



A Sensitive Biosensor Based on Plasmonic-Graphene Configuration for Detection of COVID-19 Virus

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Abstract

In this paper, four individual structures based on graphene-plasmonic nano combinations are proposed for detection of corona viruses and especially COVID-19. The structures are arranged based on arrays in the shapes of half-sphere and one-dimensional photonic crystal formats. The half-sphere and plate shaped layers are made of *Al*, *Au*, *SiO₂* and graphene. The one-dimensional photonic crystals lead the wavelength and peak corresponding to the absorption peak to lower and higher amounts, respectively. In order to improve the functionality of the proposed structures, effects of structural parameters and chemical potentials are considered. A defect layer of *GZO* is positioned in the middle of one-dimensional photonic crystal layers to shift the absorption's peak wavelength to the appropriate wavelength range for diagnosing corona viruses (~300 nm to 600 nm). The last proposed structure is considered as a refractive bio-sensor for detection of corona viruses. In the final proposed structure (based on different layers of *Al*, *Au*, *SiO₂*, *GZO* and graphene), corona viruses are considered as the biomolecule layer and the results are obtained. The proposed bio-sensor can be a good and functional candidate for detection of corona viruses and especially COVID-19 in photonic integrated circuits with the satisfying sensitivity of ~664.8 nm/RIU (refractive index unit).

Keywords Bio-sensor · Corona virus · COVID-19 · Graphene · Photonic crystal · Plasmonic

Introduction

Coronavirus disease 2019 (COVID-19) is an easily transmissible and very contagious disease which is caused by severe respiratory syndrome coronavirus 2 (SARS-CoV-2). It was first reported in Wuhan, China in December 2019 and spread with an unbelievable speed worldwide. As people around the world were severely infected by this virus, it was identified as a severe and dangerous pandemic. Various symptoms were reported for this disease as fever,

cough, headache, fatigue and breath difficulties. The respiratory symptoms are the most serious signs, which can put human's health in jeopardy. As reported by the world health organization (WHO), more than 300 million (~390 million) people were infected by this virus and unfortunately more than 5 million (~5.7 million) lost their lives. If the infected cases can be diagnosed and monitored in early stages, they can undergo various treatment approaches. This can lead to the significant reduction of death cases. Therefore, developing new and strong technologies for detecting and monitoring this virus is of great importance and many researches have devotedly worked on them since the beginning of the pandemic [1]. Many approaches were proposed for detecting the virus in infected people including different tests and sensors. Various biosensors for detecting COVID-19 were reported which indicated interesting results [2, 3]. The optical biosensors can diagnose the COVID-19 very fast and with precise results. They mainly operate based on the changes of refractive index (RI) in the sensing medium [1]. They attracted excessive attentions due to their high sensitivities, low costs, small sizes (nano-meter dimensions) and high precisions [4].

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The optical biosensors can be considered as the graphene or plasmonic nano-combinations in different configurations [5]. These structures have amazing behaviors such as very high optical confinement, low losses and tunability [4]. Plasmonic nano-structures are based on the combination of metal-insulator configurations which have very interesting specifications in nano-scaled dimensions [6]. Graphene structures are based on the combination of carbon atoms in organized configurations which have unbelievable electrical, optical and thermal characteristics [7]. They can be considered in different configurations like plate-shaped, cylindrical-shaped [8], ring-shaped [9] or 1-D (one-dimensional) photonic crystal (PC) -shaped [10] structures.

The most important aspect of the plasmonic-graphene structures is the surface plasmon resonances (SPR) [4, 6]. In fact, in the plasmonic/graphene nano structures, the interaction of free electrons (in plasmonic or graphene medium) and electromagnetic (EM) light-wave which is known as the SPR can help scale down the structure's dimensions (about or less than the operating wavelength). In other words, SPR can be utilized to conquer the diffraction limits in nano-dimension optical structures. Therefore, the plasmonic-graphene nano structures can be considered as the biosensors for detecting different elements like hemoglobin [8], glucose [11] and also for detection of different viruses like COVID-19 [12], MERS [13] and etc.

Interesting applications of graphene were reported which were utilized to excite Tamm resonance in PCs [14–19]. In [14], by considering the resonant dip of the Tamm plasmon (in a structure based on layers of gyroidal graphene and porous silicon), a refractive index sensor was proposed. The sensitivity and figure of merit of $1347.7 \text{ THz}/RIU$ and $554.405 /RIU$ were reported, respectively [14].

In another research [15], a gas sensor based on various layers of gyroidal graphene with the sensitivity of $2431 \text{ THz}/RIU$ was suggested. Also in [16], a refractive index sensor based on gyroidal graphene (considering the Tamm plasmon polaritons) with the sensitivity and quality factor of $18.6 \text{ THz}/RIU$ and 26300 was proposed. In [17], a refractive index gas sensor based on the graphene-metals layers considering the Tamm resonance was proposed. The sensor indicated acceptable sensitivity, figure of merit and quality factor of $5.5 \text{ THz}/RIU$, 341 RIU^{-1} and 210 , respectively. Also in [18], a biosensor based on graphene-porous silicon photonic crystals considering the Tamm resonance was reported with the sensitivity and figure of merit of $4.75 \text{ THz}/RIU$ and 475 RIU^{-1} , respectively.

Many researchers have also been fascinated by the amazing specifications of the graphene-plasmonic nano-structures and reported their works in the bio-sensing technologies. In [20], a biosensor for detection of glucose concentration in blood sample was proposed based on graphene-gold ellipse shaped structure.

In [8], various graphene-plasmonic based structures were reported for detecting hemoglobin concentrations in the blood samples. They reported the sensitivity of $570 \text{ nm}/RIU$ for their proposed sensor [8]. In another research [21], efficient miniaturized plasmonic sensor with narrow line shapes in THz frequencies was suggested for detection of SARS-CoV-2 virus protein at low level. In [22], graphene and graphene-related materials (GRMs) were considered as interesting candidates for conquering COVID-19. Another research indicated amazing results in detection of COVID-19 very fast and with low errors. In this research, graphene field-effect transistor decorated with gold nano particles was proposed for detection of COVID-19 virus [23]. Also in [24], detection of COVID-19 virus with graphene based field-effect transistor was considered. The proposed sensor indicated very good sensitivity leading to precise results. In another interesting report [2], by utilizing the laser spectroscopic techniques and fiber optic–nano photonic approaches, rapid detection of COVID-19 viruses and especially a single virus detection were feasible [2].

In this research, different configurations of graphene-plasmonic nano structures for detection of corona viruses and especially COVID-19 virus are considered. Eventually, a sensitive biosensor for diagnosing COVID-19 based on graphene-plasmonic combinations in the 1-d photonic crystal and half-sphere shaped nano structures is proposed.

