to increase the absorption of biomaterials and increase the interaction with light thus increasing the sensitivity and performance of the biosensor. The sensitivity of the proposed biosensor has increased compared to previous work and is about 1.5 degrees for $\Delta n = 0.01$, and by definition, the sensitivity is $150\,\frac{deg}{RIU}$, which is high sensitivity.

References

[1] B. Kaur, S. Kumar, and B.K. Kaushik, "Recent advancements in optical biosensors for cancer detection," Biosensors and Bioelectronics, vol.197, pp.113805, 2022.

[2] S. Akgönüllü and A. Denizli, "Recent advances in optical biosensing approaches for biomarkers detection," Biosensors and Bioelectronics: X. vol. 12, pp.100269, 2022.

[3] G. Nava, G. Zanchetta, F. Giavazzi, and M. Buscaglia, "Label-free optical biosensors in the pandemic era," Nanophotonics. vol. 11, pp.4159-4181, 2022.

[4] A. Mohapatra, M. Garhnayak, P. Sahoo, and S. Panda, *Development of optical biosensor for diagnosis of microbial pathogens*, Biosensors for Emerging and Re-Emerging Infectious Diseases: Elsevier, 2022.

[5] S. Dey, M. Dolci, and P. Zijlstra "Single-Molecule Optical Biosensing: Recent Advances and Future Challenges," ACS Physical Chemistry Au. vol. 3, pp.143-156, 2023.

[6] Q. Wang, Z.H. Ren, W.M. Zhao, L. Wang, X. Yan, A. Zhu, F. Qiu, and K.K. Zhang,"Research advances on surface plasmon resonance biosensors," Nanoscale. vol. 14, pp. 564-591, 2022.

[7] J.H. Park, Y.W. Cho, and T.H. Kim,"Recent advances in surface plasmon resonance sensors for sensitive optical detection of pathogens," Biosensors, vol. 12, pp.180, 2022.

[8] Das S, Devireddy R, Gartia MR. Surface plasmon resonance (SPR) sensor for cancer biomarker detection. Biosensors. 2023;13(3):396.

[9] D. Gowdhami, V. Balaji, M. Murugan, S. Robinson, and G. Hegde, "Photonic crystal based biosensors: An overview," ISSS Journal of Micro and Smart Systems, vol. 11, pp.147-167, 2022.

[10] Z.A. Zaky ,M. Al-Dossari, N. Saleh, M.M. Abdelhady, A. Sharma, V.D. Zhaketov, and A.H. Aly"Photonic crystal with magnified resonant peak for biosensing applications," Physica Scripta. vol. 98, pp.055108, 2023.

[11] Y. Xiong ,S. Shepherd, J. Tibbs, A. Bacon, W. Liu, L.D. Akin, T. Ayupova, S. Bhaskar, and B. T. Cunningham, "Photonic crystal enhanced fluorescence: a review on design strategies and applications," Micromachines. vol. 14, pp. 668, 2023.

[12] C. Fenzl, T. Hirsch, and O.S. Wolfbeis, "Photonic crystals for chemical sensing and biosensing," Angewandte Chemie International Edition. vol. 53,pp. 3318-3335, 2014.

[13] M. Esfandiari, S. Jarchi, P. Nasiri-Shehni, and M. Ghaffari-Miab, "Enhancing the sensitivity of a transmissive graphene-based plasmonic biosensor," Applied Optics. vol. 60, pp.1201-1208, 2021.

[14] X. Ge, Z. Chai, Q. Shi, Y. Liu, and W. Wang, *Graphene superlubricity: A review. Friction*, Springer, 2023.

[15] J. Wu, H. Lin, D.J Moss, K.P Loh, B. Jia, "Graphene oxide for photonics, electronics and optoelectronics. Nature Reviews Chemistry," vol. 7, pp. 162-83, 2023.

[16] A.A. Rifat, G.A. Mahdiraji, R. Ahmed, D.M. Chow, Y.M. Sua, Y.G. Shee, and F.R.M. Adikan, "Copper-graphene-based photonic crystal fiber plasmonic biosensor," IEEE Photonics Journal. vol. 8, pp. 1-8, 2015.

[17] A.K. Paul, A.K. Sarkar, S.A. Razzak, "Graphene coated photonic crystal fiber biosensor based on surface plasmon resonance," 2017 IEEE Region 10 Humanitarian Technology Conference (R10-HTC); 2017:

[18] R. Arunkumar, T. Suaganya, S. Robinson, "Design and analysis of 2D photonic crystal based biosensor to detect different blood components. Photonic Sensors," vol. 9, pp. 69-77, 2019.

[19] L. Qi, Z. Yang, F. Lan, X. Gao, and Z. Shi, "Properties of obliquely incident electromagnetic wave in one-dimensional magnetized plasma photonic crystals," Physics of Plasmas. vol. 17, pp. 042501(1-8) , 2010.

[20] M. Sharifi, H. Pashaei Adl, and H. Tajalli, "Bahrampour A. Design of surface plasmon resonance biosensor with one dimensional photonic crystal for detection of cancer," Iranian Journal of Physics Research. vol. 16, pp.133-138, 2019.