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On transmittance and localization of the electromagnetic wave in two-dimensional graphene-based photonic crystals

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ABSTRACT

Two-dimensional graphene-based photonic crystal (GPC) formed by a periodic array of the homogeneous dielectric cylinders etched in the alternating graphene and dielectric layers and its inverse counterpart are considered. The transmittance of the photonic crystal is obtained. The waveguide due to the localization of the electromagnetic wave on the lattice defect that breaks the translational symmetry of the GPC of two different topologies is studied. The different topologies of GPC are characterized by different photonic band structures with different widths of photonic band gaps (PBG) and provide different frequencies for the localized electromagnetic wave due to the defect. The frequencies of the localized mode for both type of the GPC, located inside the lowest PBG, are in the range of THz or tens of THz depending on the topology of the GPC. It is shown that the photonic band gap always can be tuned by changing the chemical potential of graphene to provide formation of the localized photonic mode due to the defect. The technological advantages of the GPC, as well as the opportunity to tune the PBG and the frequency of the localized electromagnetic wave in the terahertz region of spectrum for the GPC are discussed.

1. Introduction

Photonic crystals are artificial periodic composite structures comprised of two or more materials with different dielectric constants. After the publication of two milestone papers on photonic crystals in 1987 [1,2] the usage of electromagnetic wave propagation in photonic crystals has shown in the last decades an increasing number of applications in condensed matter physics, especially in photonics (see Refs. [3,4] and the references therein).

Photonic crystals have the ability to inhibit the propagation of electromagnetic energy over certain ranges of frequencies, forming what are known as photonic band gaps (PBG). Furthermore, this selective inhibition allows for the confinement, guiding, or focusing of electromagnetic waves if a defect is introduced into the structure of a photonic crystal. Different materials have been used as the constituent elements for the photonic crystals including dielectrics, metals, semiconductors, liquid crystals and even superconductors. The photonic crystals with the dielectric, metallic, semiconductor, and superconducting constituent elements have different photonic band structures and transmittance spectra, and the dissipation of the electromagnetic wave in all these photonic crystals is different (see reviews [3,4] and [5]). The achievements in experimental and theoretical studies of the optical properties of globular photonic crystals (physical objects having a crystal structure with the lattice period exceeding considerably the atomic size) were reviewed in Ref. [6].

A purely two-dimensional (2D) electron system was studied in graphene, which is a 2D honeycomb lattice of the carbon atoms, constituting the basic planar structure in graphite [7]. A 2D graphene-based photonic crystal (GPC) was proposed for the first time in Ref. [8], which triggered a number of studies of one-dimensional photonic crystals comprising graphene [9–20]. This system can be used as the frequency filters and waveguides for the infrared and far infrared regions of the spectrum. Applications of GPCs in optoelectronics largely depend on their tuning ability. Since the conductivity of graphene is a function of the chemical potential, the possibility of tuning the photonic band structure of GPCs via changing the chemical potential of graphene by applying the gate voltage doping was suggested in Ref. [8]. The tunability of the photonic band structure of 1D GPCs by changing the chemical potential of graphene via applying the gate voltage was

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studied and analyzed in Refs. [13,16,18–20]. Besides, the possibilities to tune the photonic band structure of 1D GPCs by magnetic field [12] and strain [17] were studied. In addition, the control of the PBG of graphene based annular photonic crystals was under consideration [21]. The tunability of the PBGs and the localization of the electromagnetic wave on a lattice defect of the GPC are two essential features in the fabrication and controlling of the transmittance spectrum of the graphene-based photonic crystal. While there was done a number of studies for the possibilities to control the PBG of 1D graphene-based photonic crystals by changing the chemical potential of graphene, in this letter we present the studies devoted to the control of the PBG of 2D graphene-based photonic crystals.

The two-dimensional GPC that formed by embedding a periodic array of constituent stacks of alternating graphene and dielectric discs into a homogeneous dielectric medium, was proposed in Ref. [8]. The following questions can be raised: i. what is the difference if one considers the inverse structure, – the GPC formed by the periodic array of dielectric holes in a homogeneous stack of alternating graphene and dielectric layers when each graphene layer is separated by the dielectric layer placed between them? ii. Can one consider the formation of a waveguide due to the localization of the electromagnetic wave on a lattice defect that breaks the translational symmetry of the GPCs of these two different topologies? These issues are addressed in this letter.

Below we present a comparative study of a 2D photonic crystal formed by a periodic array of dielectric holes in a homogeneous stack of alternating graphene and dielectric layers when each graphene layer is separated by the dielectric layer placed between them and its inverse counterpart. We calculate the transmittance of GPC and show that both GPCs transmit in the far infrared region of spectrum. Moreover, we consider the formation of a waveguide due to the localization of the electromagnetic wave on the lattice defect that breaks the translational symmetry of the photonic crystals of different topologies, and demonstrate that two different topologies of a GPC form different photonic band structures with different numbers of photonic band gaps. It is shown that two different topologies of GPC with defects provide different numbers of localized mode frequencies. According to our calculations, for both types of GPC the frequencies, corresponding to the localized mode, are located inside the PBGs. We demonstrate that since the PBG can be controlled by changing the chemical potential of graphene, it always can be tuned by gating, so that the formation of the localized photonic mode due to the defect is possible.

