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Transmission property of one-dimensional multilayer graphene–dielectric stack

Liwei Zhang [a,*], Guodong Wang [b], Xu Han [a], Yuhuan Zhao [a]

[a] School of Physics and Chemistry, Henan Polytechnic University, Jiaozuo 454000, PR China
[b] School of Electrical Engineering and Automation, Henan Polytechnic University, Jiaozuo 454000, PR China

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ABSTRACT

The transmission property and field distribution of one-dimensional multilayer containing graphene sheets separated by dielectric slabs are theoretically studied in terahertz. It is shown that the multilayer graphene–dielectric stack supports a series of passband and stopband whose number increases with the dielectric thickness. The field distributions show that the transmission resonances in the passband are attributed to Fabry–Perot resonances in the dielectric layer and the node numbers that appear in the field distribution in each graphene–dielectric–graphene cavity can be quantitatively given. It is also noticed that these resonances lie within a certain characteristic frequency bands which are independent of the number of unit cells making up the structure. The low frequency edge of the passband is highly tunable by the Fermi energy and the layer number of graphene sheets, while the high frequency edge is just determined by the dielectric slab. When an impurity is introduced, a defect mode can appear inside the stopband and it can be adjusted by Fermi energy of graphene controlled via a gate voltage.

1. Introduction

The use of photonic crystals (PCs) which are artificially fabricated materials with periodic modulation in dielectric properties to control electromagnetic (EM) wave propagation and energy distribution is nowadays a common practice in optics and microwaves research [1–4]. The essential property of the periodic structures is the photonic band gap (PBG) structure, PBGs have many interesting and attractive applications in optical reflectors [2], localization of photon [3], control of spontaneous emission [4], enhancement of nonlinear effects [5], etc. The simplest example is the one-dimensional (1D) PCs which are of particular interesting due to their practical applications in layered optical systems. Especially for the 1D metal-dielectric stack, although extremely thin metal layers are highly reflective at optical frequencies, the superposition of a number of these layers separated by optically thick transparent dielectric slabs has been shown to generate high transmissivity bands within a characteristic band [6,7]. The spectra for such a multilayer structures consist of a series of passband and stopband regions which are different from that for an all dielectric multilayer structure. But it is quite difficult to mimick these properties in the microwave and far-infrared regimes due to the quasiperfect conductor behavior of metals at the according frequencies. To overcome this problem, a metal film is designed on the subwavelength scale to create a metamaterial with effective Drude-like electromagnetic properties in microwave regime [8,9]. However, the performance of the metal structures is hampered because of the difficulty in varying and controlling their permittivity functions and the existence of material losses, so it is difficult to realize a dynamically tunable bandgap or passband at the frequency of interest. The recent studies about graphene have demonstrated that a free-standing graphene shows excellent metal-like characteristics under electric/magnetic biasing or chemical doping in middle, far-infrared, and terahertz ranges, which is similar to a thin metal behavior at optical frequency [10–12].

Graphene is a two-dimension substance composed of a single layer carbon atom arranged in a honeycomb lattice with a lattice constant of 0.264 nm, in general, the spatial dispersion effects introduced by graphene periodicity can be neglected at terahertz frequencies [13]. It has attracted intensive scientific interest owing to its incredible physical properties, such as optical transparency, flexibility and extraordinary electrical properties [14–18]. With the recent developments in the fabrication of graphene in experiments [19], there have been numerous graphene applications at optical, infrared, and terahertz frequencies as metamaterials, tunable photodetectors, polarizer, plasmonic sensors, modulator [12,15–18].

* Corresponding author. Tel.: +863913987817.
E-mail address: zlwhpu@hotmail.com (L. Zhang).

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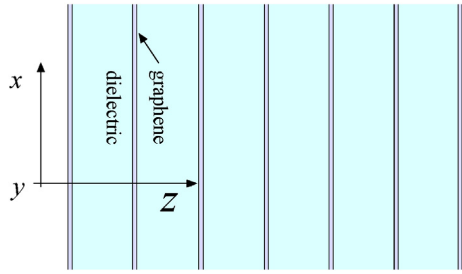

Fig. 1. Schematic of 1D GD stack consisting of alternating graphene sheets and dielectric layers, the layers are infinite in x–y plane.

Because the imaginary part of graphene conductivity can attain negative values in a certain frequency, a graphene layer effectively behaves as a "metal" layer capable of supporting a p-polarization surface-plasmon polariton which shows similar behavior to that in noble metals [15,16]. Unlike the metals, the electronic and the optical properties of graphene can be tuned through electrical or chemical modification of the charge carrier density [20,21]. According to the tunable nature of graphene, it is straightforward to achieve a tunable photonic crystal by integrating a graphene layer into the period of a dielectric structure in both THz and infrared ranges [22,23]. In Ref. [22], the transmission property and field distribution in 1D monolayer graphene–dielectric (GD) structures are studied. In this paper, we comprehensively investigate the transmission property and field distribution of 1D GD multilayer with different dielectric thickness and graphene layer. Moreover, the tunable defect mode properties are also calculated.

