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Optical properties of one-dimensional Fibonacci quasi-periodic graphene photonic crystal

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ABSTRACT

We propose a novel type of one-dimensional photonic crystal called Fibonacci quasi-periodic graphene photonic crystal (FGPC), in which the structure in each dielectric cell follows the Fibonacci sequence and the graphene monolayers are embedded between adjacent dielectric layers. The transmission properties of FGPC are investigated using transfer matrix method in detail. It is shown that both photonic band gap induced by graphene (GIBPG) and the Bragg gap exist in the structure. We study the band gaps of TE and TM waves at different incident angles or chemical potentials. It is found that the band gaps can be tuned via a gate voltage and GIBPG is almost omnidirectional and insensitive to the polarization. In order to investigate difference between the GIPBG and Bragg gap, we plot the electromagnetic field profiles inside FGPC for some critical frequencies. The propagation loss of the structure caused by absorption of graphene is researched in detail. Also, the passing bands of Fibonacci sequences of different orders and their splitting behavior at higher order are investigated.

1. Introduction

In the past several decades, extensive studies have been carried out to various kinds of photonic crystals. With the existence of photonic band gap (PBG), photonic crystal have wide applications in optical reflectors [1], localization of photon [2], control of spontaneous emission from atoms [3,4], fabrication of PC waveguides [5], etc.

Recently, the PBG of the photonic crystals containing a great diversity of materials including metals, semiconductors and metamaterials have been investigated [6–9]. It is shown that the Bragg frequency and the stopgap is a function of its dielectric and metallic nature. There is omnidirectional band gap that is insensitive to disorders, incident angles and polarizations in one-dimensional photonic crystals (1D PC) containing negative metamaterials for central frequency.

Graphene, a two-dimensional (2D) version of graphite, consist of a planar atomic layer of carbon atoms arranged in a honeycomb lattice and it is actually a gapless semiconductor [10,11], characteristics of band structure and surface plasmons supported. Due to the unique and extraordinary properties including high charge carrier mobility, electronic energy spectrum without a gap between the conduction and valence bands, and frequency-independent absorption of Electromagnetic (EM) radiation, graphene became the object of many recent experimental and theoretical studies [10–13]. Since the carrier concentration in graphene (and, hence, its frequency dependent conductivity) can be electively tuned in wide limits by applying an external gate voltage, it is a perspective material for tunable photonic components. At the frequency ranges of THz and far-IR, having small values of optical conductivity leads to lower absorption of graphene in comparison with metals [14]. Therefore, a one-dimensional graphene-dielectric photonic crystals (1D GPC) in which the graphene sheets are embedded between adjacent dielectric layers as a controlling elements attract the attention of researchers. The enhanced transmission with a graphene-dielectric microstructure at low-terahertz frequencies were carried out using a circuit-theory model [15]. The optical properties and the photonic band structures of the 1D GPC have been investigated by transfer matrix method based on Maxwell's equations [16–18].

In the present paper, we are interested in studying the photonic band structure of one-dimensional Fibonacci quasi-periodic graphene photonic crystal (1D FGPC). As a typical aperiodic system, the quasi-periodic photonic crystals had aroused significant interest in studies both in theory and experiment in last several decades due to its exotic optical properties [19–21]. In the studied Fibonacci quasi-periodic 1D GPC, we find that graphene induced photonic band gap (GIPBG) is located at low-terahertz frequencies and the structural Bragg gap is located at high-terahertz frequencies. Both of them can be tuned by the chemical potential.

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The GIPBG is omnidirectional and the structural Bragg gaps vary with the incident angle slightly. The behavior of the electromagnetic fields inside the 1D FGPC at some critical frequencies is investigated by plotting the electric field profiles. Also, we investigate the influence of absorption of graphene on band gaps. Finally, the passing bands of Fibonacci sequences of different orders and their splitting behavior at higher order are investigated.

2. Theoretical model

The one-dimensional 4-th order Fibonacci quasi-periodic graphene photonic crystal is shown in Fig. 1. Here, A and B represent two isotropic dielectric materials with the permittivity of ε_A and ε_B and thicknesses of d_A and d_B, respectively. We consider that the layers are nonmagnetic and their permeability are $\mu_A=\mu_B=1$. The structure in each dielectric cell following the Fibonacci sequence, S_j, by a recurrent relation $S_{j+1}=\{S_j, S_{j-1}\}$, with $S_0=\{B\}$ and $S_1=\{A\}$ with j is the generation number of the Fibonacci unit cell, the first few sequences are $S_2=\{AB\}$, $S_3=\{ABA\}$, $S_4=\{ABAAB\}$ and so on. In this structure, the graphene monolayers are embedded between adjacent dielectric layers. The optical conductivity of a graphene sheet for frequency ω, at temperature T, is chosen as $\sigma_g(\omega) = \sigma_g^{\text{intra}}(\omega) + \sigma_g^{\text{inter}}(\omega)$ [22,23] where

$$\sigma_g^{\text{intra}}(\omega) = -j\frac{e^2 k_B T}{\pi\hbar^2(\omega - j\Gamma)}\left[\frac{\mu_c}{k_B T} + 2\ln\left(e^{-\mu_c/k_B T} + 1\right)\right],$$

$$\sigma_g^{\text{inter}}(\omega) = \frac{-je^2}{4\pi\hbar}\ln\left(\frac{2|\mu_c| - (\omega - j\Gamma)\hbar}{2|\mu_c| + (\omega - j\Gamma)\hbar}\right)$$

where, e is the charge of an electron, $\hbar = h/(2\pi)$ is the reduced Planck's constant, k_B is the Boltzmann constant, and μ_c is the chemical potential determined by the electron concentration which can be controlled by gating, and Γ is the phenomenological scattering rate.

