Tunable properties of the absorption in a binary photonic crystal having a metamaterial as a defect layer and two graphene sheets in the range of GHz

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Abstract
Light absorption is essential in the construction of photodetectors and photovoltaic applications. In this work, the absorption properties of a defective photonic crystal are analyzed in the GHz region using the transfer matrix method. The defect layer is assumed to be a metamaterial of negative optical parameters sandwiched between two sheets of graphene. The tunable properties of absorption are investigated with the graphene chemical potential and phenomenological scattering rate and the thickness of the metamaterial layer. The results reveal that the number, position and height of the absorption resonant peaks are tuned by graphene optical properties. The spectra are studied with and without graphene sheets and an extra peak is created when two sheets of graphene are inserted on both sides of the metamaterial. The proposed photonic device can be useful in designing graphene and metamaterial-based optical devices such as absorbers, filters and sensors in the GHz region.

Keywords Photonic crystal · Transfer matrix method · Metamaterial · Defect layer · Graphene · Absorption

1 Introduction
Due to its physical properties and prospective uses in electrical, optoelectronic and energy storage devices, graphene-based structures have gotten a lot of interest in recent years (Singh et al. 2011; Ju et al. 2011; Thongrattanasiri et al. 2012; Fannin et al. 2016; Mizunoa

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The optical characteristics of graphene can be modified by altering its plasmon frequency using an externally supplied electric field to manipulate the Fermi level (Ju et al. 2011). Light absorption, on the other hand, is essential in the construction of photodetectors and photovoltaic applications. Different approaches, such as graphene-based structures (Mizunoa et al. 2009) and ordered periodic structures (Fannin et al. 2016), have been used to achieve complete absorption. Several scientists have looked at the optical absorption of the structures based on graphene so far. Thongrattanasiri et al., for example, demonstrated that a single graphene layer structured into an array of nano-disks has shown 100% light absorption (Thongrattanasiri et al. 2012). Ghasempour (Abbas Ghasempour Ardakani 2015) examined the temperature dependency of absorbance in the graphene layer. The dielectric–graphene–metal groove-grating absorber was studied by Zhu et al. They found that adjusting the applied potential difference on graphene can result in a high absorption efficiency (Zhu et al. 2013). Deng et al. studied the absorption in the spectral range THz in graphene-based devices and found that absorption may be regulated by altering chemical potentials (Deng et al. 2014). Absorbers and sensors have been the topic of numerous research papers in recent years (Sarreshtedari and Hosseini 2009; Mehdi Hosseini,"Tailoring the terahertz absorption in the quantum wells" 2016; Abbas Ghasempour Ardakani 2012). Graphene-metamaterials-based structures are also promising prospects for producing new IR and THz absorbers (Zhang et al. 2014). Metamaterials are man-made materials with sub-wavelength electric circuits. These materials have optical properties that differ from those of natural materials (Shalaev 2007). Watts et al. (Watts et al. 2012) have investigated the theory, characterization, and application of metamaterials as absorbers. Nefedov et al. demonstrated that a graphene-based hyperbolic metamaterial can achieve complete light absorption (Nefedov et al. 2013). In the far-infrared wavelength band, ideal absorbers based on graphene microribbon metamaterial were proposed by Alaee et al. (Alaee et al. 2012). Andryieuski et al. used the effective surface conductivity to construct a graphene-based metamaterial absorber in the THz range (Andryieuski and Lavrinenko 2013). Linder et al. investigated the absorption of structures based on graphene-anisotropic metamaterial and found that they could achieve near-perfect absorption over a wide range of angles of incidence (Linder and Halterman 2016). They attributed this to the coupling of the incident light and a fast-wave propagating along with the structure. Some research groups have recently investigated one-dimensional graphene photonic crystals (PCs) (Li et al. 2017; Razi and Ghasemi 2019; Aly et al. 2020).

