Photonic Bandgap Properties of One-Dimensional Graphene-Based Photonic Crystals with a Single Dielectric

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Abstract. The transfer matrix method was used to investigate the photonic bandgap properties of one-dimensional graphene-based photonic crystal (GPC) with a single dielectric medium. The first layer of the unit cell of the GPC consists of a traditional dielectric medium and the second is the same dielectric medium wherein graphene sheets are embedded. Numerical calculation results show that the width of the low frequency bandgap decreases as the period of the GPC, the permittivity of the dielectric, the thickness of the dielectric layer, the filling factor of the dielectric layer, and the period of the graphene-dielectric multilayer medium structure increase and increases as the thickness of the graphene-dielectric multilayer medium structure increases. The influence of the above parameters on the Bragg bandgap is different from their effects on the low frequency bandgap. Due to the graphene conductivity could be tuned by varying the chemical potential, so GPC is a tunable PC and may have many potential applications in photonics.

1. Introduction

These Photonic crystals (PCs), composed of periodic dielectric materials, have attracted great attention due to their unique ability to manipulate light. When an electromagnetic wave propagates in photonic crystal, due to Bragg scattering, wave of a certain frequency range can be inhibited resulting in the formation of photonic bandgap (PBG). This property facilitates the active control and manipulation of the flow of electromagnetic waves or photons and is used in various applications for a wide range of optical devices. Most of the PC-based optical devices are constructed by usual dielectric materials. In recent years, various non-conventional materials have also been used to construct PCs, such as superconducting materials, liquid crystal and a negative refractive index materials, etc. [1-3]. Due to these materials’ special electromagnetic properties, a PC which is composed by these materials usually presents some special PBG properties.

In recent years, a new type of graphene-based photonic crystals (GPCs) has also attracted much attention [4-7]. Graphene, a flat monolayer of carbon atoms packed into a dense two-dimensional honeycomb crystal lattice, has unique thermal, mechanical, electrical and optical properties. Due to the high optical transmittance and tunable electrical conductivity, graphene has been found broad application in photonics and optoelectronics fields [8, 9].

Because of the tunability of the complex conductivity of graphene, the GPC is a very important PC with tunable PBG. El-Naggar recently proposed a new design of one-dimensional (1D) GPC [10]. In this GPC, the first layer of the unit cell of the GPC consists of a dielectric wherein graphene sheets are periodically embedded. The GPC studied by El-Naggar is made up of two dielectric materials. In this paper, we propose utilizing only one dielectric material to constitute the GPC. This will be a great significance to reduce the difficulty of preparation of the GPC. By detailed numerical calculation, it
can be seen that our proposed GPC have the same optical properties as the GPC proposed by El-Naggar.

2. Theoretical model

\[ \varepsilon_A(\omega) = \varepsilon_d + i \frac{\sigma_g(\omega)}{\omega \varepsilon_0 d} \]  

(1)

where \( \sigma_g(\omega) \) is the dynamical conductivity of doped graphene for high frequencies at temperature \( T \) expressed as the sum of the intraband and interband electron transition contributions as

\[ \sigma_g(\omega) = \sigma_{g\text{ intra}}(\omega) + \sigma_{g\text{ inter}}(\omega) \]  

(2)

where

\[ \sigma_{g\text{ intra}}(\omega) = \frac{e^2 i}{4 \hbar 2\pi} \left[ \frac{16 k_B T}{\hbar \omega} \log \left( 2 \cosh \left( \frac{\mu}{2 k_B T} \right) \right) \right] \]  

(3)

\[ \sigma_{g\text{ inter}}(\omega) = \frac{e^2}{4 \hbar} H(\hbar \omega - 2\mu) - \frac{ie^2}{8\pi \hbar} \log \left( \frac{(\hbar \omega + 2\mu)^2}{(\hbar \omega - 2\mu)^2 + (2k_B T)^2} \right) \]  

(4)

Here \( e \) is the charge of an electron, \( H \) is the Heaviside step function, \( k_B \) is the Boltzmann constant, \( T \) is the temperature in K, and \( \mu \) is the chemical potential which can be tuned via electrostatic biasing.