Geometry and Theoretical Descriptions

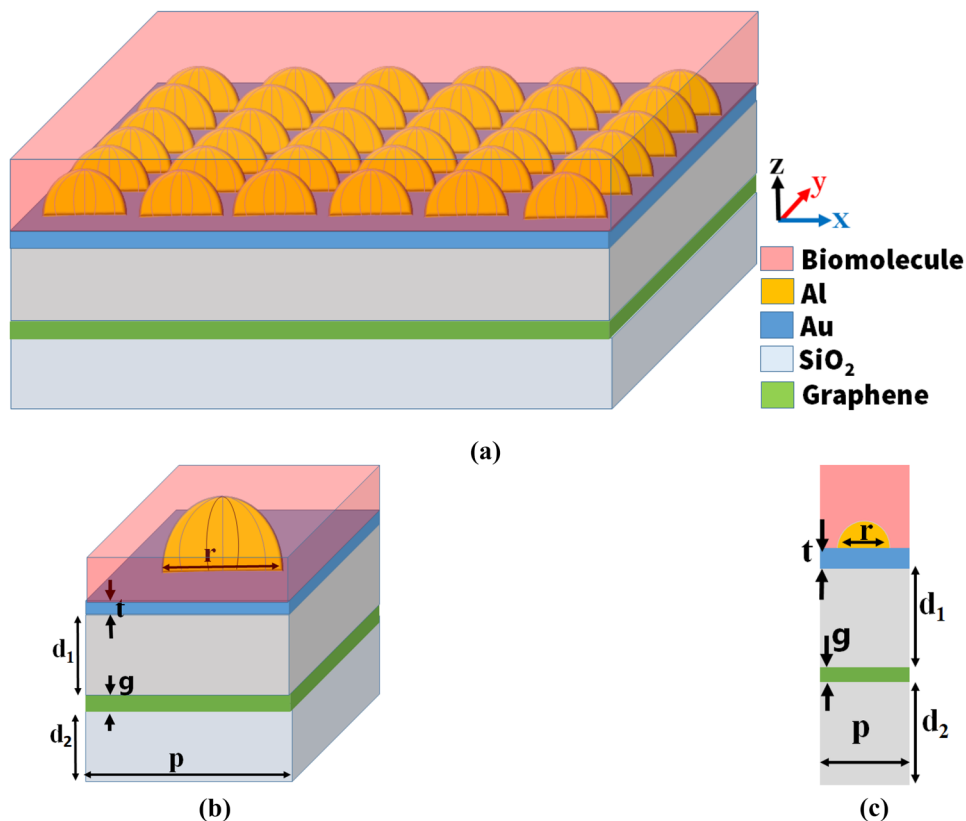
The first designed structure is based on different layers of aluminum (*Al*), gold (*Au*), *SiO*₂ and graphene in the plate and half-sphere shaped layers. It is shown in Fig. 1.

As can be seen, the proposed structure is based on the repetitive and periodic algorithm of half-sphere shaped arrays of *Al* on the plate-shaped *Au*, *SiO*₂ and graphene layers. The geometric parameters which are shown in Figs. 1b, c are tabulated in Table 1.

In this work, simulations were considered based on two-dimensional finite element based software (COMSOL Multiphysics 5.5). The structure (half-sphere shaped arrays) is periodically expanded in the y-direction (the structure is periodic in the y-direction, in other words the length of the structure in the y-direction is much longer than x or z directions). Therefore, a 2-D model (with similar results) was conducted instead of the 3-D model. This approach was considered for decreasing the time and computer resources needed for the simulations [25, 26].

Considering the proposed structure of Fig. 1, the field distributions at resonant and non-resonant wavelengths along with the absorption, reflection and transmission spectra are presented in Fig. 2.

Fig. 1 a) Schematic of the first proposed structure, b) View of the single array of the structure, c) Side view of a single array



As can be seen in Fig. 2a, the maximum absorption peak of 0.44 is achieved for $\lambda=968\text{ nm}$.

Also as can be seen in Fig. 1a, three plasmonic layers (Al, Au and graphene) are considered in the structure which can lead to Fano resonance (considering Fig. 2a) [27, 28]

Considering Fig. 2a, the following relation can be considered between the transmission, absorption and reflection spectra [7, 8]:

$$A(\omega) = 1 - R(\omega) - T(\omega) \tag{1}$$

In order to improve the functionality of the structure (to be used as a sensor), the absorption should be increased, so the transmission and reflection should be decreased. Therefore, for having a proper sensor, the absorption parameter $A(\omega)$ should become as much as possible. This can be achieved by considering different combinations of graphene

Table 1 Geometric parameters of Fig 1.

Parameter	Value (nm)
r	30
t	10
d_1	100
d_2	100
g	1

and plasmonic layers (in the plate and half-sphere shapes) [7, 8]. Graphene and plasmonic (metal) nano structures are considered for improving the absorption parameter. Kubo formula can be considered for realization of the surface conductivity of a graphene layer [7, 8]:

$$\sigma_g(\omega, \mu_c, \Gamma, T) = \sigma_{g-real} + \sigma_{g-imag} = \sigma_{intra} + \sigma_{inter} \tag{2}$$

in which ω, μ_c, Γ and T stand for the operation frequency, the chemical potential, the phenomenological scattering rate and the absolute temperature, respectively.

In Eq. (2), the intra-band (σ_{intra}) and inter-band (σ_{inter}) electro-photon scattering parameters can also be described as [7, 8]:

