



Absorption behavior in graphene-based one-dimensional photonic crystals containing a x-cut lithium niobate layer



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ABSTRACT

This paper theoretically shows that nearly perfect absorption can be achieved by adjusting the period numbers of the two graphene based photonic crystals surrounding a lithium niobate (LiNbO₃) layer. Since LiNbO₃ is an electro-optical (EO) material with voltage dependent refractive index and high EO coefficient, peak wavelength tunability of absorption has been revealed. Our investigations show that the relation between the peak wavelength and applied external voltage is linear, so that the peak wavelength moves toward shorter wavelengths by increasing the applied external voltage. Moreover, it is possible to achieve multi-peak by varying the thickness of LiNbO₃ defect layer. Finally, we discuss the possibility of control of the absorption via controllable parameter (chemical potential) of the graphene. The results indicate that for a given structure, i.e. definite period numbers surrounding the LNO layer, the enhanced absorption can be achieved, by adjusting the chemical potential.

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1. Introduction

Graphene, a flat monolayer of graphite with carbon atoms arranged in a two-dimensional (2D) honey-comb lattice, has dramatically changed the electronic and photonic worlds due to a number of unique and extraordinary properties, such as high charge carrier mobility, flexibility, robustness, stability, and the most importantly, the ability of controlling its electronic and optical properties by applying an external gate voltage [1–6]. A suspended atomically thin layer of intrinsic graphene is poorly absorbing in the infrared (IR) to visible frequency ranges (about 2.3% absorption) [7]. Although this property of graphene is used for designing of transparent electrodes and optical display materials [8], its photoresponsivity is limited for graphene-based photodetectors [9]. Here, we focus on the latter applications, where increasing light absorption in graphene is preferable.

So far, several studies have been performed on enhancement of the absorption of graphene, e.g., putting graphene in a one-dimensional (1D) periodic structures [10–15], 2D photonic crystal (PC) cavities [16,17], using resonant metal back reflector [18], and exploiting the attenuated total reflectance [19–21].

In this work, by integrating an electro-optical (EO) tuning material LiNbO₃ (LNO) as a defect layer, we prepare a graphene based 1D photonic crystal (GB1DPC). First we show that by certain choice of this structure, almost complete absorption is

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obtained in the near-IR wavelength range. Then, we discuss the behavior of absorption by applying external electric field on the LNO layer. Finally, the effect of chemical potential of graphene sheets on the optical absorption is investigated.

2. Structural model and calculation method

Fig. 1 shows our considered structures i.e. Air/(LGHG)^m D (GLGH)ⁿ/Sub and Air/(LGHG)^m D (GHGL)ⁿ/Sub, that are labeled as A and B, respectively. As this figure shows, the graphene monolayers are embedded between adjacent dielectric layers, where H and L stand for the high and low-index layers, respectively and D represents an EO defect material, i.e. LNO. In our numerical calculations, we used TiO₂ as a layer H and SiO₂ as a layer L with refractive indices, 2.17 and 1.45, respectively. Also, both layers have quarter wavelength optical thicknesses, that is,

$$n_{TiO_2} d_{TiO_2} = n_{SiO_2} d_{SiO_2} = \frac{\lambda_0}{4}, \tag{1}$$

where λ₀ (design wavelength) is chosen to be 1.35 μm. Furthermore, the substrate is assumed to be usual glass with n_s = 1.52. We suppose the optical wave travels in the x direction and is polarized in the z direction. When an external voltage is applied on x-cut LNO along the z-axis (c-axis) (as in Fig. 1), it will produce an electric field (E) in the same direction and the relevant optical index is the extraordinary index n_e, so that it can be evaluated by the Pockel's equation [22]:

$$n'_e = n_e - 0.5n_e^3\gamma_{33}E, \tag{2}$$

where γ₃₃ = 30.9 pm/v is the EO coefficient and E = V/t (t = 0.4 mm is the distance between the electrodes). Also, n_e is wavelength dependent extraordinary refractive index in the absence of voltage which can be calculated by the following Sellmeier equation [23,24]:

$$n_e = \left(4.5820 - \frac{0.099169}{0.044432 - \lambda^2} - 0.021950\lambda^2 \right)^{1/2}, \tag{3}$$

where λ is the wavelength in μm. In the case of graphene, which we denoted with G, the following surface conductivity is used [4]:

$$\sigma(\Omega, \mu_c, T) = \frac{e^2}{4h} \left[\frac{1}{2} + \frac{1}{\pi} \arctan \frac{\hbar\Omega - 2\mu_c}{2k_B T} + \frac{i}{2\pi} \left\{ \frac{16k_B T}{\hbar\Omega} \ln \left(2 \cosh \frac{\mu_c}{2k_B T} \right) - \ln \frac{(\hbar\Omega + 2\mu_c)^2}{(\hbar\Omega - 2\mu_c)^2 + (2k_B T)^2} \right\} \right]. \tag{4}$$

Here, Ω = ω + iτ⁻¹, e is the charge of an electron, ħ = h/2π is the reduced Planck's constant, k_B is the Boltzmann constant, T is the temperature in K, τ is the electron relaxation time (inverse of scattering rate), ω is the angular frequency of the incident wave and μ_c is the chemical potential. Finally, to calculate the absorption spectra in the proposed structures, we use the transfer-matrix-method [25]. According to this method, absorption is determined by

$$A = 1 - \left| \frac{M_{21}}{M_{11}} \right|^2 - n_s \left| \frac{1}{M_{11}} \right|^2, \tag{5}$$

where M₁₁ and M₂₁ are the elements of the total transfer matrix of the structure that is given by

$$M = \begin{pmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{pmatrix} = D_{Air,1} P_1 D_{0,1} P_1 \dots P_N D_{N,Sub}. \tag{6}$$

Here, D_{i,j} is dynamical matrix expressed as

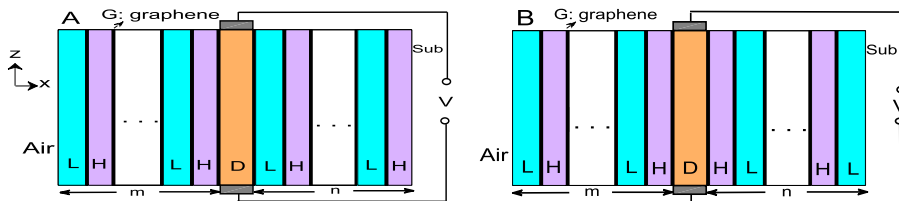


Fig. 1. Schematic drawing of A: Air/(LGHG)^m D (GLGH)ⁿ/Sub and B: Air/(LGHG)^m D (GHGL)ⁿ/Sub structures. The external voltage is applied along the z direction (c-axis).

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