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Tunable terahertz optical properties of graphene in dc electric fields

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ABSTRACT

We develop a simple theoretical approach to investigate terahertz (THz) optical properties of monolayer graphene in the presence of an external dc electric field. The analytical results for optical coefficients such as the absorptance and reflectivity are obtained self-consistently on the basis of a diagrammatic self-consistent field theory and a Boltzmann equilibrium equation. It is found that the optical refractive index, reflectivity and conductivity can be effectively tuned by not only a gate voltage but also a driving dc electric field. This study is relevant to the applications of graphene as advanced THz optoelectronic devices.

1. Introduction

Graphene is a dense honeycomb two-dimensional (2D) Dirac system. It is of excellent electronic and optical properties such as high carrier density and mobility [1], high optical transmittance [2], large optical nonlinearity [3], ultrafast saturable absorption [4], to mention but a few. Graphene has been proposed as an advanced material for new generation of electronic and optical devices. In recent years, the tunable optical properties of monolayer graphene have been studied extensively using various approaches. Kakenov et al. experimentally observed a tunable coherent perfect absorption of terahertz (THz) radiation in graphene [5] via applying a gate voltage, which leads to efficient active THz components, such as tunable THz mirrors and modulators. It has been demonstrated experimentally that anisotropic light-matter interacts with tunable field enhancement and optical reflectance in the graphene-nanoengineered metal structure [6]. On the other hand, the results obtained from theoretical studies showed that with increasing the gap width, the optical reflectivity of graphene-coated plates decreases more than 8 times depending on the values of frequency and mass-gap parameter [7]. Theoretical calculations showed that electric field is able to induce optical second-harmonic generations in doped graphene [8]. Elton et al. have reported the electric-field dependence of the effective dielectric constant in graphene, which shows that both the out-of-plane and the in-plane dielectric constants depend on the value of applied external field perpendicular to graphene layer [9]. By applying a small gate voltage, the reflectance of graphene is modulated from a minimum of 0.79% to a maximum of 33.4% using graphene-ionic liquid structures at room temperature, and the reflection tuning is uniform within a wide spectral range from 0.1 THz to 1.5 THz [10]. Moreover, it is found that optical properties and magneto-optical Kerr effect of graphene can be controlled by a gate voltages V_g in THz region [11], which can be served as THz devices based on electrically gated graphene. These important and interesting research findings indicate that the presence of electric fields and/or gate voltages play an important role in modulating optical properties of graphene based systems.

With the development of the device fabrication technology, more and more advanced optoelectronic devices have been realized. One of the main schemes to design and realize these devices is via electrical manipulation of optical properties of electro-optical materials and devices. At present, the experimental investigation in this field of research has been rather intensively undertaken. However, the corresponding theoretical study lags rather behind the experimental activities. In particular, the systematic and concise theoretical modes and approaches are relatively lack for solving related problems. We have previously carried out a systematical study of the optical properties of graphene in the absence of a driving electric fields [12]. On the other hand, we have developed a theoretical model to investigate the electronic transport properties of graphene in the presence of strong dc driving fields [13]. Motivated by our foregoing research and the above mentioned research findings, in this work we intend to investigate the THz optical properties in graphene in the presence of the external dc electric fields applied along the 2D plane of the graphene layer. We

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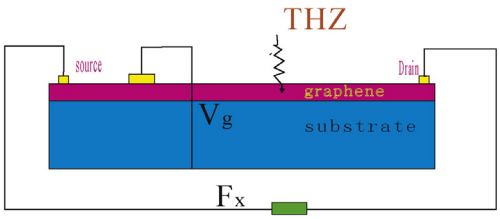

Fig. 1. Configuration of a graphene based THz optoelectronic device in the presence of dc electric fields F_x.

would like to examine theoretically the effects of the driving electric field on optical coefficients of graphene and to obtain relatively simple expressions for these coefficients in order to gain more easily an in-depth understanding of the corresponding optical properties.

2. Theoretical approach

In this study, we consider a gate-controlled graphene film on a dielectric SiO_2 wafer, similar to the sample devices used in the experiments as Fig. 1 [14,15]. In such a device structure, the carrier density in graphene can be effectively modified by the gate voltages V_g and the electric current in graphene can be tuned by a dc driving electric field applied along the x-direction of the graphene sheet from the source to drain electrode. The wave function and energy spectrum near the Dirac point for electrons in graphene are given respectively as $\psi_{\mathbf{k}}(\mathbf{r}) = 2^{-1/2}[1, e^{i\vartheta}]e^{i\mathbf{k}\cdot\mathbf{r}}$ and $E(\mathbf{k}) = \gamma|\mathbf{k}|$. Here, $\mathbf{k} = (k_x, k_y)$ is the wave vector for an electron, $\mathbf{r} = (x, y)$, and $\gamma = \hbar v_F$ with $v_F = 10^8$ cm/s being the Fermi velocity in graphene. ϑ is the angle between $\mathbf{k}$ and the x-axis. In our previous work, we have employed the usual balance-equation approach on the basis of the Boltzmann equation to investigate on the electronic transport properties of such graphene systems successfully [13]. The drift velocity of electrons v_x and the electron temperature T_e in graphene have been evaluated self-consistently for a given electric field with a strength F_x, where the electron interactions with impurities and acoustic- and optic-phonons have been taken into account along with the inclusion of electron-electron interactions in graphene system [13,16].