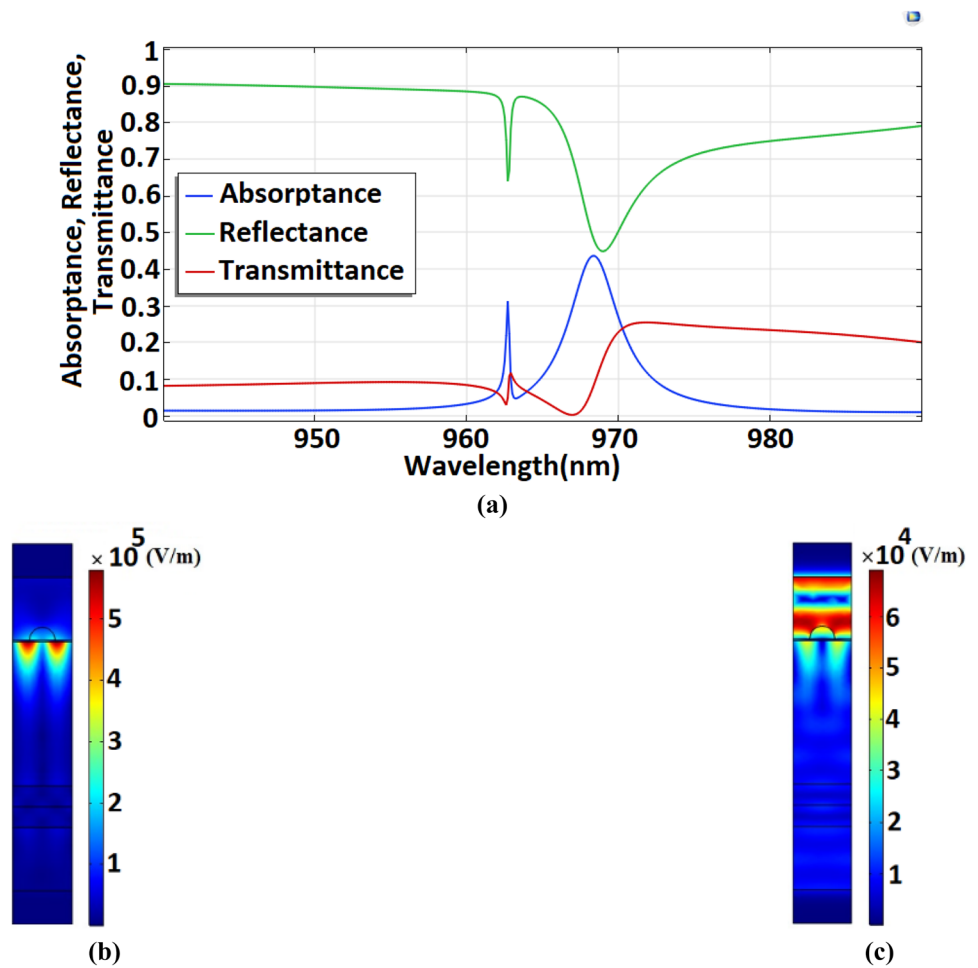
$$\sigma_{intra} = -j \frac{e^2 k_B T}{\pi \eta^2 (\omega - j2\Gamma)} \times \left[\frac{\mu_c}{k_B T} + 2 \ln \left(\exp \left(\frac{\mu_c}{k_B T} \right) + 1 \right) \right] \tag{3}$$

$$\sigma_{inter} = -j \frac{e^2}{4\pi\eta} 1n \left[\frac{2|\mu_c| - (\omega - j2\Gamma)\eta}{2|\mu_c| + (\omega - j2\Gamma)\eta} \right] \tag{4}$$

in which k_B, T and e represent Boltzmann constant, temperature and electron charge, respectively.

In order to define the dielectric function of the metals, Drude model can be considered [29, 30]:

Fig. 2 a) Schematic of the absorption, reflection and transmission spectrum, Field distribution of the proposed structure at b) $\lambda=968\text{ nm}$, c) Field distribution at $\lambda=975\text{ nm}$



$$\epsilon(\omega) = \epsilon_{\infty} - \frac{\omega_p^2}{\omega^2 + i\omega\gamma} \tag{5}$$

in which $\epsilon_{\infty} = 3.7$ (dielectric constant at infinite frequency), $\gamma = 0.018\text{ eV}$ (collision plasma angular frequency) and $\omega_p = 9.1\text{ eV}$ (bulk plasma angular frequency) [29, 30].

By applying the incident field to the first proposed structure (Fig. 1a), field distribution spectrum can be considered. As can be seen by considering $\lambda=968\text{ nm}$ and $\lambda=975\text{ nm}$, the resonant and non-resonant spectra can be achieved in Figs. 2b, c, respectively. In fact, the absorption's peak value of 0.44 is achieved in $\lambda=968\text{ nm}$, which should be enhanced for improving the functionality of the structures. It should also be considered that, biosensors with the ability of detecting COVID-19, mainly operate in the wavelength range of (300 nm - 500 nm) [30–32], therefore, the structure should be engineered for functioning in this range. For enhancing the functionalities of the proposed structure, different combinations of graphene and plasmonic in the plate and half-sphere shapes are applied

to the structures. Effects of different structural parameters (r, t, d) and chemical potentials are also investigated for increasing the resonance peak's values. The results are presented in the following parts.

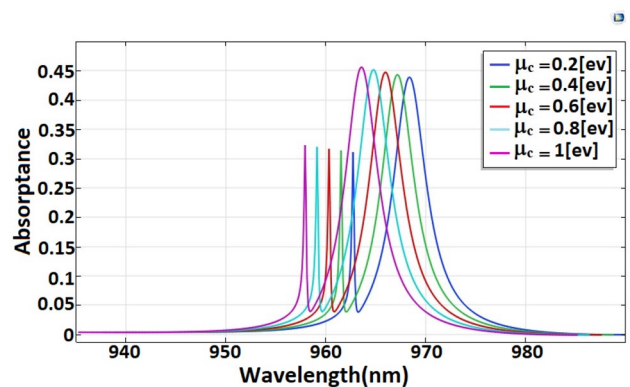


Fig. 3 Schematic of the absorption spectrum versus wavelength for different values of chemical potential (μ_c)

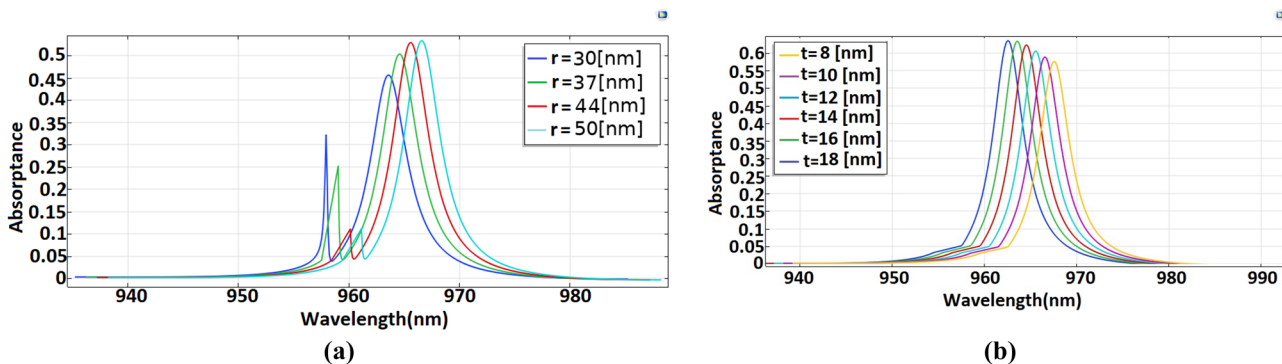


Fig. 4 Absorption spectrum versus wavelength for different values of a) *r*, b) *t*

Results and Discussions

In this section, 4 different configurations based on the graphene-plasmonic nano structures in the plate and half-sphere shapes are considered. The first one was presented in Fig. 1a. As stated for improving its functionality (increasing the absorption’s peak value), effects of the structural parameters (*r*, *t*) and chemical potential (μ_c) should be investigated. By considering values from 0.2 eV to 1 eV for the chemical potential, its effect on the wavelength and peak corresponding to the absorption peak can be shown in Fig. 3.