The variations of refractive index and electric permittivity of the graphene 2D material have been analyzed (Kumar et al. 2020). The optical properties of 1D PC with graphene and dielectric materials have been analyzed (Kumar et al. 2020). Double-defect PC has been formed to realize double-mode absorption (Bian et al. 2020). For the upper defect, graphene sheets are placed on the top of a PC acting as the surface defect, whereas for the lower one, the pure dielectric defect of a PC serves as the internal defect (Bian et al. 2020). Magneto-optical properties of a 1D PC with a graphene sheet as a defect layer have been investigated (Shiri and Khalilzadeh 2020). It has been shown that the medium behavior completely depends on the intensity of the magnetic field (Shiri and Khalilzadeh 2020).

We propose a novel PC to achieve tunable properties of absorption in the GHz band in this work. A metamaterial sandwiched between two graphene layers is used as a defect layer to enhance absorption. The presence of graphene and metamaterials have a notable effect on the optical properties of the PC and hence on the absorbance, reflectance and transmittance spectra. The proposed photonic device is useful to design graphene metamaterial-based absorbers, filters and sensors. The novelty of the current paper lies in the fact that many published works
have investigated absorption in Graphene-based PC but, to the best of the authors’ knowledge, very few papers have investigated absorption in metamaterial-Graphene based PC.

The remaining parts of the paper are organized as follows: the theoretical model using the transfer matrix approach is presented in Sect. 2, and the numerical results and discussions are analyzed and reported in Sect. 3. At the last, the conclusions are explained and discussed in Sect. 4.

2 Design and theoretical model

A defective binary photonic crystal (BPC) of the structure (Si/SiO₂)ᴺ/ defect / (Si/SiO₂)ᴺ is proposed for the investigation of the absorption properties as shown in Fig. 1. This structure is surrounded by air from both sides. The defect is assumed as a metamaterial layer of simultaneously negative permittivity and permeability surrounded by two graphene sheets.

The permittivity ($\varepsilon_L$) and permeability ($\mu_L$) of the metamaterial are assumed to obey Lorentz medium model as (Sabah and Uckun 2007)

$$\varepsilon_L(\omega) = \varepsilon_0 \left(1 - \frac{f_{eo}^2 - f_{ep}^2}{f^2 - f_{eo}^2 + i\Gamma_e \omega}\right)$$  \hspace{1cm} (1)

$$\mu_L(\omega) = \mu_0 \left(1 - \frac{f_{mp}^2 - f_{mo}^2}{f^2 - f_{mp}^2 + i\Gamma_m \omega}\right)$$ \hspace{1cm} (2)

where $\omega$ is the angular frequency and $f_{eo}$, $f_{ep}$ and $\Gamma_e$ are the electric resonance, plasma and damping frequencies. $f_{mo}$, $f_{mp}$ and $\Gamma_m$ are the same but magnetic instead of electric.

The graphene permittivity can be written as (Montaseri et al. 2022)

$$\varepsilon_G = 1 + \frac{i\sigma_G}{\omega\varepsilon_0 d_G}$$ \hspace{1cm} (3)

where $d_G$ and $\varepsilon_0$ are the thickness of the graphene sheet and permittivity of vacuum. The surface conductivity $\sigma_G$ of a graphene sheet is given by Zhang et al. (2014)
\[\sigma_G = \frac{e^2}{\pi h^2} \frac{k_B T}{\Gamma_G - i\omega} \left[ \frac{\mu_C}{k_B T} + 2\ln(e^{\frac{\Delta C}{k_B T}} + 1) \right]\]  

(4)

where \(k_B\) is the Boltzmann constant, \(T\) is the temperature, \(\Gamma_G\) is the phenomenological scattering rate of graphene, and \(\mu_C\) is the chemical potential.

