Islamic Azad University

Journal of
Optoelectronical Nanostructures

Spring 2022 / Vol. 7, No. 2

Research Paper

Design and Modeling of Photonic Crystal Absorber by Using Gold and Graphene Films

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Received: **24 Mar. 2022**
Revised: **20 May. 2022**
Accepted: **10 Jun. 2022**
Published: **15 Jun. 2022**

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Keywords:
Photonic Crystals, Absorber, Gold Nanostructures, Graphene.

Abstract:

A novel absorber based on a one-dimensional photonic crystal (PhC) is proposed by combining the absorption property of gold and graphene films. We designed two photonic crystals consisting of silicon and silicon dioxide layers with lattice constants 125 and 260 that alternate in one dimension. We placed a 125-nanometer-thick layer of graphene between the two photonic crystals and an 8-nanometer-thick layer of gold at the end of the second photonic crystal. When graphene is placed between two photonic crystals, a topological edge mode excitation creates a strong absorption enhancement. In this study, the absorbing spectrums and field distribution are analyzed by using the transfer matrix and the 2.5 dimensional variational finite difference time domain method (2.5 var.FDTD). The absorption spectrum for different angles was studied (θ=0 to 60), and more than 87 percent absorption can be maintained for θ =40°. The results of our studies will enhance the interaction between light and matter. Thus, opening up the possibility of their application for the absorption and modulation of light.

Citation: Maryam Heidary Orojloo, Masoud Jabbari, Ghahraman Solooki nejad, Foozieh Sohrabi. Design and modeling of photonic crystal Absorber by using Gold and graphene films.**Journal of Optoelectronical Nanostructures. 2022; 7 (2): 1-10**
DOI: 10.30495/JOPN.2022.28915.1235

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1. INTRODUCTION

High-absorption structures have found wide applications in solar cells, thermal detectors, filters, and optical lasers in recent years. The perfect absorber was first introduced by Padilla in 2008 [1]. In recent years, one of the structures that has been extensively used in the design of the absorbers is photonic crystals. Photonic crystals are alternating structures of dielectric material that can be in one, two, or three dimensions. This periodicity in photonic crystals creates a band gap frequency range, which has led to the widespread use of photonic crystals in various fields [2]. As defects are introduced into a photonic crystal structure, the periodicity of the structure is broken, resulting in defect modes [3]. Structures such as cavities, waveguides, and fibers may be created by adding various defects in the photonic crystal [4, 5].

Some researchers use liquid crystals or magnetic fluids inside the holes coated with graphene or metal. This method has been developed during the past decade because of developments in materials science. The application value of photonic crystal devices can be examined both theoretically and practically. Aside from replacing conventional electronic devices, photonic crystal devices may also be used in biosensors, optical communications, and imaging. Furthermore, photonic crystal microcavities have a wide range of uses, including lasers [6, 7], optical switches [8, 9], and sensors [10, 11], due to their tight field confinement, high quality factor, and small mode volumes. Because of graphene's special properties, there has been a lot of interest in designing optoelectronic devices based on this material [12].

In this paper, the ability of graphene to generate surface plasmons resonances (SPR) has been studied. SPR is defined as the process in which charge-density oscillations are optically excited by exposing a metallic layer to a polarized light beam. This can be applied to the interface between a metallic layer and a dielectric surface [12, 13]. In other words, the SPR is an optical effect that occurs when an electromagnetic wave interacts with electron conduction in a metal [12, 13]. In 1907, Zenneck started a scientific study of the phenomena of SPR [14]. In recent decades, gold nanostructures have been thoroughly researched due to their special properties in surface Plasmon resonance. Silver, aluminum, and copper are chemically unstable metals. As compared to these metals, gold is more stable for SPR applications. A metal film can often be coated onto photonic crystals, or metal nanowires can be introduced into the air holes despite the photonic crystal's flexible nature. The common boundary between materials with a positive dielectric constant and materials with a negative dielectric constant, such as metals, can emit special electromagnetic waves called surface Plasmon waves that remain close to the surface [15]. The coherent motion of electrons in the conduction band causes this SPR., which interact with the electromagnetic field. The frequency and width of Plasmon absorption depend on metal nanoparticles' shape and scale, as well as the dielectric constant of the medium and the metal. Many intermediate metals have only a small, wide absorption band in the ultraviolet field, whereas noble metals such as gold has a very high visible Plasmon resonance.

This paper describes a novel structure consisting of two photonic crystals alternately layered with silicon and silicon. Lattice constants for the layers are 125 and 260, respectively. The two photonic crystals are separated by a 125-nanometer layer of graphene and an 8-nanometer layer of gold attached to the end of the second photonic crystal.

