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Tunable terahertz omnidirectional photonic gap in Thue-Morse quasi-periodic photonic crystal containing graphene monolayers

L. LI[a*], M CAO[b*], L. MENG[a]

[a]*College of Electronics, Communication and Physics, Shandong University of Science and Technology, Qingdao 266590, China*

[b]*College of Information and Electrical Engineering, Shandong University of Science and Technology, Qingdao 266590, China*

The band structures of the one-dimensional Thue-Morse quasi-periodic graphene photonic crystal is studied with transfer matrix method. A new type of omnidirectional gaps named graphene induced photonic band gap (GIBPG) is found. In contrast to the Bragg gaps, GIBPG is insensitive to the polarization and the incident angles, and is invariant on the change of the ratio of the thicknesses of two media. An advantage of the suggested structure is that the graphene conductivity could be tuned by varying the chemical potential of the graphene sheets via a gate voltage, which may provide a flexible method to tune omnidirectional gaps. It is found that GIBPG exists in all the Thue-Morse squence, and it is rather stable and independence of the structure sequence.

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Keywords: photonic crystal; graphene; Thue-Morse; Tunability; Omnidirectional

1. Introduction

Graphene is the two-dimensional stable single layer of carbon atoms densely packed in a honeycomb lattice and has attracted considerable interest owing 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 radiation, graphene became the subject of intense research in both object experimental and theoretical studies [1-4]. The photonic crystals containing a great diversity of materials including metals, semiconductors and metamaterials can be used to filter light propagation in the far-infrared region[5-8].Since the carrier concentration in graphene can be electively tuned in wide limits by applying an external gate voltage, it is a perspective material for tunable photonic components. Therefore, a novel type of one dimensional graphene-based photonic crystal is worth investigating. Recently, scientists have studied the optical properties of graphene-based photonic crystals. For example, the optical properties and the photonic band structures of the 1D GPC have been investigated by transfer matrix method [9-13].

However, up to now most works focus on the periodic structure. Quasi-crystals(QCs) is a kind of non-period structure which lacks long-range translational symmetry, but possesses a certain orientation order. As we know, the quasi-periodic is classified as intermediate between ordered and disordered systems[14,15], which has significant and common features like fractal spectrum and self-similar behavior[16, 17]. The most common examples of 1D QCs are the Fibonacci and the Thue-Morse squence(TMs)structures. These two types are distinguished by the presence of delta-functionlike peaks in the Fourier spectrum of Fibonacci structures, and singularities in the Fourier spectrum of TMs structures[18,19]. Recently, the study of the propagation and the localization of light in one dimensional quasi-crystal graphene-based photonic crystal was poor. Most recently, Zhang[20] investigated the transmission properties of Fibonacci quasi-periodic graphene photonic crystal using transfer matrix method.

In the present paper, we are interested in studying the photonic band structure of one-dimensional Thue-Morse quasi-periodic graphene photonic crystal. (1D TMGPC). As a typical aperiodic system, TMs lattices, also known as aperiodic structures, were thought to be more random than Fibonacci lattices. The TMs lattice has a deterministic geometry structure, and its electronic properties are also of great interesting. In the studied graphene-based TMs, We find that a new type of omnidirectional gaps named GIBPG is found. In contrast to the Bragg gaps, GIBPG is insensitive to the polarization and the incident angles, and is invariant on the change of the ratio of the thicknesses of two media. In addition, an advantage of the suggested structure is that the graphene conductivity could be tuned by varying the chemical potential of the graphene sheets via a gate voltage, which may provide a flexible method to tune omnidirectional gaps. It is found that GIBPG exists in all the Thue-Morse squence, and it is rather stable and independence of the structure sequence.

The paper is organized as follows. In Section 2, we introduce the Thue-Morse structure, and the transfer-matrix method is used. The transmission spectra for TMs are calculated and discussed in Section 3. Finally, we draw conclusions in Section4.

2. Theoretical model

TMs lattices can be generated by an inflation rule where the (n+1)st TMs lattice is obtained from the *n*th lattice by replacing A by AB and replacing B by BA. The lowest-order TMs lattice are represented by the strings S_0=A, S_1=AB, S_2=ABBA, S_3=ABBABAAB, etc. The corresponding structure of S_3 is shown in Figure 1. 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 $\sigma_g(\omega)=\sigma_g^{intra}(\omega)+\sigma_g^{inter}(\omega)$ [21,22] where

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

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

Here, 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 and Γ is the phenomenological scattering rate.

