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Terahertz planar waveguide devices based on graphene

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We present a theoretical study on graphene-semiconductor planar structures. The frequency of the photonic modes in the structure, which can be efficiently tuned via varying the sample parameters, is within the terahertz (THz) bandwidth. Furthermore, it is found that a roughly linear dispersion relation can be obtained for photonic modes in the THz region. Hence, the proposed graphene-semiconductor planar structures can be served as THz waveguide with desirable transmission characteristics.

Keywords: THz waveguide; graphene; linear dispersion; planar structure; transmission characteristics.

1. Introduction

Photonic crystals (PCs) are dielectrically mismatched periodic structures which have been widely applied as optical devices used in, e.g. optic communications. The investigation into optical properties of PCs[1,2] has become an important and fast growing field of research in the area of material science and optics in the past decades. In particular, planar structures[3] consisting of several layers of materials with different dielectric constants are popularly employed PCs which can be served as optic waveguide and other optic devices.[4,5] In a typical planar PC, the light modes are confined in one direction by total internal reflection when the dielectric index of the middle material layer is larger than that of the surrounding material layers. At present, the fabrication of practical photonic crystal devices is still a difficult and challenging task, especially for the application in terahertz (10^{12} Hz

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or THz) bandwidth, due to the fact that the periodicity of the PCs has to be of the similar wavelength of the THz light waves. Furthermore, it should be noted that the traditional materials, such as quartz and semiconductors, often absorb THz light waves quite strongly due to, e.g. free carrier absorption. Therefore, the design and fabrication of PCs to be applied as THz devices need to take considerations from both materials and optics points of views. Recently, progress made in the fabrication of graphene and related structures and in the demonstration of its exceptional electronic and optoelectronic properties[6,7] has caused a surge of research achievements.[8–12] More generally, graphene represents a conceptually new class of material which can offer new inroads into physics and technology of low-dimensional systems. Particularly, graphene has a relatively low dielectric constant ($\varepsilon \sim 4$) in comparison with most semiconductor materials ($\varepsilon \sim 10$). Together with the fact that graphene is a two-dimensional electronic system with a very thin material layer, one would expect that in graphene-semiconductor combined structures, the strong mismatch of the dielectric constant at graphene-semiconductor interface can be achieved. In this study, we intend exploring the possibility to use graphene-based structures as new kind of THz PCs.

2. Sample Structure and Theoretical Approach

Here, we propose a 5-layer planar structure shown in Fig. 1. Namely, two graphene sheets are sandwiched among three semiconductor layers. For the structure shown as Fig. 1, the relative dielectric constant of the photonic crystal along the x-axis can be written as:

$$\varepsilon = \begin{cases} \varepsilon_1, & \text{for } |x| < d_0 \text{ (area I);} \\ \varepsilon_G, & \text{for } d_0 \le |x| \le d_1 \text{ (area II);} \\ \varepsilon_2, & \text{for } d_1 < |x| < d_2 \text{ (area III);} \\ 1.0, & \text{for } |x| \ge d_2 \text{ (area IV).} \end{cases} \tag{1}$$

Here, ε_1 and ε_2 are the high-frequency dielectric constants for respectively the inner (area I) and outer (area III) semiconductor layers, ε_G is the high-frequency dielectric constant of graphene layer (area II), and the thickness of the graphene layer is d with $d = d_1 - d_0$. Such a structure resembles those of the conventional PCs, where the higher refractive index of the core layer compared to the lower one of the graphene layer allows for traditional index guiding. Because of the relative lower dielectric constant of graphene, a strong mismatch of the dielectric constant at the interface between graphene and semiconductor layers can be achieved. This can result in the existence of the photonic states in the proposed structure.

Considering the direction of the light propagation being along the z-axis and the single transmission frequencies ω, we can assume $E(x, y, z) = E_0 \exp(i\omega t) \exp(ik_z z)$, where E_0 relates to the power carried by the optical modes and k_z is the wave vector (or propagation constant) along the z-axis.

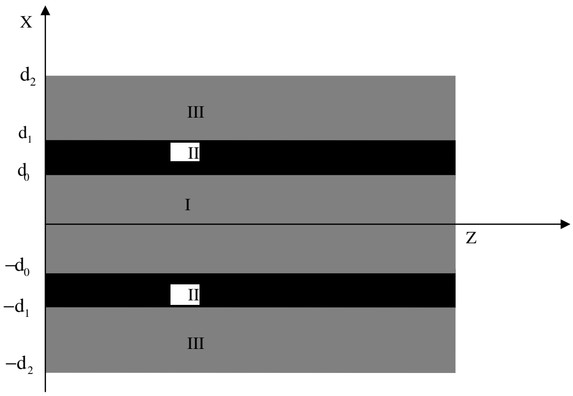

Fig. 1. The proposed graphene-semiconductor planar structure. The shaded areas stand for three semiconductor layers (areas I and III). The graphene layers are in area II. The thickness of the graphene layer is $d = d_1 - d_0$. Here d_2 and d_0 correspond respectively to the position of the upper and lower semiconductor layers. The outermost (area IV) is air.

