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EFFECT OF THE ELECTRON DRIFT IN GRAPHENE ON THE POLARIZATION CONVERSION OF A NORMALLY INCIDENT WAVE

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Abstract. The polarization conversion of an electromagnetic wave normally incident on graphene with a direct electric current is investigated in the hydrodynamic approach. It is shown that the dynamic conductivity of graphene depends on the direction of electron drift even in the absence of spatial dispersion (i.e., for long electromagnetic waves). This changes the polarization of electromagnetic radiation at terahertz frequencies. The real part of the dynamic conductivity of graphene with electron drift can be negative, which leads to amplification of terahertz wave.

Key words: graphene, terahertz radiation, polarization conversion.

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Introduction

Detection [1,2], amplification [3,4] and polarization conversion [5] of terahertz (THz) radiation have been actively investigated in graphene-based structures lately. The polarization conversion is possible in systems with broken symmetry, which can be created by the geometry modification of the structure [6], applying the constant magnetic field [7], as well as due to electronic drift in graphene [8]. The motion of charge carriers in graphene can be described by a hydrodynamic approach, which is valid when the frequency of interparticle collisions in graphene is the greatest characteristic frequency in the system [9]. The validity of hydrodynamic approach and the limits of its applicability were confirmed experimentally [10,11].

1. Materials and Methods.

In this work, we study the polarization conversion of a plane homogeneous electromagnetic wave (TEM wave) incident at normal direction on hydrodynamic graphene with a direct electric current (DC) flowing at arbitrarily angle φ to the direction of the electric field of the incident wave. The structure under study consists of a monolayer graphene lying in the *xoz*-plane on the interface between two semi-infinite dielectric media with dielectric constants ε_1 and ε_2 (Fig. 1). The TEM wave is normally incident on graphene from medium 1.

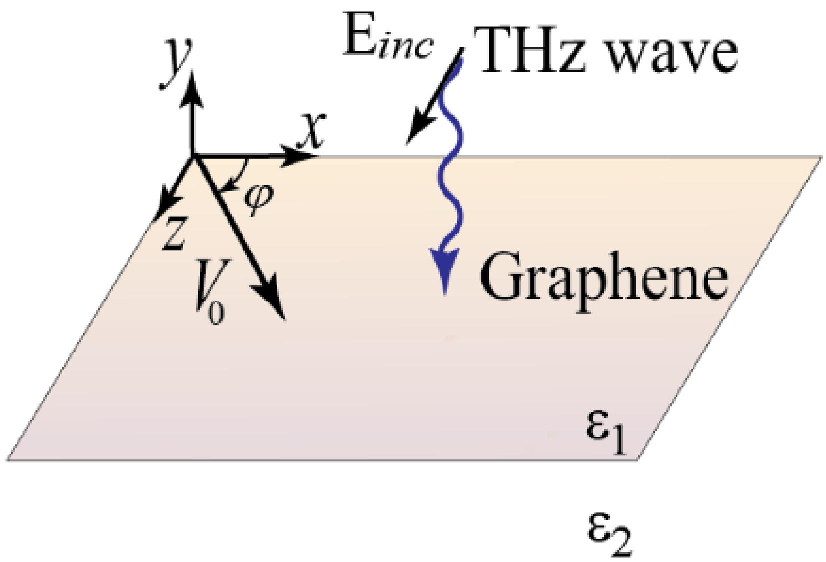

Fig. 1. Schematic representation of the studied structure.

The dynamic conductivity of graphene is obtained by solving the hydrodynamic equations, which in the case of a homogeneous acting electric field of the incident wave are written as

$$\frac{\partial \mathbf{S}}{\partial t} + e\mathbf{E}N = -\gamma \mathbf{S}, \tag{1}$$

$$\frac{\partial W}{\partial t} + eN\mathbf{E} \cdot \mathbf{V} = 0, \tag{2}$$

where Eq. (1) is the electron momentum balance equation and Eq. (2) is the energy balance equation for two-dimensional motion of electrons in graphene. In Eqs. (1)-(2) N is the charge carrier density, $\mathbf{V}$ is the hydrodynamic velocity, $\mathbf{S}$ is the macroscopic momentum density, W is the macroscopic energy density, e is the elementary charge $e > 0$ (we assume that the charge carriers in graphene are electrons for definiteness), $\mathbf{E}$ is the in-graphene-plane electric field, and $\gamma = 1/\tau$ with τ being the electron momentum relaxation time in graphene. The relations between the physical quantities entered Eqs. (1)-(2) are [9]