Let a wave be incident from a vacuum at an angle θ onto a TMs containing graphene-based photonic crystal, as show in Fig. 1. For the transverse electric (TE) wave, the electric field **E** is assumed in the x-direction (the dielectric layers are in the $x-y$ plane), and the z-direction is normal to the interface of each layer. In general, 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 [9,23]:

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

Here, $q_j=(-k_{zj}/\omega\mu_0\mu_j)$ 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 TM 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 GMGPC. Then, from transfer matrix we can obtain the transmissivity T and reflectivity R of the structure as

$$T=\left|\frac{2q_0}{(q_tT_{11}+q_0T_{22})-(T_{21}+q_0q_tT_{12})}\right|^2,$$

$$R=\left|\frac{(q_tT_{11}-q_0T_{22})-(T_{21}-q_0q_tT_{12})}{(q_tT_{11}+q_0T_{22})-(T_{21}+q_0q_tT_{12})}\right|^2,$$

T_{11}, T_{12}, T_{21} and T_{22} are the elements of the entire transfer matrix. The treatment for a TM wave is similar to that for a TE wave.

3. Numerical results and discussion

In this work, we study the electromagnetic waves that propagating in 3-th order Thue-Morse quasi-periodic graphene photonic crystal of N periods that is expressed as $(ABBABAAB)^N$ which is shown in Fig.1 at the THz frequency range. In the simulations, we take the optical and geometrical parameters of the system as follows: $d_A= d_B$=10μm, N=3, $\varepsilon_A=5+i\gamma$, $\varepsilon_b=2.5+i\gamma$, μ_c=0.2eV, $\Gamma=0$ and T=300K.

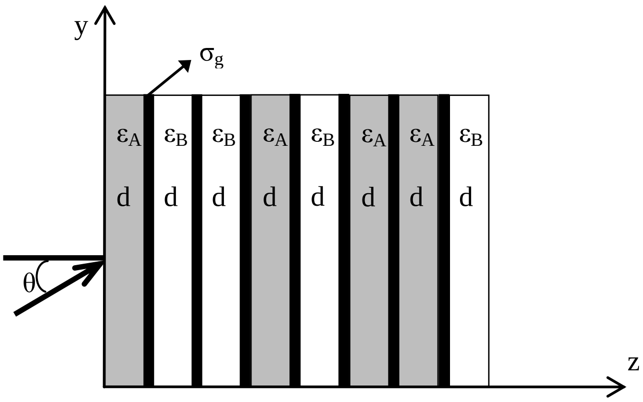

Fig. 1. Structure of the 3-th order 1D TMGPC.

At first, 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(a) and (b) for the structure without and with the graphene sheets, respectively. In Fig.2(a), the red lines show the transmission for the case of lossless dielectric materials (γ=0) while the green (γ=0.01) and blue (γ=0.05) represent the results for the case of lossy materials. It can be seen that the system without graphene sheets has three frequency band gaps that are the structural Bragg gaps. On the other hand, Fig.2(b) represents 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 photonic band gap (GIPBG). The effect of introducing the graphene sheets is because imaginary part of the conductivity depends on the frequency in the low frequency range and has small values in the frequency range f >5THz while the real of the conductivity varies slowly in that frequency range and its value is small in comparison to that of imaginary part of the conductivity[13].

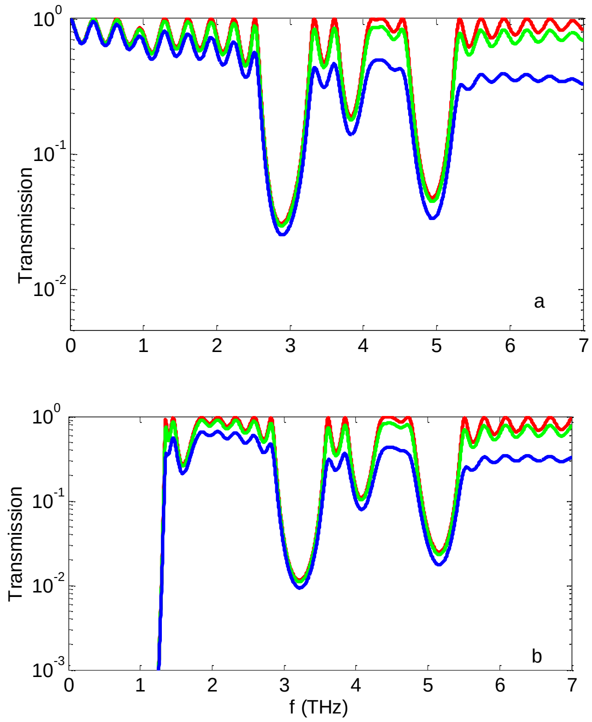

Fig. 2. The transmission spectrum of 1D TMGPC for the cases of (a) σ_g=0 and (b) $\sigma_g\neq0$ for the normal incidence of the waves.