For the transverse EM waves (TE waves), the components of the EM field are E_y, H_x and H_z, and their relationships are given as

$$\begin{cases} k_z E_y = -\mu\omega H_x, \\ \partial E_y/\partial x = i\mu\omega H_z, \\ ik_z H_x - \partial H_z/\partial x = -i\omega\varepsilon H_z. \end{cases} \tag{2}$$

If $\psi(x) = E_y\ (x)$ is the components of the electric fields along the x direction, we can easily get a scalar equation which satisfies Eq. (2)

$$\frac{d^2\psi(x)}{dx^2} + [k^2 - k_z^2]\psi(x) = 0, \tag{3}$$

where $k^2 = \mu_0\varepsilon_0\varepsilon(x)\omega^2$.

For case where layers I and III are the same semiconductor material (i.e. $\varepsilon_1 = \varepsilon_2$), the structure shown in Fig. 1 becomes a symmetric planar waveguide. Taking into consideration of the condition that the electric field should continue at different interfaces, the electric field in the different areas can be written as

$$\begin{cases} \psi_{+2} = A_{+0}\cos\delta_{+0}\,\mathrm{ch}(K_2 d + \delta_{+1})\cos[K_1(x - d_1) + \delta_{+2}]/(\mathrm{ch}\,\delta_{+1}/\cos\delta_{+2}), \\ \qquad\qquad d_1 < x \le d_2, \\ \psi_{+1} = A_{+0}\cos\delta_{+0}\,\mathrm{ch}[K_2(x - d_0) + \delta_{+1}]/\mathrm{ch}\,\delta_{+1}, \quad d_0 \le x \le d_1, \\ \psi_{+0} = A_{+0}\cos[K_1(x - d_0) + \delta_{+0}], \quad 0 \le x < d_0, \\ \psi_{-0} = A_{-0}\cos[K_1(x + d_0) - \delta_{-0}], \quad -d_0 < x \le 0, \\ \psi_{-1} = A_{-0}\cos\delta_{-0}\,\mathrm{ch}[K_2(x + d_0) - \delta_{-1}]/\mathrm{ch}\,\delta_{-1}, \quad -d_1 \le x \le -d_0, \\ \psi_{-2} = A_{-0}\cos\delta_{-0}\,\mathrm{ch}(K_2 d + \delta_{-1})\cos[K_1(x + d_1) - \delta_{-2}]/(\mathrm{ch}\,\delta_{-1}/\cos\delta_{-2}), \\ \qquad\qquad -d_2 < x \le -d_1, \end{cases} \tag{4}$$

where $K_1 = (\mu_0\varepsilon_0\varepsilon_1\omega^2 - k_z^2)^{1/2}$, and $K_2 = (k_z^2 - \mu_0\varepsilon_0\varepsilon_G\omega^2)^{1/2}$, and A_{+0}, A_{-0}, δ_{+0}, δ_{-0}, δ_{+1}, δ_{-1}, δ_{+2}, and δ_{-2} are constants to be determined. Due to the fact that there is no electric field in the air (area IV), we get

$$\cos(K_1 d_{12} + \delta_{+2}) = \cos(K_1 d_{12} + \delta_{-2}) = 0, \tag{5}$$

with $d_{12} = d_2 - d_1$. Moreover, the tangential components should also be continuous across the core-cladding interfaces. Thus, we obtain the eigenvalue equation as

$$2K_1 d_0 = m\pi + 2\arctan\left[\frac{K_2}{K_1}\tanh\left(K_2 d + \arctan h\left(\frac{K_1}{K_2}\cot(K_1 d_{12})\right)\right)\right] \tag{6}$$

where $m = 0, 1, 2 \ldots$. By solving Eq. (6), we can obtain the eigenvalue frequency from which the photonic states in the system can be determined.

3. Results and Discussion

In this study, the semiconductor layers in the areas I and III are taken as InAs (i.e. $\varepsilon_1 = \varepsilon_2 = 11.9$) for its high refractive. The dielectric constant for graphene is taken to be $\varepsilon_G = 4.0$ and the thickness of the graphene sheet is $d = 0.3$ nm.