The PC optical properties are designed and simulated using a variety of approaches. The transfer matrix method is a simple and flexible tool for analyzing the optical properties of PCs. In this work, the structure of air/multilayer/substrate is considered. The parameters needed for the air and substrate materials are just their refractive indexes, \(n_0\) and \(n_s\). In terms of \(E_s\) and \(H_s\) (fields in the substrate layer), \(E_0\) and \(H_0\) (incident fields) can be expressed in a matrix form as (Almawgani et al. 2022a)

\[
\begin{bmatrix}
E_0 \\
H_0 
\end{bmatrix} = \prod_{j=1}^{N} D_j \begin{bmatrix}
E_s \\
H_s 
\end{bmatrix} = \begin{bmatrix}
b_{11} & b_{12} \\
b_{21} & b_{22} 
\end{bmatrix} \begin{bmatrix}
E_s \\
H_s 
\end{bmatrix}
\]

(5)

where \(D_j\) is the characteristic matrix of one layer and \(b_{ij}\) are the \(D_j\) elements. The matrix \(D_j\) can be expressed as (Almawgani et al. 2022b)

\[
D_j = \begin{bmatrix}
\cos(\delta_j) & -\frac{i\sin(\delta_j)}{\gamma_j} \\
-i\gamma_j \sin(\delta_j) & \cos(\delta_j) 
\end{bmatrix}
\]

(6)

where \(\delta_j\) is the phase change due to the propagation through the \(j\)th layer (Taya et al. 2022).

\[
\delta_j = \frac{2\pi}{\lambda} n_j h_j \cos\theta_j
\]

(7)

where \(n_j\) and \(h_j\) are the refractive index and thickness of the layer. \(\theta_j\) is the angle of incidence into the layer. In terms of the incidence angle \(\theta_0\), \(\theta_j\) is given as (Almawgani et al. 2022b)

\[
\cos\theta_j = \sqrt{1 - \left( \frac{n_0 \sin(\theta_0)}{n_j} \right)^2}
\]

(8)

\(\gamma_j = n_j \cos(\theta_j)\) for transverse electric (TE) and \(\gamma_j = \cos(\theta_j)/n_j\) for transverse magnetic (TM) waves. \(n_0\) is the refractive index of the incidence medium. The transfer matrix \(D_0\) for one period is written as \(D_0 = D_{S\text{il}} D_{SiO_2}\). The transfer matrix \(D\) of the whole BPC with a metamaterial layer between two graphene sheets can be written as (Almawgani et al. 2022a)

\[
D = (D_0)^N D_M D_G (D_0)^N = \begin{bmatrix}
D_{11} & D_{12} \\
D_{21} & D_{22} 
\end{bmatrix}
\]

(9)

where \(D_M\) and \(D_G\) are the transfer matrices of the metamaterial and graphene layers and \(D_{ij}\) are the elements of the \(D\) matrix. In terms of \(D_{ij}\), the transmittivity can be written as [X6]

\[
T = \frac{\gamma_{out}}{\gamma_{in}} \left( \frac{2\gamma_{in}}{(D_{11} + D_{12}\gamma_{out})\gamma_{in} + (D_{21} + D_{22}\gamma_{out})} \right)^2
\]

(10)

and the reflectivity can have the form (Almawgani et al. 2022b)
Finally, the absorption ($A$) is obtained as

$$A = 1 - T - R$$  \hspace{1cm} (12)$$

For TE and TM modes, $\gamma_{\text{in}} = \gamma_{\text{out}} = \cos(\theta_0)$ since the BPC is assumed to be surrounded by air from both sides.

