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Tunable multichannel absorber composed of graphene and doped periodic structures

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ABSTRACT

A new design for a tunable multichannel compact absorber, which is achieved by using an asymmetric photonic crystal with graphene monolayers, is theoretically proposed. The graphene monolayers are periodically embedded into the first and last dielectric layers. The absorption, reflection, and transmission spectra of the absorber are studied numerically. A perfect absorption channel is achieved because of impedance matching, and channel number can be modulated by changing periodic number. The characteristic properties of the absorption channel depend on graphene conductivity, which can be controlled via the gate voltage. The proposed structure works as a perfect absorber that is independent from polarization. It has potential applications in the design of multichannel filters, thermal detectors, and electromagnetic wave energy collectors.

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1. Introduction

As a type of artificial material, one-dimensional (1D) photonic crystals (PCs) with a periodic arrangement of refractive index have attracted considerable attention for the past few years because of their capability to create a range of forbidden frequencies known as photonic band gap (PBG) [1]. PBGs have many interesting and attractive applications in optical filters [2], reflectors [3], and nonlinear diodes [4], as well as in fabricating PC waveguides [5,6]. Different materials have been used to dynamically control the transmittance spectrum of a PC. The electromagnetic (EM) properties of PCs, which are composed of metals [7,8], plasma [9,10], metamaterials [11,12], and superconductor elements [13,14], have been investigated. These materials have an advantage given that their permittivity can be transformed by an external magnetic field, outside voltage, or temperature. Consequently, the EM properties of devices with PCs, including tunable elements, can be adjusted.

Graphene, as a planar atomic layer of carbon atoms arranged in a honeycomb lattice, is actually a type of semiconductor [15–17]. In addition to distinct properties such as high charge carrier mobility, electronic energy spectrum without a gap between the conduction and valence bands, and frequency independent absorption of EM radiation [18–20], another superiority of graphene is that its carrier concentration can be electrically modulated within a wide frequency range by altering outside gate voltage. Given these unique characteristics, 1D graphene-based PCs have been investigated extensively. Madani et al. [21] focused on transmission properties in a 1D PC with graphene monolayers. A new type of omnidirectional PBG in the THz region, which was nearly insensitive to polarization, was theoretically analyzed. Zhang et al. [22] investigated strong second-harmonic generation from bilayer graphene embedded into 1D PC. Naggar [23] focused on the properties of a tunable THz omnidirectional PBG by periodically introducing graphene sheets into the first layer of a conventional 1D PC. Entezar [24] and Zhang [25] researched on the optical properties of a defective 1D PC with graphene monolayers and Fibonacci quasi-periodic graphene PCs, respectively. Photonic applications, such as multi-peak or broadband absorbers, were proposed by Miloua [26] and Ning [27]. However, However, polarization-independent absorbers with tunable multichannels and high absorption characteristics are rarely reported.

In the current study, a tunable multichannel compact absorber produced using an asymmetric PC with graphene monolayers is theoretically investigated. The absorber has a compact structure,

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and the absorption channel can be dynamically modulated within the THz range. We research on the effects of parameters, such as the number of PCs, the chemical potential, and the distance between the graphene sheets, on the optical response of the structure. The possibility to achieve a polarization-independent and tunable multichannel perfect absorber is discussed.

2. Theoretical model and method

A schematic cross-sectional view of the absorber is shown in Fig. 1 as follows: $GC(BA)^N(AB)^NCG'$, where G and G' are composed of graphene sheets separated by thin dielectric layers. A and B are dielectric layers with low and high dielectric constants ε_A and ε_B, respectively; N is the periodic number of the structure; and layer C is the same material as layer A but with a different thickness. The frequency-dependent effective permittivity, $\varepsilon_{G,G'}$, of the grapheme sheets separated by dielectric layers with a dielectric constant ε_d and a thickness d is given by the Kubo formula as follows [24]:

$$\varepsilon_{G,G'} = \varepsilon_d + i\frac{\sigma_g(\omega)}{\omega\varepsilon_0 d} \tag{1}$$

where the surface conductivity $\sigma_g(\omega)$ of the graphene sheet can be written as the sum of the intraband and interband electron transition contributions as [23]

$$\sigma_g(\omega) = \sigma_g^{\text{int }ra}(\omega) + \sigma_g^{\text{int }er}(\omega) \tag{2}$$

where

$$\sigma_g^{\text{int }ra}(\omega) = \frac{e^2}{4\hbar}\frac{i}{2\pi}\left[\frac{16k_BT}{\hbar\omega}\log(2\cosh(\frac{\mu}{2k_BT}))\right] \tag{3}$$

$$\sigma_g^{\text{int }er}(\omega) = \frac{e^2}{4\hbar}\left[\frac{1}{2} + \frac{1}{\pi}\arctan\frac{\hbar\omega - 2\mu}{2k_BT} - \frac{i}{2\pi}\left[\log(\frac{(\hbar\omega + 2\mu)^2}{(\hbar\omega - 2\mu)^2 + (2k_BT)^2})\right]\right] \tag{4}$$

In Eq. (4), e is the charge of the electron, $\hbar$ is the Planck constant, ω is the radian frequency, k_B is the Boltzmann constant, T is the temperature (K), and μ is the chemical potential that can be controlled via the gate voltage.