In El-Naggar’ model [10], \( \varepsilon_b \) is not equal \( \varepsilon_d \). In this paper, we will mainly discuss the bandgap characteristic of GPC presented in figure 1 when \( \varepsilon_b \) is equal to \( \varepsilon_d \). The study of the bandgap properties of 1D GPCs will be carried out using the well-known transfer matrix method (TMM).

3. Numerical results and discussion

In the figure 2 we are presenting the results of the numerical calculation of the transmission spectrum in the 1D GPCs at normal incidence of light. Figure 2 (a) shows the transmission spectrum of the PC structure discussed by El-Naggar. The parameters used in the calculation are: \( d_a = 2 \mu m, d_b = 6 \mu m, \varepsilon_d = 10.9, \varepsilon_d = 5.07, d = 200 \) nm, the chemical potential \( \mu = 0.2 \) eV, the temperature \( T = 300 \) K. Here, the relative dielectric constant \( \varepsilon_b \) in layer B is different to the relative dielectric constant \( \varepsilon_d \) in layer A. It can be seen from figure 2 (a) that the GPC exhibits a low-frequency bandgap (LFBG), which is can’t be found in the PCs constructed by the conventional dielectric materials. El-Naggar called this LFBG.
by graphene PBG, which is associated with a very strong dependence of the imaginary part of the graphene complex conductivity in the low frequency range. In addition to the LFBG, GPCs also have Bragg bandgap (BBG) which exists in traditional PCs.

\[ \varepsilon_B = 10.9 \]
\[ \varepsilon_d = 5.07 \]

(a)

(b)

Figure 2. Transmission spectra of the GPC

\[ \varepsilon_B = \varepsilon_d = 5.07 \]
\[ \varepsilon_B = \varepsilon_d = 10.9 \]

\[ (a) \]
\[ (b) \]

Figure 3. Transmission spectra of the GPC as a function of the permittivity of the dielectric

Figure 4. Transmission spectra of the GPC as a function of the period of the layer A

Figure 2 (b) show the transmission spectrum of the GPC structure with \( \varepsilon_B = \varepsilon_d \). This structure is the focus of this paper. It can be seen that when \( \varepsilon_B = \varepsilon_d \), the GPCs also have LFBG and BBG, and both bandgap shifts toward the lower frequency as the relative permittivity increases. The width of the two bandgap decreases with the increase of the relative permittivity increases. It can be seen that GPC constructed with the same dielectric material have the same bandgap as the GPC composed of different dielectric materials, and the GPC made of the same kind of materials is simpler in preparation.

The bandgap characteristics of the GPCs constructed with the same dielectric material will be discussed in detail below. First, we study the dependency of the PBG on the permittivity of the dielectric at normal incidence. We plot color maps of the transmittance through the GPCs versus the frequency and the permittivity of the dielectric in figure 3. It can be seen from figure 3 that with the increase of the relative permittivity, the bandgap width of the LFBG and the first BBG decreases and the center of the bandgap moves to the low frequency. Therefore, in order to get a larger PBG, relatively small relative permittivity of the dielectric material can be used to form GPCs.

Figure 4 illustrates the calculated transmittance through the GPC as a function of the period d of the graphene-dielectric multilayer medium structure A. In the calculation, \( \varepsilon_B = \varepsilon_d = 8 \), and the other parameters used are similar to that used in figure 2. It can be seen from figure 4 that, the bandgap width of the LFBG and the first BBG decreases with the increase of \( d \). Therefore, in order to obtain a larger PBG, a graphene-based multilayer structure with a smaller period \( d \) can be used to construct a GPC.
Figure 5 shows the transmission spectrum of GPCs with the change of the thickness $d_B$ of the layer B. In our calculation, $d = 200$ nm, and the other parameters used are similar to that used in figure 4. It can be seen from figure 5 that in our calculated frequency range, when the $d_B$ is small, there is only LFBG, with the increase of $d_B$, the width of the LFBG decreases, and the other BBG appear in turn. The center frequency for all bandgaps moves to the low frequency direction with the increase of $d_B$.