$$\mathbf{S} = M\mathbf{V},\ W = MV_{\mathrm{F}}^2 - P,\ \ P = M(V_{\mathrm{F}}^2 - \mathbf{V}^2)/3, \tag{3}$$

where M is the hydrodynamic mass density, P is the hydrodynamic pressure, and $V_{\mathrm{F}} = 10^6$ m/s is the Fermi velocity in graphene. Equations (1) and (2) are solved by decomposing all variables over degrees of amplitude of the acting electric field with keeping only the linear term in the decomposition, $A = A_0 + A_1 \exp(-i\omega t)$, where ω is the angular frequency and indices 0 and 1 refer to the stationary and oscillating quantities, respectively.

In the case of a homogeneous oscillating electric field, the linearized Eq. (1), with taking into account Eq. (3), gives expressions for the components of the oscillating hydrodynamic velocity

$$V_{x1} = -\frac{M_1 V_{x0}\left(\gamma - i\omega\right) + e\,E_{x1}\ n_0}{M_0\left(\gamma - i\ \omega\right)}, \tag{4}$$

$$V_{z1} = -\frac{M_1 V_{z0}\left(\gamma - i\omega\right) + e\,E_{z1}\ n_0}{M_0\left(\gamma - \mathrm{i}\ \omega\right)}, \tag{5}$$

where E_{x1} and E_{z1} is the projections of the oscillating electric field in graphene on the *ox*- and *oz*-axes, respectively, n_0 is the stationary electron concentration in graphene, M_0 and M_1 are the stationary and oscillating hydrodynamic electron mass density, V_{x0} and V_{z0} are the components of electrons stationary drift velocity $\mathbf{V}_0$, and V_{x1} and V_{z1} are the components of hydrodynamic oscillating velocity. From Eqs. (2) and (3), we obtain the expression for the oscillating hydrodynamic mass density

$$M_1 = -\frac{e\,n_0(E_{x1}V_{x0} + E_{z1}V_{z0}) + V_{x1}(3eE_{x0}n_0 - 2iM_0V_{x0}\omega)/3 + V_{z1}(3eE_{z0}n_0 - 2iM_0V_{z0}\omega)/3}{i\omega(-2V_F{}^2 - V_{x0}{}^2 - V_{z0}{}^2)/3}, \quad (6)$$

where E_{x0} and E_{z0} are the components of stationary electric field producing the electron drift. As can be seen from Eq. (6), the hydrodynamic mass density oscillates only in the presence of electron stationary drift in graphene. Using Eqs. (4), (5), and (6) the linearized Ohm's law $J_{x1(z1)} = -en_0V_{x1(z1)}$, we obtain the expression for the dynamic conductivity of graphene, which has the form of a tensor with elements

$$\begin{aligned}
\sigma_{xx} &= \Sigma\left[\omega\left(2V_{\mathrm{F}}^2 - 2V_{x0}^2 - V_{z0}^2\right) - 3i\gamma\left(V_{x0}^2 - V_{z0}^2\right)\right],\\
\sigma_{zz} &= \Sigma\left[\omega\left(2V_{\mathrm{F}}^2 - 2V_{z0}^2 - V_{x0}^2\right) + 3i\gamma\left(V_{x0}^2 - V_{z0}^2\right)\right],\\
\sigma_{xz} &= \sigma_{zx} = \Sigma(\omega + 6i\,\gamma)V_{x0}V_{z0},
\end{aligned} \quad (7)$$

where $\Sigma = \dfrac{e^2n_0\left(V_{\mathrm{F}}^2 - V_{x0}^2 - V_{z0}^2\right)}{\left(\omega + i\,\gamma\right)[\omega\left(2V_{\mathrm{F}}^2 - V_{x0}^2 - V_{z0}^2\right) + 3i\left(V_{x0}^2 + V_{z0}^2\right)\gamma]\varepsilon_{\mathrm{F}}}$ with ε_{F} being the steady-state Fermi energy in graphene, $V_{x0} = V_0\cos\varphi$ and $V_{z0} = V_0\sin\varphi$.

