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Multi-mode absorption in multi-cavity photonic crystal with two graphene monolayers

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ABSTRACT

Multi-mode absorption is achieved theoretically at terahertz frequencies by using the one-dimensional photonic crystal (PC) incorporating multiple Fabry-Perot resonance cavities. To simulate this multilayered structure, the method of rigorous coupled-wave analysis is adopted. Results show that for single-cavity PC with two graphene monolayers in this cavity, there are two near-unity absorption modes with low Q-factors. By cascading one empty cavity without graphene behind, an extra high-Q mode is induced in the middle. The number of modes is controlled directly by changing the positions of graphene sheets. Also, these modes are allowed to tune separately and be shifted by many manners. After another empty cavity is cascaded, two modes with higher Q-factors replace the middle one and then four near-unity absorption modes arise. Thus, the multi-cavity PC with a small number of graphene monolayers has the ability to gain multiple strong absorption modes.
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1. Introduction

Due to the unique optoelectronic properties, graphene is focused considerably to design various functional devices. When the graphene nanolayer is embedded into a one-dimensional photonic crystal, the novel multilayer not only exhibits the common characteristics of PC, such as photon bandgap and photon localization, but also presents special behaviors related to graphene, such as loss-free density-of-optical-states peaks [1] and tunable electrically defect modes [2]. Up to now, the graphene-embedded photonic crystal (GPC) has been employed in the realization of spectral-selective mirror [3], ultra-broadband absorber [4], magneto-optic modulator [5] along with biosensor [6], etc. The GPC-based structures own many advantages. Firstly, the graphene is unpatterned so that no extra loss channels are from atomic scale roughness of the edges [7]. Secondly, for these embedded graphene sheets, they are isolated completely so as to be immune for any unexpected doping from external environment [8]. Thirdly, the system response is weakly dependent on the polarization of the incident wave, especially at the normal incidence [9]. Whereas, GPC is a promising candidate to achieve the pursued optical or electric components.

As for the GPC absorbers, both of single-mode absorption and multi-mode absorption can be obtained. For the former, a simple approach conceptually is to integrate the graphene sheet in the microcavity of PC [10,11]. Depending on the Fabry-Perot (FP) resonance, one can gain the desirable absorption level. For the latter, effective strategies are provided in Refs. [12,13], where graphene dielectric stack are used. Similarly, the light is confined nearby the graphene layers, and as a result multiple absorption peaks arise. However, the corresponding fabrication is troublesome, since the process refers to repetitive

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graphene transfer [14], and worse still, it is a challenge task to prepare a large number of graphene membranes with identical electric parameters. Stem from the feasibility angle, the GPC-based multi-mode absorbers should not contain excessive graphene layers.

In this paper, in order to achieve multi-mode absorption with a small amount of graphene sheets, we introduce multiple FP resonance cavities into the PC. In one cavity, two graphene monolayers are embedded. In the others, there is no graphene. It is shown that compared with the double-mode absorption in the single-cavity PC, there are three strong absorption modes in the double-cavity PC. Two of them with low Q factors depend on the graphene cavity. The remaining one with high Q factor relies on the empty cavity. The number of absorption modes is exactly determined by the positions of two graphene layers in the graphene cavity. The shift of modes is enabled by changing the characteristic parameters of graphene, PC or incident wave. For the three-cavity PC, four near-unity absorption modes appear, two of which are narrow related to the two empty cavities. Obviously, the multi-cavity PC realizes the function of multi-mode absorption with the help of two graphene monolayers.