The photonic band gap as a function of incident angle is plotted in Fig. 3, where the blue areas are the forbidden bands. As shown in Fig. 3, the Bragg gap shifts to high frequency for both TE and TM waves as the incident angle increases. The band edges and width of the Bragg gap are greatly affected by the polarization and the incident angle. The result reveals that the Bragg gaps are polarization sensitive and depends on the incidence angle. While, the GIPBG at the frequency range of 0-1.25 THz remains nearly invariant under a various incident angle for both TE and TM polarizations. Even when incident angle increases to 85^0, the edge of GIPBG only shifts a little. The insensitivity of the edge to the incident ange and polarization indicates that there exists an omnidirectional gap. These properties may provide us aspects for applications such as omnidirectional reflector with a fixed bandwidth.

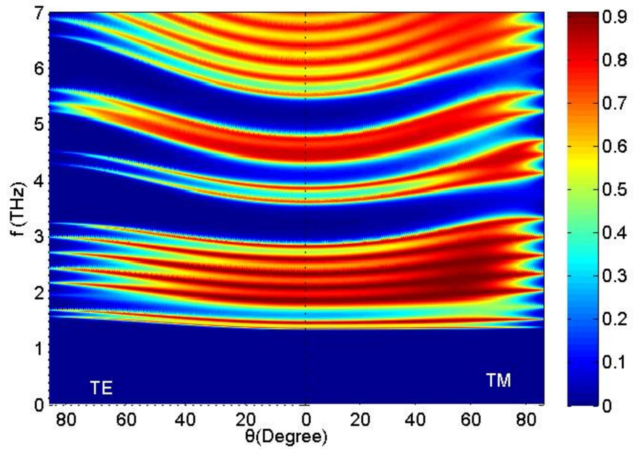

Fig.3 Color map of the transmittance through 1D TMGPC versus the frequency and incidence angles for TE waves (a) and TM waves (b).

Next, we study the behavior of the electric field intensity inside graphene-based phonic crystal to understand the difference between the Bragg gap and the GIPBG. In Fig. 4, we plot the tangential transverse electric-field distributions for the two transmission peaks that can be observed in Fig. 2 for the case of μ_c=0.2eV at the first and second band gaps (calculated at the frequencies of 0.95 and3.2 THz, respectively) along the propagation direction z. It can be observed that the transverse electric field with the frequency at the GIPBG does not show the oscillatory behavior in contrast to that with frequency in the Bragg gap (see Fig.4 (a)). While electric field displays damped oscillation at the second band gap as shown in Fig.4 (b).

In Fig.5, we plot the dependence of the gaps on the ratio of the thicknesses of the two media at normal incidence. The red solid line is the transmittance through the structure with thickness of *dA*= *dB*=10μm. The green dashed and green dotted lines represent the transmittance through the same media but the unit cell size is scaled by 5/4 and 2/1. It is clear from Fig.4 that Bragg gap is affected greatly by the change of the ratio of the thicknesses. Conversely, the GIPBG only shifts a little.

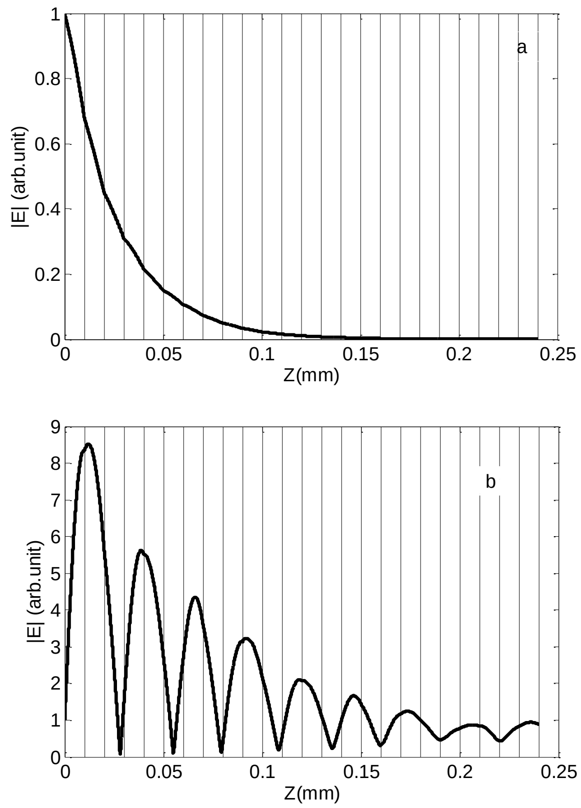

Fig. 4. Electric-field distributions for the frequencies (a) f=0.95THz at the mid of the first gap, (b) f=3.2THz at the mid of the second gap. The waves are incident normal to the interfaces and the other parameters are the same as Fig. 2(b).

