Tunable THz absorption in photonic crystal including graphene and metamaterial

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Received: 05 February 2021 / Accepted: 17 November 2021 / Published online: 30 January 2022

Abstract: In this paper, a photonic crystal containing graphene and metamaterial layers is investigated. The absorption spectrum of the structure in the terahertz range is obtained using the transfer matrix method. The results show that when the Si, SiO₂ or metamaterial layer is sandwiched between two graphene layers, the terahertz absorption increases significantly. The results also reveal that in a wide range of physical parameters, an approximately complete absorption (~100%) occurs. Furthermore, the results indicate that the structure with the metamaterial layer has the highest absorption.

Keywords: Photonic crystal; Graphene; Metamaterial

1. Introduction

In recent years, graphene-based materials have attracted much attention due to their physical characteristics and potential applications in electronic and optoelectronic devices, chemical sensors, and energy storage [1]. The optical properties of the graphene can be tuned by adjusting its plasmon frequency via manipulating the Fermi level using an externally applied electric field [2]. On the other hand, light absorption plays an important role in the designing of photodetectors and photovoltaic devices. The perfect absorption has been achieved by different methods such as using (1) sparseness and imperfect alignment of the vertical single-walled carbon nanotubes [3], (2) ordered periodic structures [4], and (3) graphene-based structures [5].

So far, several researchers have investigated the optical absorption of graphene-based structures. For example, Thongrattanasiri et al. showed that a single sheet of doped graphene, patterned into a periodic array of nano-disks, exhibits 100% light absorption [5]. The temperature dependence of the absorption in the graphene layer was investigated by Ghasempour [6]. Zhu et al. studied the dielectric–graphene–metal groove-grating absorber. They found that a high efficiency (95%) absorptive spectrum in the near-infrared range can be achieved by tuning the applied voltage on graphene [7]. Deng et al. investigated the terahertz (THz) absorption spectrum in graphene-based structures and indicated that the THz absorption could be controlled by adjusting the chemical potentials [8].

The THz devices such as absorbers, sensors, and sources are subjects of many research studies in the last years [9–13]. The graphene-based metamaterials are also good candidates for developing new absorbers in terahertz (THz) [14, 15] and infrared ranges [16]. Metamaterials are artificial materials that include sub-wavelength electric circuits and can exhibit optical properties beyond natural materials [17, 18]. In this regard, Watts et al. reported extensively the theory, characterization, and implementation of metamaterial perfect absorbers [19]. Nefedov et al. have shown that the perfect light absorption can be obtained in a graphene-based hyperbolic metamaterial [20]. Alaee et al. introduced perfect absorbers based on the graphene micro-ribbon metamaterial in the far-infrared wavelength region [21]. Andryieuski et al. designed a graphene-based metamaterial absorber using the effective surface conductivity in the THz regime [22]. Linder et al. studied the absorption properties of graphene-based anisotropic metamaterial structures and achieved a nearly perfect absorption over a broad range of incidence angles [23]. They found that this is due to the coupling of the incident light and a fast-wave propagating along with the structure.

Recently, the one-dimensional graphene photonic crystals are investigated by some researchers [24–28]. In this paper, we propose a new photonic crystal (PC) to obtain tunable perfect absorption in the terahertz region. The
article is organized as follows: We describe the theoretical framework in Sect. 2. Then, the results are discussed in Sect. 3, and finally, the conclusions are given in Sect. 4.

2. Theoretical model

As shown in Fig. 1, we consider a PC containing different layers: glasses with thickness \(d_{Gl}\) (gray regions), titanium dioxide with thickness \(d_{Ti}\) (red), graphene with thickness \(d_{G}\) (purple), and metamaterial, Si or SiO\(_2\) with thickness \(d_{x}\) (yellow region).