As can be seen in Fig. 3, by increasing μ_c from 0.2 eV to 1 eV, the wavelength and peak corresponding to the absorption peak experience a blue shift and very light and smooth enhancement, respectively.

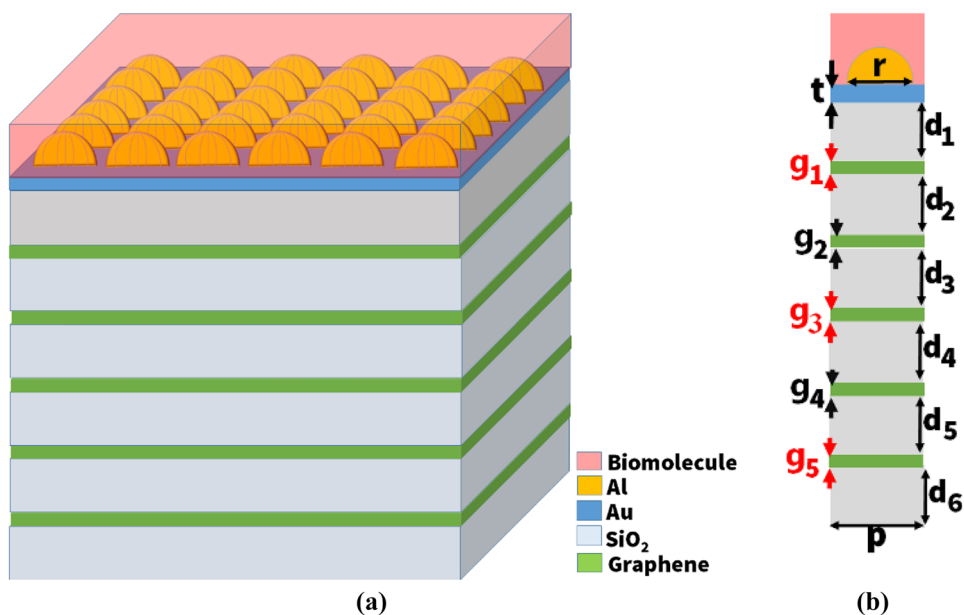
The absorption’s peak wavelength variations can be explained by the circuit theory. In the circuit theory, graphene

is considered as a shunt admittance which can be altered by the geometrical parameters (*r*, *t*) and chemical potential μ_c [8, 33]. In fact, graphene can be substituted by resistors, capacitors and inductors. Therefore, varying μ_c can change the absorption’s peak wavelength according to [8, 33]:

$$\lambda = 2\pi c\sqrt{LC} \tag{6}$$

in which *c*, *L* and *C* stand for the speed of light in vacuum, capacitance and inductance of the circuit, respectively. It can be concluded that enhancing μ_c diminishes *L* [34], which would shift the absorption’s peak wavelength to lower values (blue shift). Also by changing μ_c from 0.2 eV to 1 eV, the absorption peak’s value experience a smooth and slow increase. Therefore, by considering $\mu_c=1$ eV, the peak and wavelength corresponding to the absorption peak of 0.455 and 963 nm are achieved, respectively. Effects of the geometrical parameters (*r*, *t*) are also considered and depicted in Fig. 4.

Fig. 5 a) Schematic of the second proposed structure, b) Side view of a single array



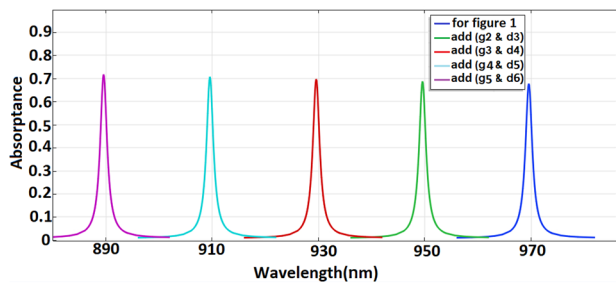


Fig. 6 Effects of different 1-d PhC layers on the absorption spectrum

As indicated in Fig. 4a, increasing half-sphere's diameter (from 30 nm to 50 nm) causes both of the wavelength and peak corresponding to the absorption peak to experience higher amounts [35]. In fact, for $r=50\text{ nm}$, the absorption's peak wavelength shifts to higher values (red-shifted to $\lambda=966\text{ nm}$) and the absorption's peak value reaches 0.5 . For the following structures $r=50\text{ nm}$ should be considered.

In Fig. 4b, effects of the gold layer's (*Au*) height (t) on the absorption spectrum is considered ($r=50\text{ nm}$). As shown, the wavelength and peak corresponding to the absorption peak lead to lower and higher amounts, respectively [36]. By changing t from 8 nm to 18 nm , the wavelengths and peaks corresponding to the absorption peak shift from 968.5 nm to 962 nm and from 0.57 to 0.645 , respectively. For the first proposed structure, the best obtained wavelengths and peaks corresponding to the absorption peak are 962 nm and 0.645 , respectively. As a result, $r=50\text{ nm}$ and $t=18\text{ nm}$ are considered as the geometrical parameters for the following

structures. The second proposed structure with periodic 1-d photonic crystal (1-d PhC) combinations of graphene- SiO_2 layers is presented in the next section.

Second Structure

The second proposed structure is depicted in Fig. 5. As shown, periodic 1-d PhC layers of graphene- SiO_2 are added to the first structure (shown in Fig. 1a).

In Fig. 5(a), PhC layers were added gradually (not instantly), therefore effects of considering each part (for Fig. 1a) on the absorption spectrum were considered and depicted in Fig. 6.

It is concluded from Fig. 6, that adding more layers of 1-d PhC (to Fig. 1a) for designing Fig. 5a) would shift the absorption's peak wavelength to lower values [7] and also increase the absorption's peak value smoothly. As stated, for designing a biosensor with the ability of detecting COVID-19 virus, the absorption spectrum should be placed in the wavelength range of 300 nm to 500 nm . For achieving this goal, a defect layer (with specific material) would be placed in the middle of 1-d PhC layers. Interesting materials which can replace materials like gold, silver, aluminum and etc. in plasmonic structures (they function almost the same as metals) with the ability of operating in visible ranges ($\sim 300\text{ nm} - 800\text{ nm}$) with low losses were proposed in recent decade [37, 38]. Therefore, a defect array is considered in Fig. 5a (shown as Fig. 7b) which is filled with different materials (*GZO* (Gallium doped Zinc Oxide), *TiN* (Titanium Nitride), *ZrN* (Zirconium Nitride) and *ITO* (Indium Tin Oxide)), and the results are shown in Fig. 7b.