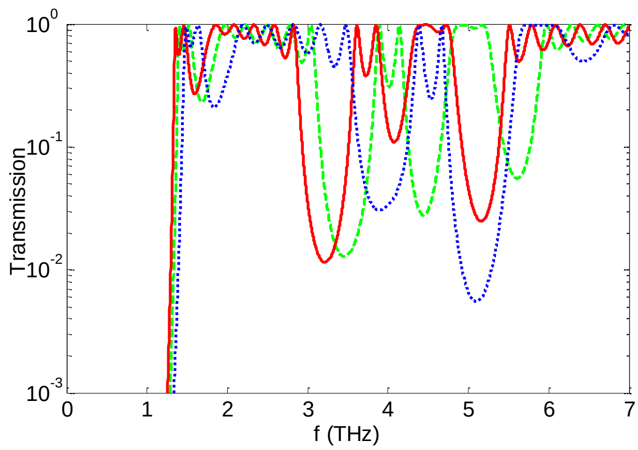

Fig.5 Transmission with different the ratio of the thicknesses.

Because the electronic and optical characteristics of graphene depend on its graphene sheets conductivity, which can be modified by the gate voltage through tuning the chemical potential. Therefore, we study the dependence of the photonic band gap on the graphene chemical potential μ_c. In Fig. 6 we plot color maps of transmittance of the one-dimensional Thue-Morse quasi-periodic graphene photonic crystal as a function of μ_c at $\theta=0^{\circ}$ for both TE and TM polarizations. We observe that increasing the chemical potential leads to an increase in the GIPBG width and . On the other band, the Bragg gap are shifted to high frequency but width is not expanded.

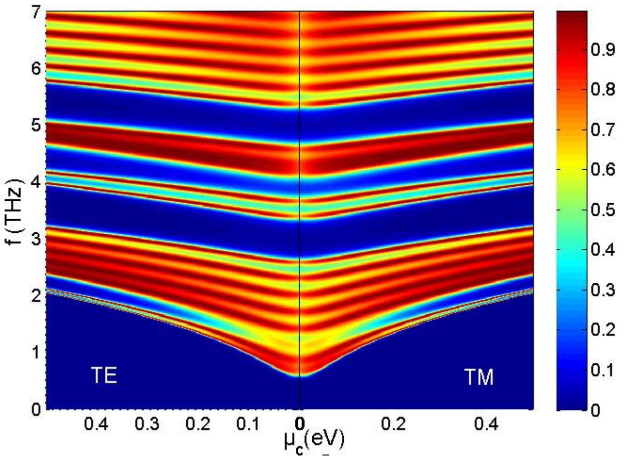

Fig. 6. Color map of the transmittance through 1D TMGPC versus the frequency and chemical potential at normal incidence for TE waves (a) and TM waves (b).

Now, we turn to study the photonic spectra for the other successive TMs of the quasiperiodic structure, i.e., for S_4 to S_{11}. The photonic spectra is schematically shown in Fig.7. It can be seen from the figure that the position and size of GIPBG is same in the structure for all the levels. The two Bragg gaps are insensitive to the Thue-Morse level. The passing bands are not split into more and more narrow sub-bands as *n* increases in the structures and the different to the Fibonacci quasi-periodic structure.

Fig.7 The photonic spectra for the first nine successive levels of Thue-Morse photonic structures

4. Conclusion

To conclude, using transfer matrix method, we have discussed the transmission properties of the one-dimensional Thue-Morse quasi-periodic graphene photonic crystal. We have shown that a new type of omnidirectional gaps named GIBPG is found. In contrast to the Bragg gaps, GIBPG is insensitive to the polarization and the incident angles, and is invariant on the change of the ratio of the thicknesses of two media. In addition, an advantage of the suggested structure is that the graphene conductivity could be tuned by varying the chemical potential of the graphene sheets via a gate voltage, which may provide a flexible method to tune omnidirectional gaps. It is found that GIBPG exists in all the Thue-Morse squence, and it is rather stable and independence of the structure sequence. We hope such Thue-Morse structure will have applications perfect stop filter, and may potentially improve switches and reflectors in the THz region.

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*Corresponding author: lileitai@163.com
my-cao@263.net