In the following Figs. 2–4, the ground photonic state for the semiconductor-graphene planar structure corresponds to $m = 0$ and $n = 0$ (solid line) and the first excited state to $m = 1$ and $n = 0$ (the dot-dashed line); the highly excited state corresponds to $m = 0$ and $n = 1$ (the dashed line) and to $m = 1$ and $n = 1$ (the dotted line).

It can be clearly seen from Fig. 2 that the transmission frequencies ω of the fundamental mode ($m = 0$, $n = 0$) are nearly constants with varying d_0, when the sample thickness is fixed at $d_2 = 100$ μm. Similar effect can be observed for higher order modes. This suggests that the position of the graphene sheets affects rather weakly the transmission frequency of the structure.

The transmission frequency decreases with increasing d_2 in Fig. 3. Thus, the optical wavelength which can transmit steadily in the structure becomes longer. This is resulted from the fact that the transmission wavelength must satisfy the condition of the stationary wave. Hence, it is a feature of the graphene-semiconductor planar structures that the transmission frequency becomes higher when d_2 becomes thinner.

Figure 4 shows the dispersion relation of the photonic modes in a graphene-semiconductor structure. In sharp contrast to those observed in conventional PC structures, we find that the transmission frequency in relatively long-wave vector regime ($k_z > 3 \times 10^4$ m^{-1}) increases almost linearly with k_z. The slight slope difference of the dispersion relation between the fundamental mode and the higher-order modes implies that there is weak inter-mode dispersion in the structure.

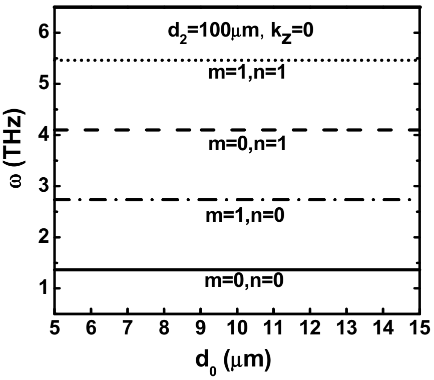

Fig. 2. The frequency of the photonic modes versus the position of the graphene layer d_0 at a fixed sample thickness $d_2 = 100$ μm. Here the propagation constant $k_z = 0$ and n stands for the nth solution of the eigenvalue equation.

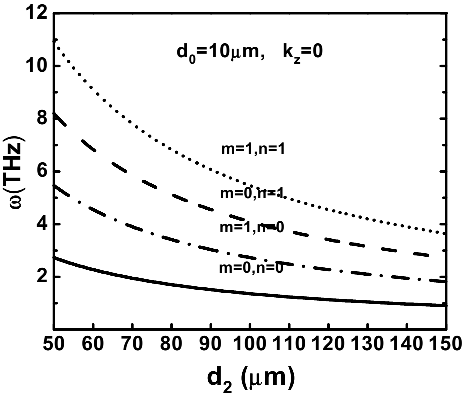

Fig. 3. The frequency of the photonic states as a function of the position of the outer semiconductor layer at a fixed $d_0 = 10$ μm and $k_z = 0$.

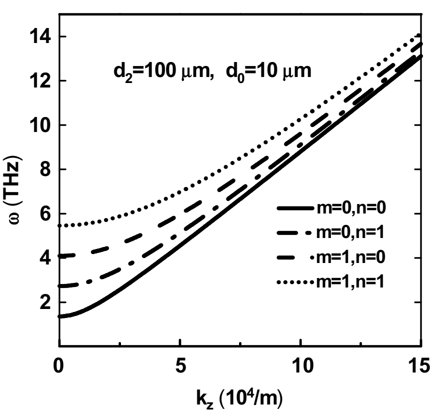

Fig. 4. The dispersion relation of the photonic states at the fixed d_0 and d_2 as indicated.

4. Conclusions

Two most important conclusions can be drawn from the present theoretical study. Firstly, when the position of the outer semiconductor layer d_2 is about 100 μm, the frequencies of different photonic modes are within the THz bandwidth and they can be tuned efficiently via altering d_2. Secondly, roughly linear dispersion relation can be observed for photonic modes in semiconductor-graphene planar structures when propagation constant $k_z > 3 \times 10^4$ m^{-1}. Thus, there is a weak effect of group velocity dispersion in the semiconductor-graphene devices over a wide range of k_z. Hence, the proposed structure can be applied for transmission of THz waves with a weak effect of light wave broadening in the remote transmission.

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