In the present study, we consider the conducting carriers in graphene are electrons or in the presence of a positive gate voltage. When an electric field is applied to graphene, electrons are accelerated and heated. Thus, the non-equilibrium distribution of electrons is achieved and the electron temperature T_e can be higher than lattice temperature of the surrounding medium T. Meanwhile, a light field is applied normal to the surface of graphene sheet and polarized linearly along the x-direction of the system. In such a case, the electrons in graphene can absorb photons so that the optical conductance or absorption can be induced and the optical reflection and transmission also occur as shown in Fig. 1. To describe these effects theoretically we introduce $\mathcal{F}[E(\mathbf{k}')]$ to be as the non-equilibrium electron distribution function, which can be assumed as the drifted energy distribution function for electrons in graphene in the presence of the driving electric field F_x, where $\mathbf{k}' = \mathbf{k} - \mathbf{k}_v$ with $\mathbf{k}_v = k_F\mathbf{v}/v_F$, $\mathbf{v} = (v_x, 0)$ is the drift electron velocity, and $k_F = \sqrt{\pi n_e}$ is the Fermi wave vector with n_e being the electron density in graphene.

We have developed a tractable theoretical approach to study the plasmon and coupled plasmon-phonon modes in graphene by calculating the dynamical dielectric function [16,17]. In a diagrammatic self-consistent field theory, the complex dynamical dielectric function can be written as

$$\widetilde{\epsilon} = 1 - \frac{V_q}{2}\sum_{\mathbf{k}}(1 + A_{\mathbf{kq}})\Pi(\mathbf{k}, \mathbf{q}; \omega), \tag{1}$$

where

$$\Pi(\mathbf{k}, \mathbf{q}; \omega) = g_s g_v \frac{\mathcal{F}[E(\mathbf{k}' + \mathbf{q})] - \mathcal{F}[E(\mathbf{k}')]}{\hbar\omega + E(\mathbf{k} + \mathbf{q}) - E(\mathbf{k}) + i\delta}, \tag{2}$$

is the pair bubble or density-density correlation function in the absence of e-e screening and the non-equilibrium electron distribution has been considered. Moreover, $g_s = 2$ and $g_v = 2$ count respectively for the spin and valley degeneracy, $\mathbf{q} = (q_x, q_y)$ is the change of electron wavevector during an electron-electron interaction event or is the photon momentum for electron-photon scattering, $V_q = 2\pi e^2/\epsilon_\infty q$ is the 2D Fourier transform of the Coulomb potential with ϵ_∞ being the high frequency dielectric constant for graphene, and $A_{\mathbf{kq}} = (k + q\cos\theta)/|\mathbf{k} + \mathbf{q}|$ with θ being an angel between $\mathbf{k}$ and $\mathbf{q}$. $\widetilde{\epsilon}$ contains real ϵ_1 and imaginary ϵ_2 parts so that

$$\widetilde{\epsilon} = \epsilon_1 - i\epsilon_2. \tag{3}$$

The electrons can be heated and are at high temperature in the present of high dc electric fields. Consequently, the electrons in graphene are in nondegenerate states with a Maxwellian distribution function. In this study, we take Maxwellian distribution function as statistical energy-distribution function for electrons in graphene [16,18], namely $\mathcal{F}[E(\mathbf{k}')] \simeq Ce^{-E/k_BT_e}$ with $E = \gamma[(k_x - k_F v_x/v_F)^2 + k_y^2]^{1/2}$ and C being a normalization coefficient. Based on the law of charge number conservation with $n_e = g_s g_v \sum_{\mathbf{k}} Ce^{-E/k_BT_e}$, C can be determined. Considering $\lim_{\eta\to 0^+}(x \pm i\eta)^{-1} = P(1/x) \mp i\pi\delta(x)$, with $P(x)$ being the principal values, we can obtain ϵ_1 and ϵ_2 as

$$\epsilon_1 \simeq 1 + \frac{\pi e^2\gamma^2 n_e}{8\epsilon_\infty c\hbar^2\omega k_B T_e}[4 + 2\beta_1\beta_2 - \beta_1\beta_2\cos(2\phi)], \tag{4}$$

and

$$\epsilon_2 = \frac{e^2\gamma^2\tau^3 n_e\hbar\omega}{4\epsilon_\infty c(\hbar^2 + \hbar^2\omega^2\tau^2)^2}[4 + 2\beta_1\beta_2 + \beta_1\beta_2\cos(2\phi)], \tag{5}$$

with $\beta_1 = E_F/(k_BT_e)$, $\beta_2 = v_x/v_F$, $E_F = \gamma k_F$ being the Fermi energy, ω being the frequency of the incident light field, c being the speed of light in vacuum, ϕ being an angle between photon wave vector $\mathbf{q}$ and the x-axis. τ is the momentum relaxation time due to photon scattering in graphene [12,19], which depends on a phenomenological scattering rate Γ, such as charged impurity scatterings [20]. The typical value of τ can be obtained by experiments [21]. The optical absorptions rely on the momentum relaxation time τ.

With ϵ_1 and ϵ_2, we can calculate the refraction coefficient n and the extinction coefficient κ, which read respectively

$$n = \left(\frac{\sqrt{\epsilon_1^2 + \epsilon_2^2} + \epsilon_1}{2}\right)^{1/2}, \tag{6}$$

and

$$\kappa = \left(\frac{\sqrt{\epsilon_1^2 + \epsilon_2^2} - \epsilon_1}{2}\right)^{1/2}. \tag{7}$$

Thus, the complex refractive index of light is given as,

$$\widetilde{n} = n - i\kappa, \tag{8}$$

and the optical reflectivity R is,

$$R = \frac{(n-1)^2 + \kappa^2}{(n+1)^2 + \kappa^2}, \tag{9}$$

which are the macroscopical optical constants which can be measured experimentally.

Moreover, the optical conductivity and absorption coefficient are respectively given by

$$\sigma = \omega\epsilon_2/(4\pi), \tag{10}$$

and

$$\alpha = 4\pi\sigma/(nc). \tag{11}$$