2. The transmittance for the photonic crystal with an ideal lattice structure

Let us consider the periodic arrangement of a stack of alternating equally-doped graphene monolayers and dielectric layers, that is a multilayer graphene. Using the multilayer graphene and a homogeneous dielectric we can fabricate a two-dimensional photonic crystal that is periodic along two of its axes and homogeneous along the third axis. One can consider two different topologies: a periodic array of the cylindrical holes etched in the multilayer graphene shown in Fig. 1a and a periodic array of the cylindrical rods (pillars) of alternating graphene and dielectric discs, presented in Fig. 1b. We refer to these periodic structures as the graphene hole photonic crystal (GHPC) and graphene rod photonic crystal (GRPC), respectively. It is clear that the GHPC is the inverse structure of the GRPC proposed in Ref. [8]. As an example, we are considering a square lattice for the GRPC and GHPC. In Fig. 1 the square lattice of GRPC is surrounded entirely by air and holes in GHPC are filled by air as well. It is obvious that the holes in the GHPC can be filled by any suitable dielectric including the dielectric that separates graphene layers. Also in the GRPC the dielectric

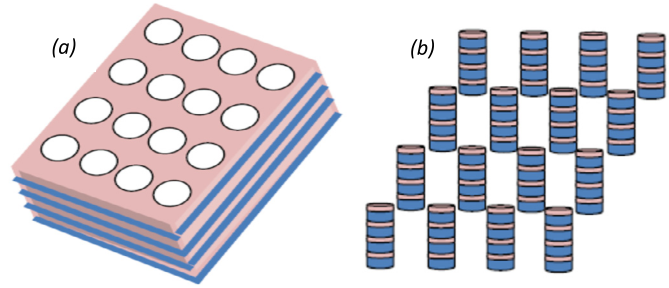

Fig. 1. Two-dimensional graphene-based photonic crystals. a) A GHPC formed by a periodic array of the cylindrical holes in a multilayer graphene system. The cylindrical holes can be filled by the same dielectric as the dielectric placed between the graphene layers. b) A GRPC formed by a periodic array of the cylindrical rods of alternating graphene and dielectric discs embedded in a dielectric medium. The dielectric between graphene discs can be the same as the material of the dielectric medium.

that separates the graphene layers can be the same as a dielectric homogeneous medium that surrounds the rods.

Below we focus on a GHPC and present a comparative analysis with the ideal GRPC, which was studied in Refs. [8,22]. On the other side, our consideration of a one-dimensional GPC in Ref. [9] shows that there is the localization of an electromagnetic wave by a defect of the photonic crystal formed by an extra dielectric stripe placed in the position of one stack of alternating graphene and dielectric stripes. The latter motivates us to consider localization of the electromagnetic wave on the defect for both topologies of two-dimensional GPCs.

We consider two physical realizations of the GPC: the GRPC and GHPC with the dielectric constant ε_d and the dielectric function $\varepsilon_g(\omega)$ for a dielectric and graphene multilayers separated by a dielectric material, respectively. Let us consider the case when the wave vector $\mathbf{k}$ of the incident electromagnetic wave is parallel to the plane of the graphene layers and perpendicular to the axis of the cylindrical holes or rods. The wave equation for the electric field $\mathbf{E}$ that is perpendicular to the plane of the graphene layers and parallel to the axis of the cylindrical holes or rods for the both physical realizations of GPC can be written as

$$-\nabla^2 E_z(x,y) - \frac{\omega^2}{c^2}\left[\varepsilon_{\text{out}} + (\varepsilon_{\text{in}} - \varepsilon_{\text{out}}) \sum_{\{\mathbf{n}^{(l)}\}} \eta(\mathbf{r} \in S)\right] E_z(x,y) = 0, \quad (1)$$

where $\eta(\mathbf{r} \in S)$ is the Heaviside step function: $\eta(\mathbf{r} \in S) = 1$ if $\mathbf{r}$ is inside of a cylinder with cross sectional area S, and otherwise $\eta(\mathbf{r} \notin S) = 0$, $\mathbf{n}^{(l)}$ is a vector of integers that gives the location of scatterer l at $\mathbf{a}(\mathbf{n}^{(l)}) \equiv \sum_{i=1}^{D} n_i^{(l)} \mathbf{a}_i$ ($\mathbf{a}_i$ are real space lattice vectors and D is the dimension of the lattice) and the summation in Eq. (1) goes over all lattice nodes characterizing positions of cylinders. In Eq. (1) the first term within the brackets is associated to the medium, while the second one is related to the cylinders and for the ideal lattice of the GPC

$$\varepsilon_{\text{out}}(\mathbf{r},\omega) = \begin{cases} \varepsilon_d, & \text{for GRPC} \\ \varepsilon_g(\omega), & \text{for GHPC} \end{cases} \quad (2)$$

and

$$\varepsilon_{\text{in}}(\mathbf{r},\omega) = \begin{cases} \varepsilon_g(\omega), & \text{for GRPC} \\ \varepsilon_d, & \text{for GHPC.} \end{cases} \quad (3)$$

In Eqs. (2) and (3) ε_{out} is the dielectric function of the material outside the cylinder and ε_{in} is the dielectric function of the material inside the cylinder, and one can see that for the ideal lattice

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