2. System model and calculation method

To illustrate that only very few graphene layers and many FP resonance cavities can give rise to multi-mode absorption, three PC resonators are constructed in Fig. 1. In the panel (a), the single-cavity PC $(AB)^m G_{dc}(BA)^q$ is given, which contains the top partial mirror $(AB)^m$, the bottom perfect mirror $(BA)^q$ and the middle cavity G_{dc}. Here, SiO_2 and Si are used as A and B, as well as m (q) denotes the periodic number of bilayer AB (BA). G_{dc} is constituted by the graphene-dielectric compound, where SiO_2 is selected as the background dielectric and two graphene monolayers Gr_1 and Gr_2 are inserted. As a result, the SiO_2 block in the graphene cavity G_{dc} is divided into three cakes. In the panel (b), to harvest more absorption modes, an empty cavity without graphene is cascaded to develop the double-cavity PC $(AB)^m G_{dc}(BA)^n C(BA)^q$, where the material and thickness of defect C is SiO_2 and d_C. In the panel (c), in order to verify further that cascading empty cavity can add the absorption-mode number, a three-cavity PC $(AB)^m G_{dc}(BA)^n C(BA)^p D(BA)^q$ is presented, where the D is assumed to be same as the C.

In the all of the structures mentioned above, suppose for the bilayer AB the permittivity $\varepsilon_A = 3.9$, $\varepsilon_B = 11.9$ [15], the thicknesses $d_A = c/(4f_0\sqrt{\varepsilon_A})$, $d_B = c/(4f_0\sqrt{\varepsilon_B})$, where f_0 is the reference frequency. The total length of SiO_2 block in G_{dc} is set as $L = td_A$, in which t is the multiplication factor. The normalized positions of Gr_1 and Gr_2 are labeled as l_1 and l_2, which meet the these conditions of $l_2 > l_1$, $l_1 \in (0, 1)$ and $l_2 \in (1 - l_1, 1)$. Then, three SiO_2 cakes have the lengths $l_1 \cdot L$, $(l_2 - l_1) \cdot L$ and $(1 - l_2) \cdot L$ respectively. Considering a TE-polarized plane wave impinging on the resonator from the air in the case of incident angle $\theta = 0°$, the bandgap range Δf of the perfect Bragg mirror $(BA)^q$ can be calculated by [16]

$$\Delta f = \frac{4f_0}{\pi}\sin^{-1}\left(\frac{\left|\sqrt{\varepsilon_A} - \sqrt{\varepsilon_B}\right|}{\sqrt{\varepsilon_A} + \sqrt{\varepsilon_B}}\right). \tag{1}$$

Hence, the system in the range becomes a single-port one so that it can break through the 50% upper limit of symmetric structure and thus the near-unity absorption could occur [17].

For the graphene-embedded multilayered structure, two simulation technologies are effective. The first one is the modified transfer matrix method (TMM) [18,19], where graphene is characterized as a two-dimensional material by the complex surface conductivity σ_g. Thanks to the existence of graphene, the electromagnetic boundary condition on the interface with graphene is no longer written as a unit matrix, instead modified as the one composed of σ_g. The second one is the rigorous coupled-wave analysis (RCWA) method [20], where graphene is described as a three-dimensional material with non-zero thickness by the permittivity ε_g. The RCWA is usually used to seek the light response of diffraction grating, where the

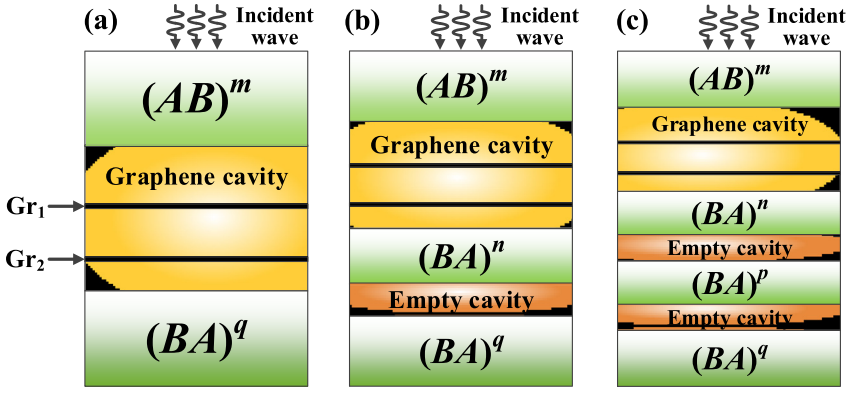

Fig. 1. (a) Single-cavity PC with one graphene cavity. (b) Double-cavity PC with one graphene cavity and one empty cavity. (c) Three-cavity PC with one graphene cavity and two empty cavities.

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