2. Model and theory

Considering the 1D multilayer GD stack of $(GA)_N G$ in air background as shown in Fig. 1, where graphene sheets G are separated by dielectric layers A with thickness d_A and relative permittivity ε_A, N is the number of periods. The period of the layered structure is $d = d_A + d_g$, d_g is the effective graphene thickness. We choose the layers to be parallel to the x–y plane and the z-axis normal to the interfaces of the layers. A graphene monolayer is electrically characterized by the local isotropic sheet conductivity $\sigma(\omega, E_F)$, which is highly dependent on the working frequency and Fermi energy E_F. Within the random-phase approximation and without external magnetic field, the graphene is isotropic, the surface conductivity $\sigma(\omega, E_F)$ contains the contributions from both interband and intraband absorption mechanisms, which is the sum of intraband σ_{intra} and interband σ_{inter} contributions [24],

$$\sigma_{\mathrm{intra}} = \frac{ie^2 K_B T}{\pi \hbar^2 \left((\omega + i)/\tau\right)} \left(\frac{E_F}{K_B T} + 2\ln\left(1 + e^{-E_F/K_B T}\right)\right),$$
$$\sigma_{\mathrm{inter}} = \frac{ie^2}{\pi \hbar^2} \ln\left|\frac{2E_F - \hbar\left((\omega + i)/\tau\right)}{2E_F + \hbar\left((\omega + i)/\tau\right)}\right| \quad (1)$$

where ω is the frequency of the incident EM wave, e and $\hbar$ are the electron charge and reduced Planck's constants, respectively. E_F and τ are the Fermi energy (or chemical potential) and electron relaxation time, respectively. K_B is the Boltzmann constant, and T is temperature. E_F can be straightforwardly obtained from the carrier density in a graphene sheet which is tunable by an applied gate voltage and doping [20,21].

It is assumed that the thicknesses of the dielectric layers are thick enough to avoid the interaction between graphene layers (e.g., interlayer transitions). Hence the graphene's effective permittivity ε_g is written as $\varepsilon_g = 1 + i\sigma/(\omega\varepsilon_0 d_g)$ [11,24], where ε_0 is the permittivity in vacuum. In the calculation, effective graphene thickness is taken to be $d_g = 0.5$ nm and the electron relaxation time τ is assumed as 0.5 ps which is within the range of values considered in other studies [11,23,24].

Let a plan wave be incident from a vacuum at an angle θ onto the 1D GD stack with $+z$ direction shown in Fig. 1, here we focus on the transverse magnetic (TM) wave, the magnetic field H is assumed in the y direction. A graphene sheet with effective thickness d_g has similar property at THz frequency to that of a single negative metamaterial [2], hence in graphene layer, the real part of the refractive index is a pure imaginary number and the EM field is evanescent. The electric and magnetic fields at any two positions z and $z + \Delta z$ in the same layer can be related via a transfer matrix [2]

$$M_j(\omega, \Delta z) = \begin{pmatrix} \cos\left(k_{jz}\Delta z\right) & i\left(\varepsilon_j/\sqrt{\varepsilon_j - \sin^2\theta}\right)\sin\left(k_{jz}\Delta z\right) \\ \left(i\sqrt{\varepsilon_j - \sin^2\theta}/\varepsilon_j\right)\sin\left(k_{jz}\Delta z\right) & \cos\left(k_{jz}\Delta z\right) \end{pmatrix} \quad (2)$$

where c is the vacuum speed of light, $k_{jz} = \omega/c\sqrt{\varepsilon_j} \cdot \sqrt{1 - \left(\sin^2\theta/\varepsilon_j\right)}$ is the z component of the wave vector k_j in the jth layer, that's k_g and k_A. Suppose the matrix connecting the incident end and the exit end is $X(\omega) = \prod_{j=1}^{2N+1} M_j(\omega, d_j)$, the transmission coefficient of the monochromatic plane wave through $(GA)_N G$ can be written as

$$T(\omega) = \frac{2\cos\theta}{(x_{11} + x_{22})\cos\theta - \left(x_{12}\cos^2\theta + x_{21}\right)} \quad (3)$$

where $x_{i,j}(i, j = 1,2)$ are the matrix elements of $X(\omega)$. For an infinite periodic structure, based on Bloch's theorem and the boundary condition, the dispersion relation for TM wave follows that

$$\cos(qd) = \cos(k_{Az}d_A)\cos(k_g d_g) - \frac{1}{2}\left(\frac{\varepsilon_A k_{gz}}{\varepsilon_g k_{Az}} + \frac{\varepsilon_g k_{Az}}{\varepsilon_A k_{gz}}\right)\sin(k_{Az}d_A)\sin(k_g d_g) \quad (4)$$

q is the z-component of Bloch wave vector. When the wave vectors and the thickness of the layers satisfy the condition

$$k_{Az}d_A + k_{gz}d_g = l\pi (l \in \mathrm{int} \quad \mathrm{egers}) \quad (5)$$

the Bloch wave vector component q may be imaginary indicating the presence of band gaps, where the wave propagation is inhibited.

3. Numerical results and discussion

In Fig. 1, we show the variation of graphene's effective permittivity with frequency for $E_F = 1.0$ eV in THz region. It is seen that the permittivity is strongly dispersive with the levels of 10^4, the imaginary part which represents the loss decreases with frequency. The graphene possesses metal property in THz since the real part of the permittivity is negative, which immediately suggests the potential for graphene's usage in tunable THz multilayer GD stack with special band structure similar to that in metal-dielectric stack. In addition, we also present a typical transmission response of a multilayer $(GA)_{12}G$ consisting of thirteen graphene sheets separated by twelve dielectric layers (SiO_2) with thickness $d_A = 10$ μm