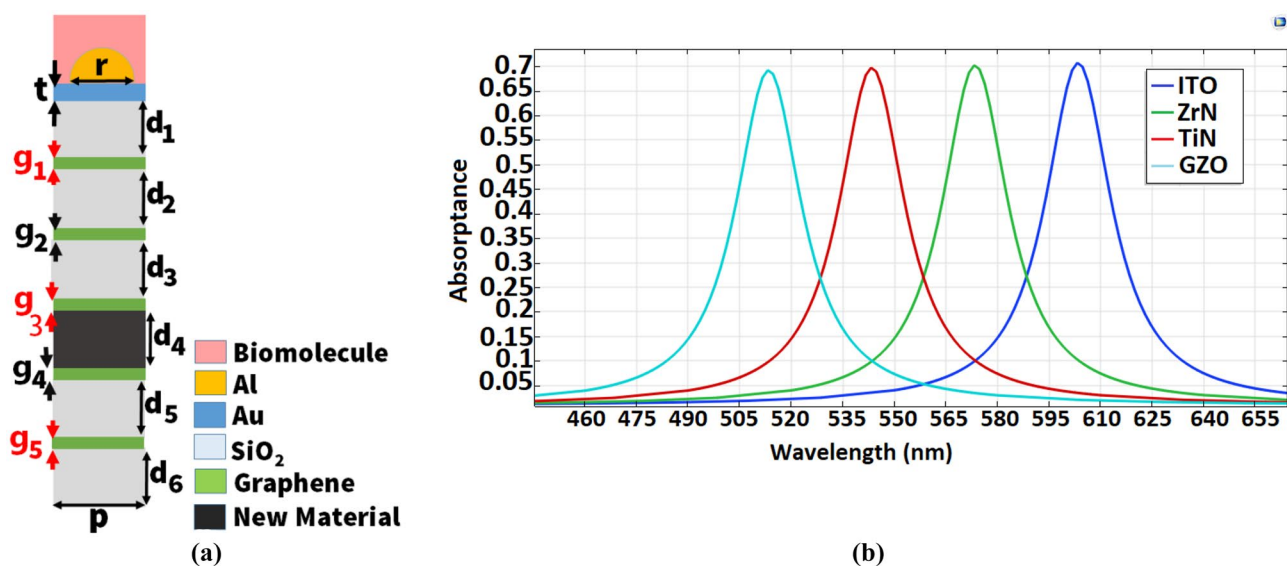


Fig. 7 a) Side view of a single array containing defect, b) Absorption spectrum versus wavelength for different defects

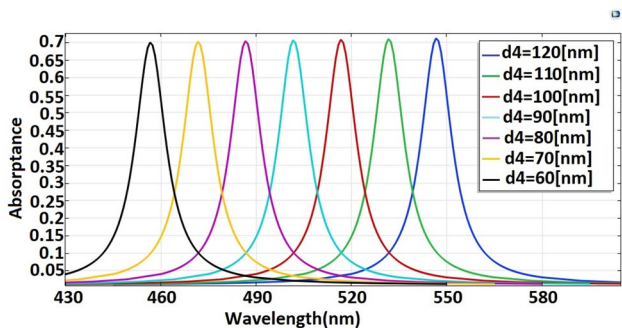


Fig. 8 Absorption spectrum versus wavelength for different values of d_4

As shown in Fig. 7b, by considering a defect layer of *GZO*, *TiN*, *ZrN* and *ITO*, the absorption’s peak wavelength would be shifted to lower amounts (blue-shift) and would be placed in the visible range [38, 39]. *GZO* is considered as a defect layer as it experiences more shifting to lower wavelengths. For improving the functionality of Fig. 7a, effects of the defect layer’s properties should also be considered. By changing its height (d_4) from 60nm to 120 nm, the absorption spectra versus wavelength would be depicted in Fig. 8.

As shown in Fig. 8, by increasing d_4 from 60 nm to 120 nm, the absorption’s peak wavelength would experience a red shift [29, 30, 40]. In fact, by increasing d_4 , distance between graphene layers “ g_3 and g_4 ” enhances and the coupling between layers become poorer. As stated for our proposed application (biosensor for detecting COVID-19 virus), $d_4=60$ nm with the absorption’s peak wavelength of 445 nm is acceptable. In the second structure, different layers of 1-d PhC were considered which improve the absorption’s peak value to 0.7 and by considering a defect layer of (*GZO*) and investigating its height’s (d_4) effects, the absorption’s peak wavelength of 445 nm was obtained. In the following structure, a hollow half-sphere shaped layer of graphene is positioned above the half-sphere *Al* layer.

Third Structure

The third proposed structure is shown in Fig. 9. As can be seen, a hollow half-sphere shaped graphene layer is added to the structure of Fig. 7a. The defect layer (gray layer) is filled with *GZO*.

In order to improve the functionality of the third proposed structure, effects of its chemical potential (μ_c of g_6) on the absorption spectrum would be considered as Fig. 10.

As can be concluded from Fig. 10, increasing μ_c from 0.2 eV to 1.4 eV, would shift the wavelength and peak corresponding to the absorption peak to lower and higher amounts, respectively. This phenomenon was explained by

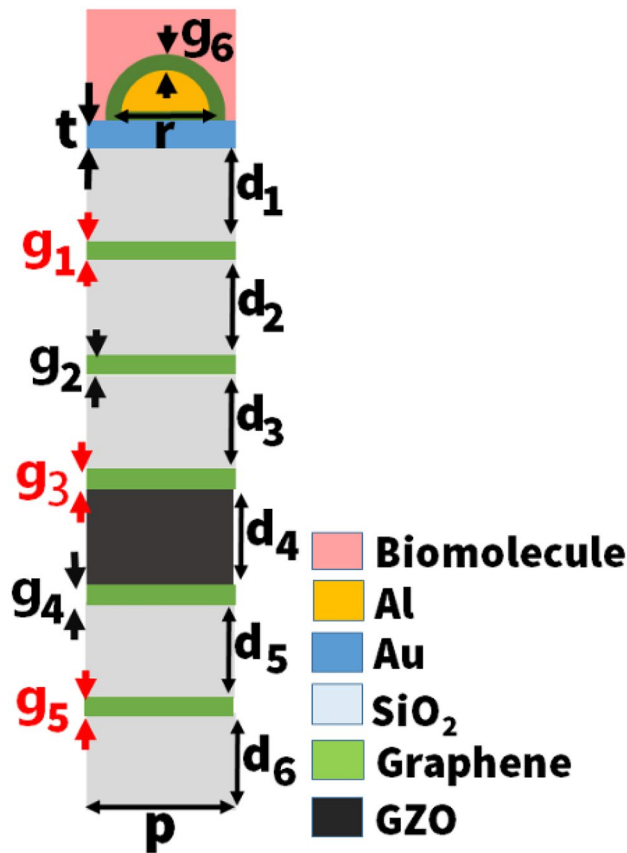


Fig. 9 Schematic of a side view of a single array of the third proposed structure