In the absence of spatial dispersion, the graphene dynamic conductivity still depends on the stationary electron drift, unlike classical two-dimensional electronic systems with massive electrons. This unique feature of graphene can be used for the polarization conversion of electromagnetic radiation.

Let us introduce the reflection and transmission coefficients

$$Y_{\mathrm{n}}^{\mathrm{m}} = \frac{|S_{\mathrm{n}}^{\mathrm{m}}|}{|S^{\mathrm{inc}}|}, \ \{\mathrm{m} = \mathrm{R}, \mathrm{T}\} \quad (8)$$

where $S_{\mathrm{n}}^{\mathrm{m}}$ is the energy flux density in reflected (m = R) and transmitted (m = T) waves with orthogonal ($n = \perp$) and same ($n = ||$) polarization of electric field in respect to that of incident wave and $S_{\mathrm{total}}^{\mathrm{m}}$ is the total energy flux density in reflected (transmitted) wave.

We also introduce the transmission coefficient for degree of polarization conversion

$$P^{\mathrm{T}} = \frac{|S_{\perp}^{\mathrm{T}}|}{|S_{\mathrm{total}}^{\mathrm{T}}|}, \tag{9}$$

where $S_{\mathrm{total}}^{\mathrm{T}}$ is the total energy flux density in transmitted wave.

2. Results.

The emerging the new component (absent in the incident wave) of the electric field in the reflected and transmitted waves is associated with different unequal elements of the graphene dynamic conductivity tensor of drift-biased graphene [Fig. 2(a)]. For some drift angles, the real part of each element of graphene dynamic conductivity tensor can become negative, which leads to an amplification of THz waves with both the initial and cross- polarization [Fig. 2(b)]. The gain in graphene develops due to electron drift and dissipation in graphene [8]. For drift angles 0 and 90 degrees, there is no cross-polarized electric field components in the reflected and transmitted waves. At the same time, for $\varphi = 90^{\mathrm{o}}$ (electron drift is co-directed with the electric field of the external wave) the amplification of the wave with initial polarization is maximal, which is associated with the maximum of $\mathrm{Re}\sigma_{zz}$ [Fig. 2(a)].

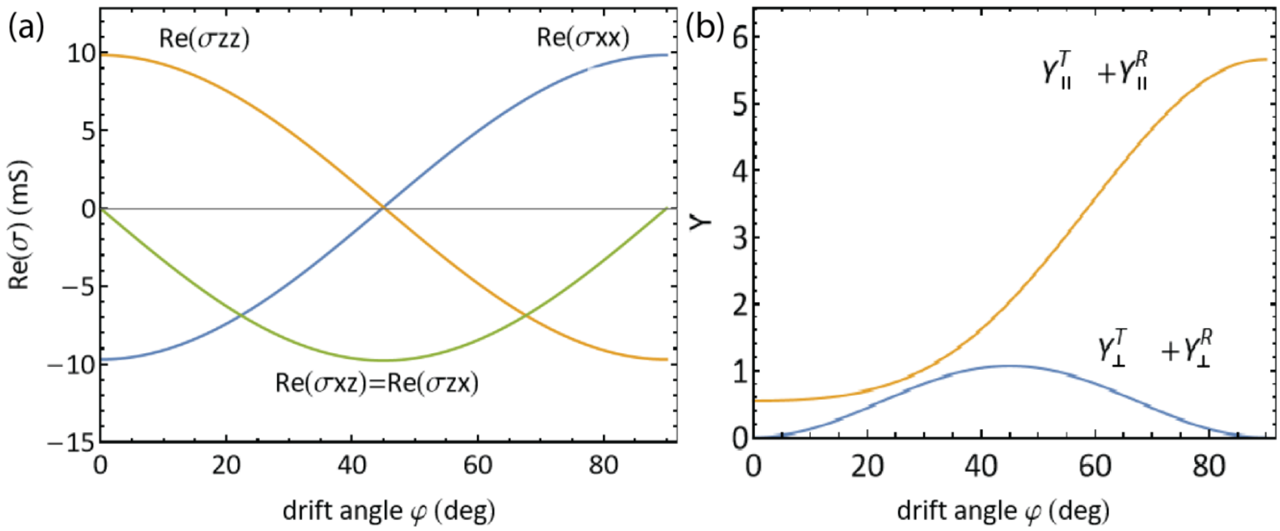

Fig. 2. (a) Dependence of the real part of graphene dynamic conductivity tensor elements on the electron drift angle and (b) total (reflected plus transmitted) polarization conversion coefficients for waves with initial polarization and cross-polarization for drift velocity $V_0 = 0.7V_F$ and frequency $\omega / 2\pi = 0.1$ THz. Graphene parameters are $\tau = 0.1$ ps and $\varepsilon_F = 500$ meV.