### 3 Results and discussions

The absorption properties of a BPC having the structure (Si/SiO$_2$)$_N$/ Graphene/ metamaterial/ Graphene/ (Si/SiO$_2$)$_N$ are investigated using Mathematica software. We restrict our investigation to the TE polarized waves. We are interested in the region in which the real parts of $\varepsilon_L$ and $\mu_L$ of the metamaterial layer are negative. The following parameters are used in the calculations as in Ref. (Kumar et al. 2020): $f_{eo} = 10.30$ GHz, $f_{ep} = 12.80$ GHz, $f_{mo} = 8.0$ GHz and $f_{mp} = 13.0$ GHz. The electric and magnetic damping frequencies are taken to be equal $\Gamma_e = \Gamma_m = \Gamma_L = 1$ GHz (Kumar et al. 2020). Figure 2 shows the real parts of the permittivity (a) and permeability (b) of the metamaterial as a function of the frequency in the spectral range 0.1 – 25 GHz according to the Lorentz model. The figure reveals that the real parts of $\varepsilon_L$ and $\mu_L$ of the metamaterial layer are negative in the spectral range of 10.4–12.7 GHz. A material is said to be a metamaterial or left-handed material when both real parts of its permittivity and permeability are simultaneously negative. So, we have plotted here only the real parts of $\varepsilon_L$ and $\mu_L$ as a function of frequency. On the other hand, when we studied the absorption properties, we have considered both real and imaginary parts of the metamaterial permittivity and permeability. In the next calculations, we will adopt the frequency range 10.4–12.7 GHz. We consider a metamaterial layer of 1 μm thickness sandwiched between two graphene sheets each of thickness of 0.34 nm. The thicknesses of Si and SiO$_2$ layers are fixed as $h_{\text{Si}} = 10$ mm and $h_{\text{SiO}_2} = 25$ mm. The Si and SiO$_2$ thicknesses are not selected based on the quarter wavelength rule but we follow

![Fig. 2](image-url) The real parts of $\varepsilon_L$ and $\mu_L$ of the metamaterial layer as a function of the frequency according to the Lorentz model for $\Gamma_L = 1$ GHz
the same principles in which the material with the lower index has a higher thickness and vice versa. The number of periods of the PC is considered $N=5$. The chemical potential and the phenomenological scattering rate of graphene are taken as $\mu_C = 0.378$ eV and $\Gamma_G = 250$ GHz, respectively.

Figure 3 shows the transmission, reflection and absorption spectra of the proposed photonic structure at the prescribed parameters. As observed from the figure, the transmittance is nearly zero. There exist five dips in the reflectance profile and five peaks in the absorbance profile. The reflectance dips and the absorbance peaks occur at the same frequencies. The number of dips and peaks can be attributed to the number of periods of the photonic device. That means the dips and peaks in the reflectance and absorbance profiles are proportional to the number of periods. In the next, we will investigate the number of dips and peaks with the number of periods. Besides, we will investigate the effects of some factors such as the chemical potential and phenomenological scattering rate of graphene and the thickness of the metamaterial layer on the absorption properties of the proposed structure. Figure 4 shows the absorption spectra of the proposed BPC for different periods. We have taken $N=3, 5, 7$ and $9$. It is clear from these figures that the number of absorption peaks increases proportionally to the number of periods. In addition, as the number of periods increases, the absorption spectra occur in a wider frequency range. The frequency separations between the first and the last peaks are found as 0.97, 1.16, 1.24 and 1.28 GHz for $N=3, 5, 7$ and $9$. The absorption spectra are shown in Fig. 5 for different chemical potentials of the graphene layers. We have assumed the values of $\mu_c$ as 0.378, 0.6, 0.8 and 1 eV. Other parameters are kept the same as in Fig. 4. The number of peaks in the absorption profile and the frequency range in which these peaks occur do not change with the variation of graphene chemical potential. The peak values show a dramatic decay when the chemical potential is increased. For more investigation of the peak decay with the increase of the chemical potential, we consider the fifth peak of each panel in Fig. 5. The maximum intensities of absorption of these peaks are presented in Table 1. More values of the chemical potential have been investigated and added to the Table. In Fig. 6, the variation of the maximum absorption of the fifth peak is plotted as a function of graphene chemical potential. The decay of the maximum absorption for $\mu_c = 0.378–0.7$ eV is faster than that for $\mu_c > 0.7$ eV. The main reason behind the fast decay of the absorption when $\mu_c$ is in the range $0.378–0.7$ eV is the greater effect of the chemical potential on the dielectric constant of graphene during this range than in other ranges. The chemical potential of graphene can be varied by using the applied gate voltage. Hence the absorbance of the proposed structure is effectively tunable with the chemical potential of graphene and the applied gate voltage.