the circuit theory in the previous section [8, 33]. As stated in this theory, graphene which is dependent to the geometrical parameters and chemical potential μ_c is considered as a shunt admittance. Therefore, geometrical parameters and Fermi energy (chemical potential) can affect its specifications. Changing μ_c can affect the absorption’s peak wavelength according to Eq. 6. As known, increasing chemical potential would decrease the inductance of the equivalent

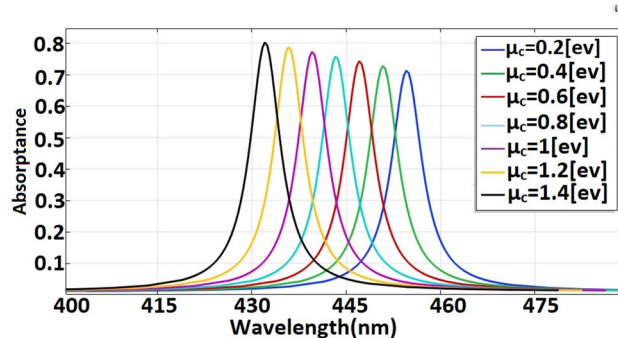
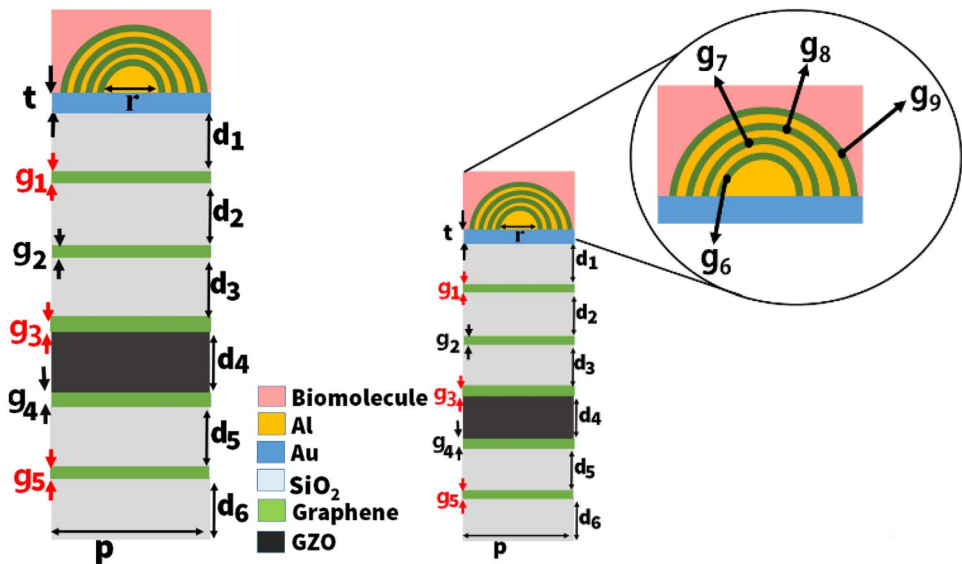


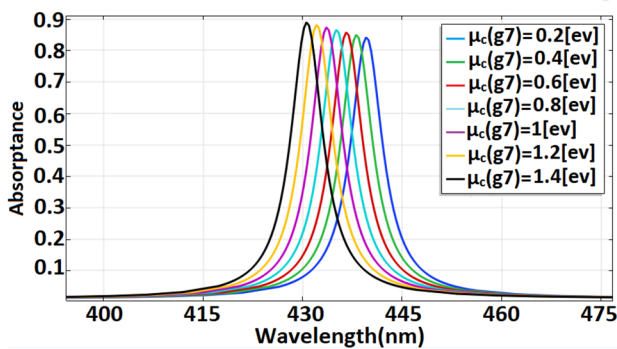
Fig. 10 Schematic of the absorption spectrum versus wavelength for the third structure for different values of chemical potential (μ_c)

Fig. 11 Schematic of a side view of a single array of the fourth proposed structure

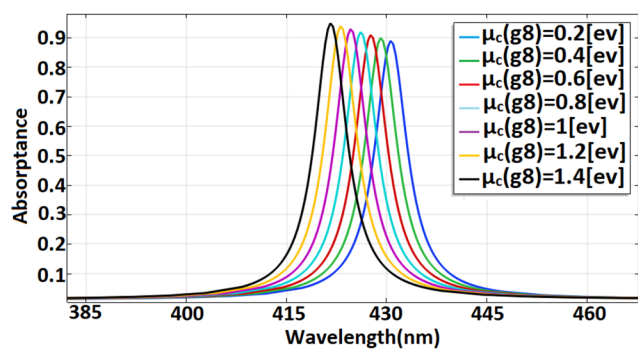


circuit (related to graphene). As a result, increasing μ_c would decrease L (inductance) [8, 24], which would lead to the blue shift of the absorption's peak wavelength. As a result, by considering $\mu_c=1.4$ eV, the peak and wavelength corresponding to the absorption peak of 0.8 and 432 nm

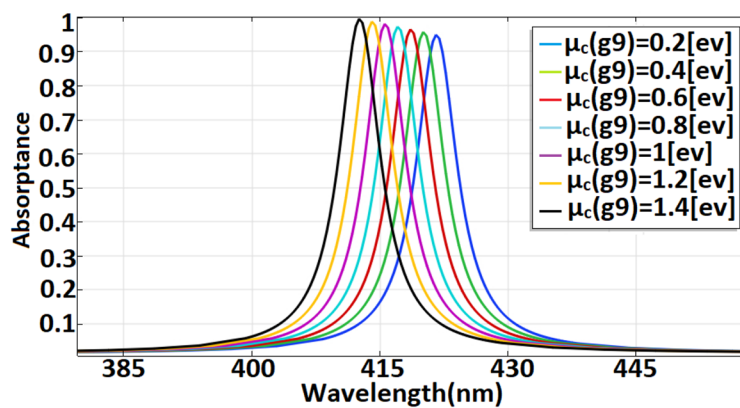
are achieved, respectively. For improving the functionality of the proposed structure (the wavelength and peak corresponding to the absorption peak), layers of graphene and Al in the half-sphere hollow shapes and 1-d PhC formats are considered in the structure of Fig. 9.