The transmitted wave can be almost totally cross-polarized at a certain drift angle, $P^T \approx 0.97$ for $\varphi \approx 30^o$ at frequency $\omega / 2\pi = 0.1$ THz in Fig 3.

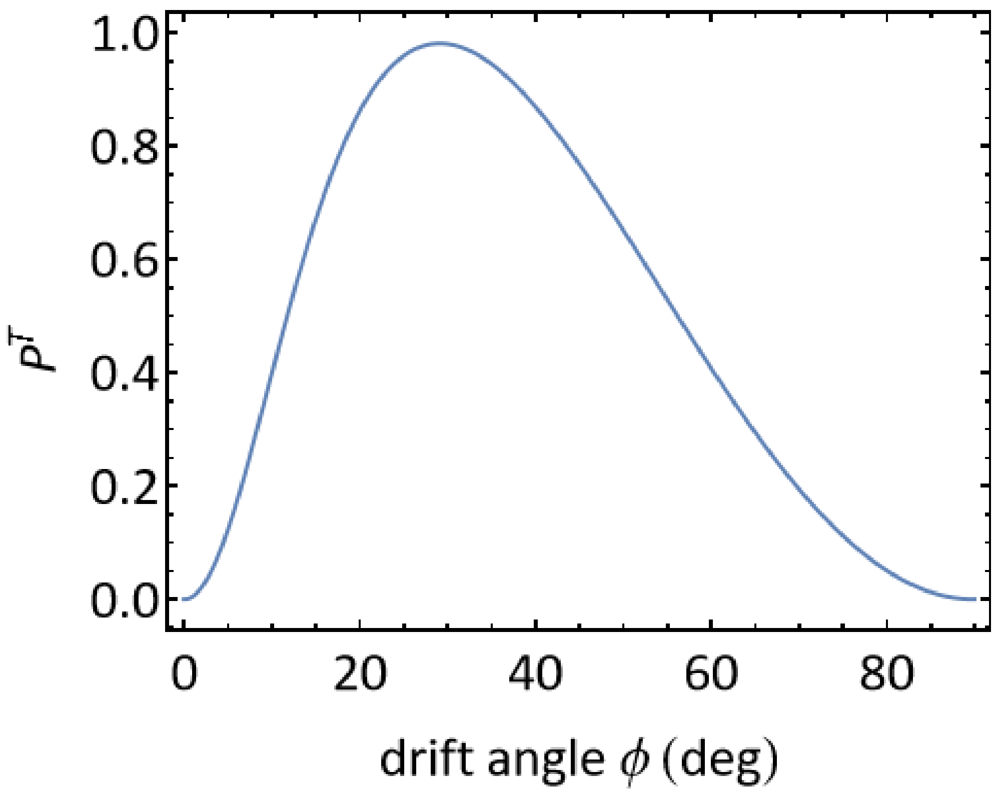

Fig. 3. The degree of polarization conversion P^T in dependence on drift angle for drift velocity $V_0 = 0.7V_F$ and frequency $\omega / 2\pi = 0.1$ THz. Graphene parameters are $\tau = 0.1$ ps and $\varepsilon_F = 500$ meV.

Conclusions.

The polarization conversion of a normally incident electromagnetic wave onto graphene with a DC current has been studied. It is shown that the dynamic conductivity of drift-biased graphene depends on the velocity and direction of electron drift even in the case of homogeneous oscillating electric field, which is not typical for classical two-dimensional electron systems with massive electrons. The tensor nature of graphene dynamic conductivity leads to the polarization conversion of electromagnetic wave incident upon graphene with the degree of polarization conversion up to 97% at the THz frequencies. The real part of each element of the dynamic conductivity of graphene with electron drift can be negative, which leads to amplification of THz wave.

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