Also, \(n_l\) and \(n_r\) are the number of the dielectric layers on the left and right sides of the PC, respectively. The relative permittivity of graphene can be calculated as follows [7, 16, 22, 29].

\[
\varepsilon_G = 1 + \frac{i\sigma_G}{\omega\varepsilon_0 d_G} \tag{1}
\]

where \(d_G\) is the thickness of the single graphene layer, \(\varepsilon_0\) is the permittivity of vacuum, and \(\omega\) is the angular frequency. The surface conductivity \(\sigma_G\) in the THz frequency range is written as [8, 15]:

\[
\sigma_G = \frac{e^2}{\pi h^2} \frac{k_B T}{\Gamma - i\omega} \left[ \frac{\mu_c}{k_B T} + 2 \ln \left( e^{-\frac{\mu_c}{k_B T}} + 1 \right) \right] \tag{2}
\]

where \(k_B\) is the Boltzmann constant, \(T\) is the temperature, \(\Gamma\) is the relaxation rate, and \(\mu_c\) is the chemical potential. The relation between electric and magnetic fields in the adjacent layers is obtained using the transfer matrix method [6, 24, 30],

\[
\begin{pmatrix} E_i \\ H_i \end{pmatrix} = M \begin{pmatrix} E_{i+1} \\ H_{i+1} \end{pmatrix} \tag{3}
\]

where

\[
M = \begin{pmatrix} \cos(kd) & -i \frac{\eta_0}{\eta_1} \sin(kd) \\ -i \frac{\eta_1}{\eta_0} \sin(kd) & \cos(kd) \end{pmatrix} \tag{4}
\]

where \(d\) is the thickness of each layer, \(n\) is the refractive index, \(\eta_0 = \sqrt{\frac{\mu_c}{\varepsilon_0}}\) is the impedance of vacuum, \(\mu_0\) is the permeability of free space, \(k = \frac{\omega}{c}\) is the wave vector, and \(c\) is the speed of light in vacuum. In this paper, the field intensity and the refractive index of each layer are assumed to be constant. The total transfer matrix of the structure is given by:

\[
M = M_1 M_2 \ldots M_n = \begin{pmatrix} A & B \\ C & D \end{pmatrix} \tag{5}
\]

where \(A, B, C,\) and \(D\) are the elements of matrix \(M\). The reflection coefficient \(r(\omega)\) and the transmission coefficient \(t(\omega)\) for the left-incident plane wave can be expressed as follows [6, 24, 28, 30],

\[
r(\omega) = \frac{A_1 + B_1 \eta_2 - C - D_1 \eta_2}{A_1 + B_1 \eta_2 + C + D_1 \eta_2} \tag{6}
\]

\[
t(\omega) = \frac{2\eta_1}{A_1 + B_1 \eta_2 + C + D_1 \eta_2} \tag{7}
\]

The reflectance, transmittance, and the absorbance of the structure at frequency \(\omega\) are defined as [6, 28]:

\[
R(\omega) = |r(\omega)|^2, \quad T(\omega) = \frac{\eta_2^2}{\eta_1^2} |t(\omega)|^2, \quad A(\omega) = 1 - R(\omega) - T(\omega) \tag{7}
\]

where \(\eta_1 = \frac{\eta_0}{\eta_l}\) and \(\eta_2 = \frac{\eta_0}{\eta_r}\) are the characteristic impedances of the right and left media, respectively.

3. Result and discussion

The material parameters used in our calculations are as follows: The refractive indices are as follows: \(n_{Gl} = 1.6\), \(n_{TiO2} = 2.9\), \(n_{Si} = 3.45\), \(n_{SiO2} = 1.97\), which are approximately constant at THz frequencies [8, 31]. Also, \(T = 300\) K, \(\Gamma = 2.5\) meV/h, \(\mu_c = 0.378\) eV, \(d_G = 0.34\) nm [6] and \(d_x = 11\) \(\mu\)m (Except in results of Figs. 2 and 6).