With the propagation of light across an interface formed by a graphene layer which separates two dielectrics, there will be surface current in graphene layer. The surface current density J of the graphene layer can be obtained from Ohm's law, namely, $J_x = \sigma E_x$ for TM waves and $J_y = \sigma E_y$ for TE waves. According to the expressions of electric and magnetic fields, the boundary conditions and the propagation matrix of light in a homogeneous medium, we obtain the transfer matrix $M_j(d_j,\omega)$ $(j=A,B)$ of a dielectric layer and a graphene sheet as

$$M_j(d_j,\omega) = \begin{pmatrix} \cos(k_{zj}d_j) & (i/q_j)\sin(k_{zj}d_j) \\ \sigma_g\cos(k_{zj}d_j) + iq_j\sin(k_{zj}d_j) & (i\sigma_g/q_j)\sin(k_{zj}d_j) + \cos(k_{zj}d_j) \end{pmatrix}$$

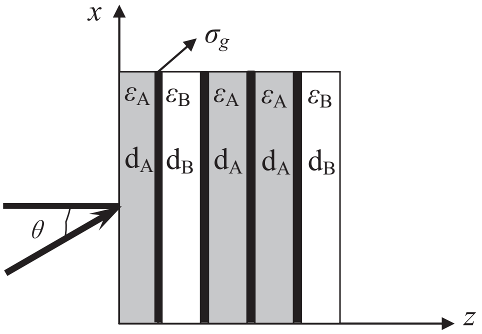

Fig. 1. Structure of the 4-th order 1D FGPC. The graphene monolayers are embedded between dielectric layers.

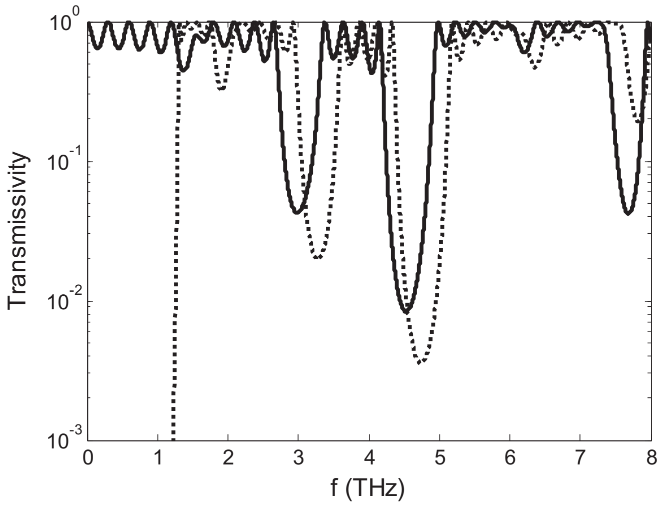

Fig. 2. The transmission spectrum of 1D FGPC for the cases of (a) $\sigma_g=0$ and (b) $\sigma_g \neq 0$ for the normal incidence of the waves.

for the TE waves and

$$M_j(d_j,\omega) = \begin{pmatrix} \cos(k_{zj}d_j) - (i\sigma_g/q_j)\sin(k_{zj}d_j) & (i/q_j)\sin(k_{zj}d_j) - \sigma_g\cos(k_{zj}d_j) \\ iq_j\sin(k_{zj}d_j) & \cos(k_{zj}d_j) \end{pmatrix}$$

for the TM waves [16]. Here, .. for TE waves and $q_j = (+k_{zj}/\omega\varepsilon_0\varepsilon_j)$ for TM waves and q_0 and q_t are defined as the corresponding q parameters of the incidence and exit media which are chosen as air.

The entire transfer matrix of a Fibonacci sequence can be expressed as $\mathrm{T}[S(n)] = \prod_{i=1}^{N} M_i$, connecting the incident and exit ends, and N is the total number of layers of 1D FGPC. Then, from transfer matrix we can obtain the transmissivity T, reflectivity R and absorptivity A of the structure as

$$T = \left|\frac{2q_0}{(q_t T_{11} + q_0 T_{22}) - (T_{21} + q_0 q_t T_{12})}\right|^2,$$

$$R = \left|\frac{(q_t T_{11} - q_0 T_{22}) - (T_{21} - q_0 q_t T_{12})}{(q_t T_{11} + q_0 T_{22}) - (T_{21} + q_0 q_t T_{12})}\right|^2,$$

$$A = 1 - R - T$$

T_{11}, T_{12}, T_{21} and T_{22} are the elements of the entire transfer matrix.

3. Results and discussion

In this paper, we study 4-th order Fibonacci quasi-periodic graphene photonic crystal of 5 periods that is expressed as $(ABAAB)^5$ at the frequency range of 0–8 THz. In the simulations, we take the optical and geometrical parameters of the system as follows: $d_A=d_B=10$ μm, $\varepsilon_A=5$, $\varepsilon_b=2.5$, $\mu_c=0.2$ eV, $\Gamma=0$ and $T=300$ K.

Firstly, we study the transmission properties of our structure and compare the results with the structure without graphene sheets. The transmissivity at normal incidence is depicted in Fig. 2, here solid line for the structure without graphene sheets, and dotted line for the structure with graphene sheets. It can be seen that the system without graphene sheets has three frequency band gaps that are the structural Bragg gaps. By contrast, there is an additional PBG in the lower frequencies for the structure containing the graphene sheets. This band gap is solely due to the existence of the graphene sheets, so we call it graphene induced