**Fig. 3** Transmission, reflection and absorption spectra of the proposed BPC. ($h_L = 1 \mu$m, $\Gamma_L = 1$ GHz, $\mu_c = 0.378$ eV, $\Gamma_G = 250$ GHz and $N=5$)
The absorption spectra of the proposed BPC are investigated for different graphene phenomenological scattering rates in Fig. 7. We have assumed the values of $\Gamma_G$ as 250, 450, 650 and 850 GHz. The number of absorption peaks does not depend on the phenomenological scattering rate of graphene. Moreover, the frequency range in which these peaks occur does not show a significant dependence on the graphene phenomenological scattering rate. The absorption peak values show an essential increase when the phenomenological scattering rate increases. For more investigation of the peak enhancement with the increase of the phenomenological scattering rate, we consider the fifth peak of each panel in Fig. 7. The maximum intensities of absorption of these peaks as a function of the phenomenological scattering rate are presented in Table 2. More values of the phenomenological scattering rate have been investigated and added to the Table. These values are plotted in Fig. 8. The absorption enhancement for $\Gamma_G = 250$–$450$ GHz is much greater than that for $\Gamma_G > 450$ GHz. The absorbance of the proposed structure is effectively tunable with graphene phenomenological scattering rate.

Figure 9 shows the absorption spectra of the proposed PC for different values of the metamaterial layer thickness. We have considered the values of $h_L$ as 100, 200, 300 and 400 μm. The maximum absorption can be enhanced with the metamaterial thickness increase. The maximum absorption of the fifth peak is found as 57%, 64%, 67% and 70% for the metamaterial layer thickness of 100, 200, 300 and 400 μm, respectively. This enhancement can be attributed to the longer optical path as the metamaterial layer thickness increases.
Fig. 5  Absorption spectra of the proposed BPC for different chemical potentials a $\mu_c = 0.378$, b $\mu_c = 0.6$, c $\mu_c = 0.8$ and d $\mu_c = 1.0$. ($h_L = 1 \mu$m, $N = 5$, $\Gamma_G = 250$ GHz and $\Gamma_L = 1$ GHz)

Table 1  Maximum intensity of the absorption as a function of chemical potential. ($h_L = 1 \mu$m, $N = 5$, $\Gamma_G = 250$ GHz , $\Gamma_L = 1$ GHz)

| $\mu_c$(eV) | 0.378 | 0.5 | 0.6 | 0.7 | 0.8 | 0.9 | 1 |
|-------------|------|----|----|----|----|----|---|
| Maximum absorbance | 0.48 | 0.41 | 0.35 | 0.3 | 0.26 | 0.23 | 0.21 |

Fig. 6  Maximum absorption as a function of graphene chemical potential. ($h_L = 1 \mu$m, $N = 5$, $\Gamma_G = 250$ GHz and $\Gamma_L = 1$ GHz)
**Fig. 7** Absorption spectra of the proposed BPC for different phenomenological scattering rates a $\Gamma_G = 250$, b $\Gamma_G = 450$, c $\Gamma_G = 650$ and d $\Gamma_G = 850$ GHz. ($h_L = \mu m$, $N = 5$, $\mu_c = 0.378$ eV and $\Gamma_L = 1$ GHz)

**Table 2** Maximum intensity of absorption as a function of $\Gamma_G$. ($h_L = 1 \mu m$, $N = 5$, $\mu_c = 0.378$ eV and $\Gamma_L = 1$ GHz)

| $\Gamma_G$(GHz) | 250 | 350 | 450 | 550 | 650 | 750 | 850 |
|-----------------|-----|-----|-----|-----|-----|-----|-----|
| Maximum absorbance | 0.48 | 0.59 | 0.70 | 0.75 | 0.82 | 0.86 | 0.90 |