For more clarity, the results are presented in three cases; (1) there is nothing between graphene layers, (2) a thin film of Si or SiO\(_2\) with \(d_x\) thickness is placed between two graphene layers, (3) \(d_x\) layer is filled with metamaterial.

![Fig. 1 A schematic diagram of our proposed one-dimensional PC](image-url)

Fig. 1 The absorbance in case (1) for different thicknesses of the dielectric layers.
Case (1) \(d_x = 0, n_L = 4, n_R = 8\).

The absorbance of this case is plotted in Fig. 2 for different values of \(d_T\) and \(d_{Gl}\). This figure shows that the structure has a low absorbance and its maximum is about 15%.

Case (2) Si or SiO\(_2\), \(d_x = 20\ \mu\text{m}, n_L = 4, n_R = 8\).

Figure 3(a) and (b) present the absorbance for the case when the layer \(d_x\) is filled with Si and SiO\(_2\), respectively. This figure reveals that the absorbance increases compared to the case (1) (Fig. 2) and that minimum is about 70%. It is also seen that the higher absorbance region (dark-red region) of Fig. 3(b) is greater than that of Fig. 3(a). These figures reveal that the approximately complete absorber could be achieved by tuning the TiO\(_2\) and glass thicknesses. Similar structures have been proposed for absorbers and filters [24, 27, 32].

Case (3) Metamaterial, \(d_x = 20\ \mu\text{m}, d_{Gl} = 20\ \mu\text{m}, d_T = 20\ \mu\text{m}.

In Fig. 4, the absorbance of the PC is plotted versus the wavelength of incident light for different values of \(n_L\) and \(n_R\). In this figure, the refractive index of metamaterial is \(-1.5\). Figure 4(a) shows that for a fixed value of \(n_R = 8\), the absorbance of \(n_L = 5\) is larger than that of other values of \(n_L\).

Also, with increasing \(n_L\), the position of the absorption peak shifts to the higher values of the wavelength. But, Fig. 4(b) reveals that for a fixed value of \(n_L = 5\), the absorbance for different values of \(n_R\) is similar in behavior and peak position.

In Fig. 5, the absorbance and wavelength of the peak position are presented versus \(d_T\) and \(d_{Gl}\) for \(n_L = 5\) and \(n_R = 8\). This figure shows that for most values of \(d_T\) and \(d_{Gl}\), the absorbance is larger than 90%. Also, the wavelength of the peak position is about in the range of 60–120 \(\mu\text{m}\).

By comparing Figs. 3 and 5, it is seen that the absorption increases substantially and tends to 100% by introducing the metamaterial layer instead of Si or SiO\(_2\). The higher contrast between refractive indices of metamaterial and TiO\(_2\) or glass could be the reason for increasing the absorption. Such structure is a nearly perfect absorber that is independent of TiO\(_2\) and glass thicknesses that could be robust for different applications. Furthermore, this complete absorbance helps us to tune the absorption peak by changing the TiO\(_2\) and glass thicknesses.

The absorbance and peak position for different values of the thickness and refractive index of metamaterial are shown in Fig. 6. From this figure, it is seen that the
absorbance increases and reaches 100% when the refractive index tends to \(-1\), especially for the higher thickness of the metamaterial layer. Figure 6(b) shows that the wavelength of the peak position is about in the range of 72–76 μm.

4. Conclusions

In this work, we have proposed a graphene photonic crystal in three cases: (1) no matter, (2) Si or SiO₂, (3) metamaterial is placed between two graphene layers. Then the effects of the thickness and number of layers, and the wavelength of the incident radiation on the absorbance are investigated. The results show that absorbance increases by inserting the Si (SiO₂) layer in the structure. However, inserting the metamaterial significantly increases the absorbance in comparison with other cases. In this case, we have a nearly perfect absorber for a wide range of dielectric thicknesses, so we can tune the absorbance peak frequency. Overall, our results indicate that a large absorbance in the terahertz region may be obtained by suitable choice of the material, the number, and the thickness of the layers.

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