Figure 6 shows the transmission spectrum of GPCs with the change of the thickness $d_A$ of the layer A. In our calculation, $d = 200$ nm, $d_B = 6$ mm, and the other parameters used are similar to that used in Figure 4. It can be seen from figure 6 that, in the calculated frequency range, the band width of the LFBG increases as $d_A$ increases. The bandgap of the other BBGs appears in turn with the increase of $d_A$, and the bandgap width gradually increases and the bandgap center moves to the low frequency. When $d_A$ increases to a certain degree, the LFBG and the first BBG will overlap to form a wide bandgap.

Figure 7 shows the transmission spectrum of the GPC with the change of the filling ratio $r$ of the layer B. $r$ is defined as $r = d_B / (d_A + d_B)$. In our calculation, $d = 200$ nm, $d_A + d_B = 12$ mm, and the other parameters used are similar to that used in figure 4. It can be seen from figure 7 that, the width of the LFBG decreases with the increase of $r$. All the other higher BBGs appear in turn as the $r$ increases, and the bandgap width first increases and then decreases, while the bandgap center moves to low frequency.

Figure 8 shows the transmission spectrum of the GPC with the change of the thickness of the unit cell of the GPC $D$. In our calculation, $r = 0.3$, $d = 200$ nm, and the other parameters used are similar to that used in figure 4. It can be seen from figure 8 that the width of the LFBG decreases with the increase of $D$. All the other higher BBGs appear in turn with the increase of $D$, and the bandgap width first increases and then decreases, while the bandgap center moves to low frequency.
4. Conclusion
A 1D GPC constituted with only one dielectric material was studied by employing the TMM in this paper. The use of one dielectric material to construct PCs helps to reduce the difficulty of preparing a PC. It can be seen that GPC constructed with one dielectric material have the same bandgap as the GPC composed of two different dielectric materials. The numerical results show that the LFBG of this GPC decreases with the increase of the thickness of the unit cell $D$, the relative permittivity of the dielectric material, the thickness of the dielectric material, the filling ratio $r$ and the period $d$ of the graphene-dielectric multilayer medium structure $A$, but increases with increasing the thickness $d_A$ of the graphene multilayer structure. While the BBG has a more complex response with the changes of those structural parameters above mentioned. Since the complex conductivity of graphene is a function of chemical potential, and the chemical potential can be changed by applying a magnetic field or bias, the complex conductivity of graphene is tunable. This means that the GPC is a bandgap tunable GPC, which makes it have a variety of potential applications in the field of photonics. Therefore, it is extremely important to study the GPC.

5. References
[1] Wu J J and Gao J X 2016 Mater. Chem. Phys. 171 91
[2] Mohamed M S, Hameed M F O, El-Okr M M and Obayya S S A 2016 Optik 127 8774
[3] Brandão E R, Vasconcelos M S and Anselmo D H A L 2016 Opt. Mater. 62 584
[4] Berman O L and Kezerashvili R Y 2012 J. Phys. Condens. Matter 24 015305
[5] Hajian H, Soltani-Vala A and Kalafi M 2013 Opt. Commun. 292 149
[6] Arefinia Z and Asgaria A 2013 Physica E 54 34
[7] Lin H, Xu D, Pantoja M F, Garcia S G and Yang H L 2014 Chin. Phys. B 23 094203
[8] Bonaccorso F, Sun Z, Hasan T and Ferrari A C 2010 Nature Photon. 4 611
[9] Avouris P and Freitag M 2014 IEEE Sel. Top. Quantum Electron. 20 6000112
[10] El-Naggar S A 2015 Opt. Quantum Electron. 47 1627
[11] Othman M A K, Guclu C and Capolino F 2013 Opt. Exp. 21 7614
[12] Zhu B F, Ren G B, Zheng S W, Lin Z and Jian S S 2013 Opt. Exp. 21 17089

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