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Tunable defect mode realized by graphene-based photonic crystal

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ABSTRACT

In this literature, we propose an active terahertz 1D photonic crystal, which consists of silicon layers and air layers. A graphene sheet is embedded at the interface between dielectric and air. Tunable photonic band gap is realized by changing the Fermi level of graphene. Transmission Matrix Method is utilized to explain the influence of the graphene layer. We also demonstrate that a dielectric slab attached with a thin sheet made of single-negative metamaterial acts like a pure dielectric slab with a thinner thickness. A tunable blue shift of the band gap can be realized by simply applying different chemical potentials on the graphene sheet. This feature can be utilized for the design of tunable high-gain antenna array and force generator in terahertz band.

1. Introduction

The special features of graphene have led to an increasing interest in the electromagnetic responses and applications in recent years, such as strong plasma phenomenon, negligible loss and absorption due to its extraordinary electronic and optical properties, mechanical flexibility and the single-atom thickness [1–8]. Graphene-based PhC has been utilized to realize tunable Magneto-optical (MO) effects, enhancement of light-matter interactions and enhanced absorption [9–12]. One of the interesting features is that the permittivity and conductivity of graphene can be modified by changing the chemical potential. In this way, we can realize a convenient control on the constitutive parameters of graphene. Another feature is the phenomenon of surface plasmon polariton (SPP) of graphene sheet. Due to this, the graphene layer can be treated as a kind of thin dielectric layer in terahertz regime.

Photonic crystals (PhCs) are periodic structures that allow the modulation of the propagation of light in spatial domain. Photonic band gaps (PBGs) are the PhC structures with defect part, which has led to a variety of applications because of its unusual transmission characteristic at the defect mode [13,14]. The photonic band gaps can be modified by changing the equivalent constitutive parameters of the dielectric stacks. That indicates graphene sheet may be utilized as a kind of reflective layer once it is embedded at the interfaces between the high-permittivity and low-permittivity dielectric quarter-wave stacks. A tunable transmission can be realized by applying different chemical potentials [10]. In spite of the thin thickness of a single graphene layer (about 0.34 nm), the optical characteristics of graphene-embedded dielectric slabs are still controllable. For this reason, tunable photonic band gap can be realized with the help of graphene without changing the geometric structure of the PhC.

In this paper, we propose a graphene-based PhC whose defect mode can be modified by changing the chemical potential. With the help of Transmission Matrix Method, we demonstrate the blue shift of defect mode can be explained by the change of equivalent thickness of the dielectric slab. This blue shift of defect mode can be utilized for the design of high-Q antenna as an active radome or a force generator. Compared with conventional PhC radome, the active radome with graphene sheet can realize a wider operating band.

2. Model and results

2.1. Model for simulation

The surface conductivity of graphene is defined as $\sigma_s = \sigma_{intra} + \sigma_{inter}$, where σ_{intra} and σ_{intra} are the interband conductivity and the intraband conductivity respectively. σ_{intra} and σ_{inter} can be defined in Eqn. (1) and Eqn. (2) [3].

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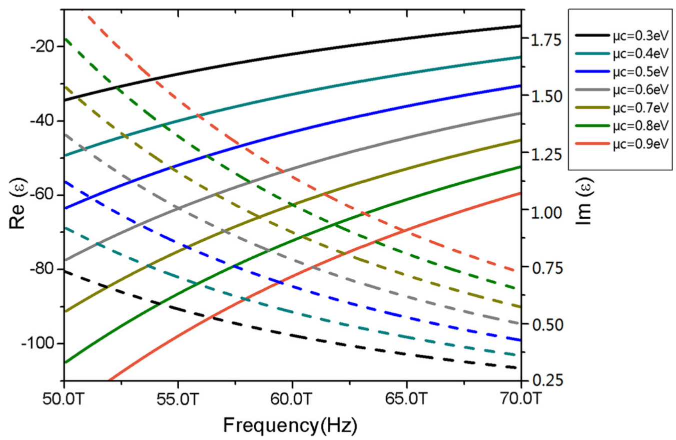