2. MATERIAL AND METHODS

A schematic design of the proposed absorber is seen in Fig. 1. We designed two photonic crystals consisting of layers of silicon and silicon dioxide that alternate in one dimension. The number of layers in PhC1 and PhC2 are considered to N = 18 and 10, respectively. To minimize the transmission and reflection, the lattice constants of phC1 and 2 are designed to 125 and 260 nm respectively. We placed a 125-nanometer-thick layer of graphene between the two photonic crystals and a 260-nanometer-thick layer of gold at the end of the second PhC. When graphene is placed between two photonic crystals, a topological edge mode excitation is created and leads to a strong absorption enhancement. In this simulation, the gold dielectric constant according to Eq. (1) and the Drude-Lorentz model is used.

$$\varepsilon_m = \varepsilon_\infty - \frac{\omega_D^2}{\omega(\omega + j\Gamma_D)} - \frac{\Delta\varepsilon\Omega_L^2}{(\omega^2 - \Omega_L^2) + j\Gamma_L\omega} \tag{1}$$

where ε_m gold permittivity, ε_∞ gold permittivity in the high frequency, $\Delta\varepsilon$ is equal to 1.09, ω is the guiding light frequency, $\omega_D/2\pi$ = 2113.6 THz is the plasma frequency, $\Gamma_D/2\pi$ =15.92 THz (damping frequency), $\Omega_L/2\pi$=650.07 THz (Lorentz oscillator frequency) and $\Gamma_L/2\pi$=104.86 THz is spectral width of the Lorentz oscillator [16]. The complex permittivity of gold used in our simulations was adapted from Johnson and Christy's experimental study [17]. Also, refractive index of graphene is defined as follows:

$$n_g = 0.3 + \frac{C_1}{3\lambda} \tag{2}$$

where λ is the incident light wavelength, and the C_1 constant equal to ≈ 5.446 μm^{-1} [18]. The absorption spectra and field distribution are analyzed using the transfer matrix method, the finite difference time domain method (FDTD), and Lumerical software.

3. SIMULATION RESULTS AND DISCUSSION

Fig. 1 shows a schematic representation of the absorber structure. We obtained the absorption spectrum of the structure for different source angles. To achieve the proposed structures' spectral response, the transfer-matrix method (TMM) is used. The TMM is a useful tool for calculating the characteristics of light propagation in 1-D photonic crystal absorbers. The transfer matrix is a matrix that describes how light propagates into a given layer. P_i and M_i are regarded as the matrices describing this propagation [19, 20].

$$P_i = \begin{pmatrix} exp(-j\phi_i) & 0 \\ 0 & exp(j\phi_i) \end{pmatrix} \tag{3}$$

$$M_i = \frac{1}{t_i}\begin{pmatrix} 1 & r_i \\ r_i & 1 \end{pmatrix} \tag{4}$$

where φ_i is the phase of the light that propagate in i^{th} layer and calculate from the following equation:

$$\phi_i = 2\pi n_i d_i \cos\theta_i / \lambda \tag{5}$$

where, n_i ,θ_i, and d_i are the refractive index, light angle and thickness of the i^{th} layer, respectively. The reflection and transmission coefficients are defined as follows using Fresnel equations as follows:

$$r_i = \left(n_{i-1}\cos\theta_i - n_i\cos\theta_{i-1}\right) / \left(n_{i-1}\cos\theta_i + n_i\cos\theta_{i-1}\right) \tag{6}$$

$$t_i = \left(2n_{i-1}\cos\theta_{i-1}\right) / \left(n_{i-1}\cos\theta_i + n_i\cos\theta_{i-1}\right) \tag{7}$$

Multiplying P_i and M_i yields the full matrix in the TMM.

$$Q = M_1 P_1 M_2 P_2 \cdots P_{2N+3} M_{2N+4} \tag{8}$$

The reflection and transmission spectra of the structures defined by:

$$R = \left| Q_{21} / Q_{11} \right|^2 \tag{9}$$

$$T = \left| 1 / Q_{11} \right|^2 \tag{10}$$

The absorption can be obtained from transmittance and reflectance as follows:

$$A = 1 - R - T \tag{11}$$

Fig. 2 shows the absorption spectra for θ =0 and 20. For θ= 20°, the electric field of the structure as seen in Fig. 3. The absorption spectrum for different angles were studied (θ=0 to 60) and the results shown in Fig. 4 (a). Most absorption occurred at θ=40, and at angles greater than 40, both reflection and transmission decreased (Fig. 4 (b)). The electric field of the structure for θ=40 is shown in Fig. 5.

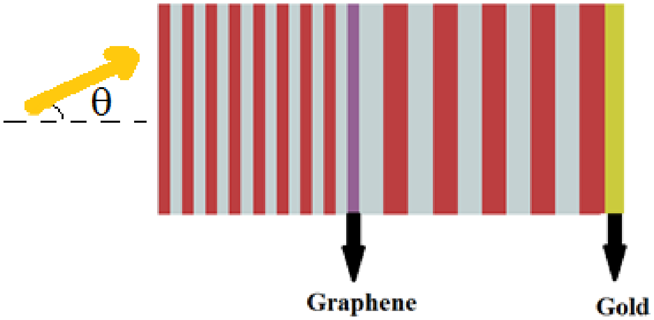

Fig. 1. The structure of the absorber.