**Fig. 8** Maximum absorption as a function of graphene phenomenological scattering rate. ($h_L = 1 \mu m$, $N = 5$, $\mu_c = 0.378$ eV and $\Gamma_L = 1$ GHz)
To show the role of the graphene sheets in the spectra of the proposed structure, the transmittance, reflectance and absorption spectra are shown without (Fig. 10a) and with (Fig. 10a) graphene. As observed (Fig. 10a), no absorption in the spectra and only four peaks appear in the transmittance and reflectance spectra in the absence of graphene sheets. From Fig. 10b, two important effects are noted in the presence of two graphene sheets. The first effect is the reduction of transmittance to very low values. The second effect is the appearance of an additional peak in the reflectance spectra. This effect is due to the large alteration in the optical path and the effective refractive index of the proposed device with the presence of two graphene sheets. The surface conductivity of graphene is responsible for the creation of additional peaks in the reflectance and absorbance profiles. Here, two graphene sheets behave like a single repetitive layer and it reflects in the result as an extra absorption peak with a high magnitude.

It is worth providing the designer with some suggestions to fabricate this PC structure. One period consists of Si/SiO$_2$ layers. Si layer can be deposited using one of the techniques: photochemical vapour deposition (CVD), hot-wire CVD, thermal CVD, and hot reactor and cold substrate CVD. Plasma chemical vapour deposition using silane (SiH$_4$) source can be used to deposit SiO$_2$ layer. Graphene monolayers can be produced or isolated in a variety of methods. At the moment chemical vapour deposition is the method that is most frequently used. A metamaterial with negative parameters can be designed in three steps: Firstly, the split ring resonators have been predicted to exhibit the resonant magnetic response to electromagnetic waves. Then, periodic arrays of split ring resonators are characterized by negative magnetic permeability. Secondly, a regular lattice of thin metallic

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Fig. 9 Absorption spectra of the proposed BPC for different thicknesses of the metamaterial a $h_L = 100 \, \mu m$, b $h_L = 200 \, \mu m$, c $h_L = 300 \, \mu m$ and d $h_L = 400 \, \mu m$. (N = 5, $\Gamma_G = 250 \, GHZ$, $\mu_e = 0.378 \, eV$ and $\Gamma_L = 1 \, GHZ$)
wires can exhibit negative permittivity. Thirdly, combining both the split ring resonators and regular lattice of thin metallic wires can give a material with both $\varepsilon$ and $\mu$ are negative. The chemical potential and phenomenological scattering rate of graphene can be varied by changing the applied gate voltage and relaxation time, respectively.

4 Conclusions

The absorption properties of a defective one-dimensional BPC are analyzed in the GHz region. The defect layer is assumed a metamaterial of simultaneously negative epsilon and mu sandwiched between two sheets of graphene. We first studied the frequency range in which the permeability and permittivity of the metamaterial are negative and found that both of them are negative in the spectral range 10.4–12.7 GHz. Tuning properties of the absorption spectra are investigated with the variation of chemical potential and phenomenological scattering rate of graphene and thickness of the metamaterial layer. The results reveal that the number of absorption peaks in the absorbance spectrum increases proportionally to the number of periods. The absorbance of the proposed structure is effectively tunable with the chemical potential of graphene. The chemical potential of graphene can be varied by using the applied gate voltage. Hence, the absorbance can be tuned by changing the applied gate voltage. The absorption peak has shown an essential enhancement when the phenomenological scattering
rate of graphene increases. The absorption can be also enhanced with the metamaterial thickness increase. The reflection and absorption spectra have been investigated with and without graphene and an extra peak is created when two sheets of graphene are inserted on both sides of the metamaterial.

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Data availability The datasets generated during or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Conflict of interests The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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