(a)



(b)



(c)

Fig. 12 Schematic of the absorption spectrum versus wavelength for the fourth structure for different values of **a)** $\mu_c(g_7)$, **b)** $\mu_c(g_8)$ and **c)** $\mu_c(g_9)$

Table 2 Refractive indices of the corona viruses [31]

Types of Viruses	Refractive index 1000 (EID concentration)
H5N1	-0.78266
H5N2	-0.75739
H9N2	-0.74807
H4N6	-0.77586
FAdV	-0.74472
IBV (Family of COVID-19)	-0.999998

EID Electronic infusion Device

Fourth Structure

The fourth proposed structure is considered in Fig. 11. As shown, layers of graphene and Al in the half-sphere hollow shapes are added to Fig. 9 which form 1-d PhC combination. It should be considered that the defect layer (gray layer) is filled with GZO.

As different graphene layers are considered in Fig. 11, their chemical potential’s effects on the absorption spectrum are investigated Fig. 12, indicates effects of $\mu_c(g_7)$, $\mu_c(g_8)$ and $\mu_c(g_9)$ on the absorption spectrum.

As shown in Fig. 12 and stated in the previous sections, chemical potential can affect the wavelength and peak corresponding to the absorption peak. Dependency of the resonance wavelength with the chemical potential was stated in the previous sections (circuit theory). As can be seen in Fig. 12a, increasing $\mu_c(g_7)$ from 0.2 eV to 1.4 eV, would shift the wavelength and peak corresponding to the absorption peak from 440 nm to 430 nm and from 0.83 to 0.89, respectively. Also by increasing $\mu_c(g_8)$ from 0.2 eV to 1.4 eV, the wavelength and peak corresponding to the absorption peak would change from 432 nm to 421 nm and from 0.89 to 0.96, respectively. In another case by changing $\mu_c(g_9)$ from 0.2 eV to 1.4 eV, the wavelength and peak corresponding to the

absorption peak would alter from 422 nm to 413 nm and from 0.95 to 1, respectively. As a result, by considering $\mu_c(g_7)=\mu_c(g_8)=\mu_c(g_9)=1.4$ eV, the proposed structure operates in the wavelength range of 300 nm - 600 nm with almost unity absorption’s peak value. Therefore, this structure can be utilized in different medical applications for its proper operating wavelength range and high absorption peak [8]. In the following part, a biosensor based on Fig. 11 with the ability of corona viruses’ detection and especially COVID-19 is proposed. For this purpose, refractive indices of corona viruses were considered from [31], which was obtained through reverse calculation. Refractive indices are tabulated in Table. 2.

Figure 13 is obtained for different corona viruses which were mentioned in [31]. As can be seen in Fig. 13, as the refractive index of the corona virus is increased, the absorption peak’s wavelength is shifted to higher values (red-shift) [8, 31, 41, 42]. By considering the following equation for the sensitivity of the proposed bio-sensor, the sensitivity value can be calculated.

$$S = \frac{\Delta\lambda}{\Delta n}(nm/RIU)nm \tag{7}$$

Considering Fig. 13 and Eq. (7), the sensitivity of ~664.8 nm/RIU can be achieved. As a result, the proposed biosensor can be an important and functional device for detection of corona viruses and especially COVID-19.

Conclusion

As COVID-19 pandemic is a vital concern to everyone in this era, biosensors for detection of corona viruses and especially COVID-19 are of great importance. For this purposed, four different configurations based on graphene-plasmonic nano structures were suggested. The structures were based on arrays in the shapes of half-sphere and 1-d photonic crystal plates of Al, Au, SiO₂ and graphene. For improving the functionality of the proposed structures effects of structural parameters (*r*, *t*, *d₄*) and chemical potentials (μ_c , μ_{g7} , μ_{g8} and μ_{g9}) on the wavelength and peak corresponding to the absorption peak were also investigated. As for detecting corona viruses and specially COVID-19, the application wavelength range should be positioned in 300 nm – 600 nm range, a defect layer of GZO was positioned in the middle of the 1-d photonic crystal structure. In the last proposed structure (fourth structure), by considering the refractive indices of the corona viruses (H5N1, H5N2, H9N2, H4N6, FAdV, IBV) in the biomolecule layer, the acceptable sensitivity of ~664.8 nm/RIU was obtained. As a result, the proposed structures can function as biosensors for diagnosing corona viruses and especially COVID-19.

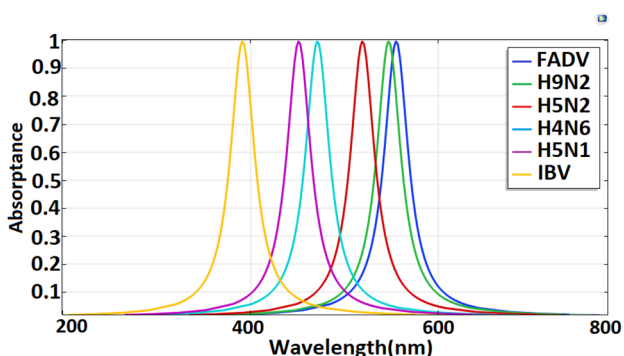


Fig. 13 Absorption spectrum versus wavelength for different corona viruses’ RIs

Author Contributions All authors contributed to the study conception and design. Idea preparation, simulation and analysis were performed by Esmat Rafiee, Roozbeh Negahdari and Zoheir Kordrostami. The first draft of the manuscript was written by Esmat Rafiee and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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Declarations