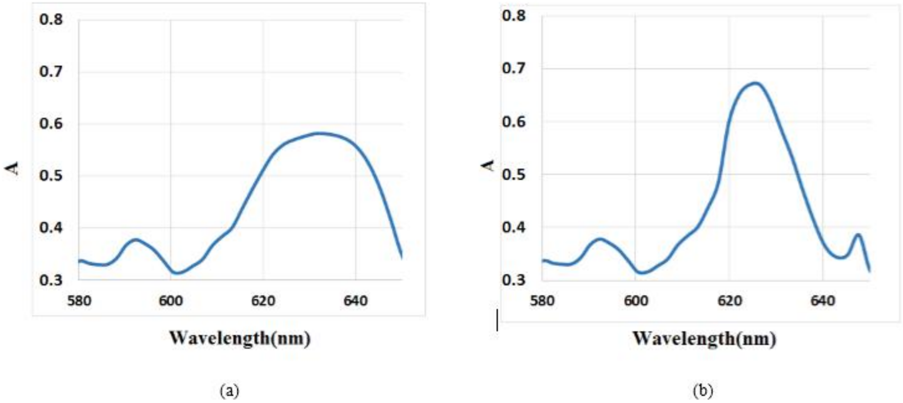

Fig. 2. Absorption spectrum for θ=0 (a) and for θ=20 (b).

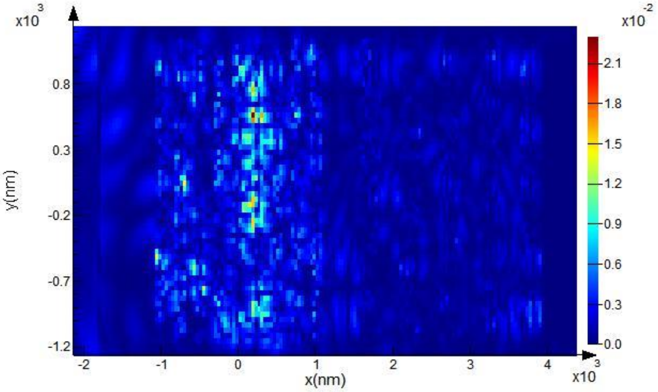

Fig. 3. The electric field profile of the structure for θ=20°.

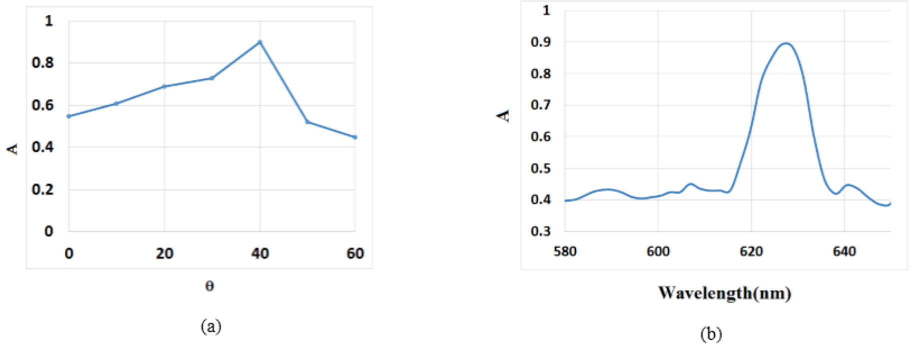

Fig. 4. Absorption spectrum for θ=0 to 60o (a) and for θ=40º (b).

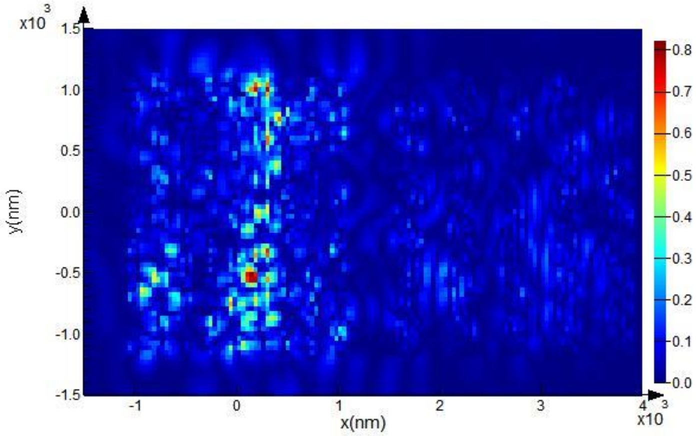

Fig. 5. the electric field profile of the structure for θ=40º.

4. CONCLUSION

The paper described an alternate layer of silicon and silicon dioxide with two photonic crystals in an innovative structure. 125 and 260 were the lattice constants for the two layers. At the end of the second photonic crystal was an 8-nanometer layer of gold attached to a 125-nanometer layer of graphene that separated the two photonic crystals. Graphene, gold nanofilms, and a 1D photonic crystal have been investigated theoretically and numerically to generate TPPs. The TMM measurements and 2.5 var.FDTD simulations showed that an increase in the absorption spectrum of the structure results from the excitation of the TPP mode between the graphene nanofilm and photonic crystal. The light absorption of 87% is possible in the proposed structure. The results presented here will enhance the light-matter interaction and expand the applications of these structures for light absorption and modulation.

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