The well-known transfer matrix method has been used to obtain reflection, transmission, and absorption [28,29] as follows:

$$R = |r|^2 = \left|\frac{m_{11}\eta_0 + m_{12}\eta_0\eta_{n+1} - m_{21} - m_{22}\eta_0}{m_{11}\eta_0 + m_{12}\eta_0\eta_{n+1} + m_{21} + m_{22}\eta_0}\right|^2, \tag{5}$$

$$T = |t|^2 = \left|\frac{2\eta_0}{m_{11}\eta_0 + m_{12}\eta_0\eta_{n+1} + m_{21} + m_{22}\eta_0}\right|^2, \tag{6}$$

$$A = 1 - T - R. \tag{7}$$

where m_{11}, m_{12}, m_{21}, and m_{22} are the elements of the total transfer matrix

$$M = [M_GM_C(M_BM_A)^N(M_AM_B)^NM_CM_{G'}] = \prod_{l=1}^{n}\begin{pmatrix}\cos\delta_l & -\frac{i}{\eta_l}\sin\delta_l \\ -i\eta_l\sin\delta_l & \cos\delta_l\end{pmatrix} \tag{8}$$

When different polarizations are considered, $\eta_l = \sqrt{\varepsilon_l}/\sqrt{\mu_l}\sqrt{1 - (\sin^2\theta/\varepsilon_l\mu_l)}$ for the TE wave and $\eta_l = \sqrt{\mu_l}/\sqrt{\varepsilon_l}\sqrt{1 - (\sin^2\theta/\varepsilon_l\mu_l)}$ for the TM wave. η_0 and η_{n+1} are defined as the corresponding η parameters of the incidence and exit media (air in this study), respectively.

3. Numerical results and discussion

In this study, a tunable multichannel perfect absorber with an asymmetric PC that contains graphene monolayers and doped periodic structures within the THz frequency range is theoretically investigated. Layers G and G' are graphene–SiO_2 systems made up of thin SiO_2 films deposited on epitaxially grown graphene monolayers. The permittivity of SiO_2 is set to $\varepsilon_d = 5.07$. [30]. The permittivity of the graphene–SiO_2 multilayer $\varepsilon_{G,G'}$ is calculated according to Eq. (1), and $\mu = 0.2$ eV and $T = 300$ K are assumed during the calculation of the surface conductivity of graphene. Layers A and B are assumed to be SiO_2 and silicon with a permittivity of $\varepsilon_A = 5.07$ and $\varepsilon_B = 10.9$, respectively. The thickness values $d_a = 9.2$ μm and $d_b = 6.3$ μm are set to satisfy $n_ad_a = n_bd_b$. $d_c = 5$ μm, $d_G = 10$ μm, and $d_{G'} = 25$ μm are selected to investigate the performance of the device within the THz frequency range.

All of the aforementioned structure parameters are selected to achieve the perfect absorption process shown in Fig. 2(a), which fulfill the requirement of the impedance matching method [31]. When only the simplest structure $GCBAABCG'$ is considered, a channel with nearly zero transmission and zero reflection but

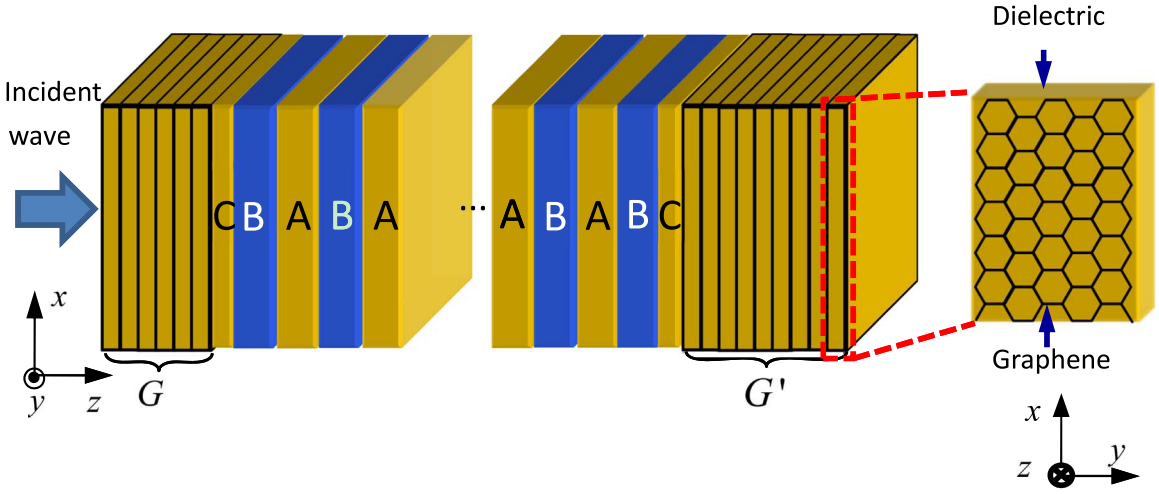

Fig. 1. Schematic diagram of the absorber with the structure $GC(BA)^N(AB)^NCG'$, in which layers G and G' are composed of graphene sheets separated by thin dielectric layers.

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