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References

1. Behera S et al (2020) Biosensors in diagnosing COVID-19 and recent development. *S I* 1:100054
2. Rajil N et al (2021) A fiber optic–nanophotonic approach to the detection of antibodies and viral particles of COVID-19. *Nanophotonics* 10:235–246
3. Samavati A et al (2022) Sustainable and fast saliva-based COVID-19 virus diagnosis kit using a novel GO-decorated Au/FBG sensor. *Chem Eng Sci*. <https://doi.org/10.1016/j.ces.2020.127655>
4. Negahdari R et al (2021) Design of tunable ring-shaped plasmonic photonic crystal filters infiltrated with optical fluids. *Opt Eng* 60:097102
5. Liu X et al (2022) Portable electrochemical biosensor based on laser-induced graphene and MnO₂ switch-bridged DNA signal amplification for sensitive detection of pesticide. *Biosens. Bioelectron* 199:113906
6. Emami F et al (2019) Plasmonic multi-channel filter based on split ring resonators: Application to photothermal therapy. *Photonics Nanostructures: Fundam Appl* 33:21–28
7. Sahraeian S et al (2021) Tunable terahertz absorber based on graphene-metal nanostructure as opto-fluid sensor. *Optik* 242:166713
8. Chahkoutahi A et al (2021) Sensitive Hemoglobin Concentration Sensor Based on Graphene-Plasmonic Nano-structures. *Plasmonics* 21:1–9
9. Sahraeian S et al (2022) Design of a tunable nano sensor based on terahertz graphene-based absorbers. *J Electromagn Waves Appl* 36
10. Long Y et al (2016) Dually guided-mode-resonant graphene perfect absorbers with narrow bandwidth for sensors. *J Phys D: Appl Phys* 49:32LT01
11. Hajshahvaladi L et al (2022) A high-sensitivity refractive index biosensor based on Si nanorings coupled to plasmonic nanohole arrays for glucose detection in water solution. *Opt Commun* 502:127421
12. Kim S et al (2022) Real-time ultra-sensitive detection of SARS-CoV-2 by quasi-freestanding epitaxial graphene-based biosensor. *Biosens Bioelectron* 197:113803
13. Kim G et al (2022) Fabrication of MERS-nanovesicle biosensor composed of multi-functional DNA aptamer/graphene-MoS₂ nanocomposite based on electrochemical and surface-enhanced Raman spectroscopy. *Sens Actuators B Chem.* 352:131060
14. Zaky ZA et al (2023) Refractive index sensor using Fibonacci sequence of gyroidal graphene and porous silicon based on Tamm plasmon polariton. *Opt Quantum Electron* 55:6
15. Zaky ZA et al (2022) Effect of geometrical and physical properties of cantor structure for gas sensing applications. *Synthetic Metals* 291:117167
16. Zaky ZA et al (2021) Gyroidal graphene for exciting tamm plasmon polariton as refractive index sensor: Theoretical study. *Opt Mat* 122-B:111684
17. Zaky ZA et al (2021) Gyroidal graphene/porous silicon array for exciting optical Tamm state as optical sensor. *Sci Rep* 11:19389
18. Zaky ZA et al (2022) Tamm resonance excited by different metals/graphene. *Photonics Nanostruct* 49:100995
19. Zaky ZA et al (2021) Modeling of a biosensor using Tamm resonance excited by graphene. *Appl Opt* 60:1411–1419
20. Sadeghi Z et al (2020) Highly Sensitive Mid-Infrared SPR Biosensor for a Wide Range of Bio-molecules and Biological Cells Based on Graphene-Gold Grating. *Physica E: Low-dimens Syst Nanostruct* 119:114005. <https://doi.org/10.1016/j.physe.2020.114005>
21. Ahmadivand A et al (2021) Functionalized terahertz plasmonic metasensors: Femtomolar-level detection of SARS-CoV-2 spike proteins. *Biosens Bioelectron* 177:112971
22. Srivastava AK et al (2020) Potential of Graphene-based Materials to Combat COVID-19: Properties, Perspectives and Prospects. *Mater Today Chem* 18:100385
23. Li J et al (2021) Rapid and unamplified identification of COVID-19 with morpholino-modified graphene field-effect transistor nanosensor. *Biosens Bioelectron* 183:113206
24. Sengupta J et al (2021) Graphene-based field-effect transistor biosensors for the rapid detection and analysis of viruses: A perspective in view of COVID-19. *Carbon Trends* 2:100011
25. Chau YF et al (2019) Strong and tunable plasmonic field coupling and enhancement generating from the protruded metal nanorods and dielectric cores. *Results Phys* 13:102290
26. Chau YF et al (2020) Ultrawide Bandgap and High Sensitivity of a Plasmonic Metal-Insulator-Metal Waveguide Filter with Cavity and Baffles. *Nanomater* 10:2030
27. Zaky ZA et al (2021) Theoretical evaluation of the refractive index sensing capability using the coupling of Tamm-Fano resonance in one-dimensional photonic crystals. *Appl Nanosci* 11:2261–2270
28. Zaky ZA et al (2022) Design and Analysis of Gas Sensor Using Tailorable Fano Resonance by Coupling Between Tamm and Defected Mode Resonance. *Plasmonics* 17:2103–2111
29. Emami F et al (2019) Design and analysis of the novel plasmonic split ring resonator power splitter appropriate for photonic integrated circuits. *J Optoelectron Adv Mater* 21:163–170
30. Emami F et al (2019) Realization of all-optical plasmonic MIM split square ring resonator switch. *Opt Quantum Electron* 51
31. Kuppawamy S et al (2020) Computation of Refractive Indices of Corona Viruses through Reverse Calculation. *Curr Opt Photonics* 4:566–570
32. Taha BA et al (2021) Detection of COVID-19 Virus on Surfaces Using Photonics: Challenges and Perspectives. *Diagnostics (Basel)* 11:1119
33. Xu Z et al (2018) Design of a Tunable Ultra-Broadband Terahertz Absorber Based on Multiple Layers of Graphene Ribbons. *Nanoscale Res Lett* 13
34. Liu C et al (2018) Symmetrical dual D-shape photonic crystal fibers for surface plasmon resonance sensing. *Opt Express* 26
35. Zhong H et al (2020) Ultra-high quality graphene perfect absorbers for high performance switching manipulation. *Opt Express* 28:37294
36. Rakhshani MR (2021) Wide-angle perfect absorber using a 3D nanorod metasurface as a plasmonic sensor for detecting

- cancerous cells and its tuning with a graphene layer., *Photonics Nanostructures - Fundam Appl* 43:100883
37. Gururaj V, Alternative V (2013) Plasmonic Materials: Beyond Gold and Silver. *Adv Mater* 25:3264–3294
 38. Aghae T et al (2019) Circuit modeling of ultra-broadband terahertz absorber based on graphene array periodic disks. *Int J Numer Model: Electron Netw Devices Fields* 33:e2586
 39. Gururaj V et al (2011) Oxides and nitrides as alternative plasmonic materials in the optical range. *Opt Mat Exp* 1:1090–1099
 40. Borzooei S et al (2020) Graphene disks for frequency control of terahertz waves in broadband Applications. *J Comput Electron* 19:759–772
 41. Hajati Y (2020) Tunable broadband multiresonance graphene terahertz sensor. *Opt Mater* 101:109725. <https://doi.org/10.1016/j.optmat.2020.109725>
 42. Rafiee E et al (2023) Cancer Cell Detection Biosensor Based on Graphene-Plasmonic Split Square-Ring-Shaped Nanostructure. *Plasmonics* 18:431–440

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