Fig. 1. The real part (solid line) and imaginary part (dash line) of a single-layered graphene's permittivity is plotted. The frequency range is from 50 THz to 70 THz. The real part of the equivalent permittivity of graphene varies from −34 to −130 by applying different chemical potentials from 0.3 eV to 0.9 eV. This significant variation ensures an obvious change of the electromagnetic properties of graphene sheet. The imaginary part of the equivalent permittivity corresponds to the dielectric loss of the graphene layer. Although the dielectric loss is larger than traditional materials in terahertz band ($\tan\delta$ varies from 0.008 to 0.05), the small thickness of graphene sheet will decrease the total dielectric loss.

$$\sigma_{intra} = \frac{-je^2 k_B T}{\pi\hbar^2(\omega - j2\Gamma)}\left(\frac{\mu_c}{k_B T} + 2\ln\left(e^{-\frac{\mu_c}{k_B T}} + 1\right)\right) \tag{1}$$

$$\sigma_{inter} = \frac{-je^2}{4\pi\hbar}\ln\frac{2|\mu_c| - (\omega - j2\Gamma)\hbar}{2|\mu_c| + (\omega - j2\Gamma)\hbar} \tag{2}$$

where $\omega = 2\pi c/\lambda$, λ is the wavelength, μ_c is the chemical potential, Γ is the scattering rate, T is the Kelvin temperature of room environment (300 K), e is the elementary charge and $\hbar = \frac{h}{2\pi}$, $\hbar$ is the reduced Plank's constant. It is assumed that the scattering rate of graphene is $\frac{1}{2\tau}$, where τ is the momentum relaxation time (0.2 ps).

The equivalent complex permittivity of the graphene is defined in Eqn. (3) [15]. Δ is the thickness of a single-layered graphene, $\varepsilon_r = \frac{\varepsilon_{eq}}{\varepsilon_0}$. The real part and imaginary part of ε_r versus chemical potential μ_c are plotted in Fig. 1. We can make the following conclusions from the calculated permittivity in Fig. 1. First, once the chemical potential is changed, the electromagnetic response of the graphene sheet will also be changed accordingly. Second, the calculated real part of graphene's permittivity in terahertz band is negative and not large (from about −30 to −130) because of the plasma effect, which is similar with some precious metal such as gold and silver in visible band. That indicates the graphene sheet can be treated as a kind of single-negative ($\varepsilon < 0$, $\mu > 0$) dielectric from 50 THz to 70 THz. Third, the imaginary part is quite small. That means graphene can be utilized as a kind of electric-controlled material in terahertz band without large dielectric loss.

$$\varepsilon_{eq} = \varepsilon_0 + \left(\frac{\sigma_s}{j\omega\Delta}\right) \tag{3}$$

The 1D PhC structure with graphene sheets embedded is plotted in Fig. 2. Defect layers are placed at the middle of the 1D array of dielectric slabs in order to generate photonic band gap. Graphene layers are embedded between the air layer and the dielectric layer. Graphene stack shows a stronger effect compared with the single-layered graphene. Once the number of graphene layers increases, the conductivity of graphene also increases accordingly [17]. Here the conductivity of an n-layered graphene is $n\sigma_s$ and the thickness becomes $n\Delta$. According to Eqn. (3), the permittivity of multi-layered graphene is the same as a single-layered one. However, it does not mean we can increase the number of graphene layers without any limit because the multi-layered graphene with more than three layers embodies the characteristics of graphite. Due to this, the number of graphene layer utilized in this manuscript is set to be 3.

2.2. Transmission matrix method

The transmission characteristic of a single layer can be described by Transmission Matrix Method [18], which is an efficient method for the calculation of the optical properties of multi-layered structures [9]. For traditional materials, whose permittivities and permeabilities are both positive, the transmission matrix can be written as:

$$\begin{bmatrix} E_2 \\ H_2 \end{bmatrix} = \begin{bmatrix} \cos(\frac{2\pi}{\lambda_0}nd) & \frac{j}{n}\sin(\frac{2\pi}{\lambda_0}nd) \\ jn\sin(\frac{2\pi}{\lambda_0}nd) & \cos(\frac{2\pi}{\lambda_0}nd) \end{bmatrix} \begin{bmatrix} E_1 \\ H_1 \end{bmatrix} \tag{4}$$

where E_1, H_1 and E_2, H_2 are the incident and transmission field respectively, λ_0 is the wavelength in free space, n and d are the refractive index and thickness of the dielectric slab, respectively. As shown in Fig. 1, the permittivity of graphene is negative with a small imaginary