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# Influence of DC current direction in graphene on dispersion and amplification of plasmons in graphene

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**Abstract.** We investigate dispersion and amplification of plasmon eigen modes in graphene with a direct electric current (DC-current) directed arbitrarily relative to the direction of plasmon propagation. Graphene is described by tensor conductivity obtained in the hydrodynamic approximation. We detected the possibility of amplification of plasmons in graphene in a certain range of DC current directions at terahertz frequencies. The most effective amplification is achieved when the drift of charge carriers and plasmons propagate co-directionally. This is due to the most effective interaction of DC current with the electric field of plasmons.

**Keywords:** hydrodynamic graphene, terahertz radiation, surface plasmon amplification

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# Влияние направления постоянного тока в графене на дисперсию и усиление графеновых плазмонов

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**Аннотация.** В настоящей работе исследована дисперсия и усиление собственных плазмонных мод в графене с постоянным током, направленным произвольно относительно направления распространения плазмонов. Графен описывается тензорной проводимостью, полученной в рамках гидродинамического приближения. Показана возможность усиления плазмонов в графене в некотором диапазоне направлений постоянного тока на терагерцевых частотах. Наиболее эффективное усиление достигается, когда дрейф носителей заряда и плазмоны распространяются сонаправленно. Это связано с наиболее эффективным взаимодействием постоянного тока с электрическим полем плазмонов.

**Ключевые слова:** гидродинамический графен, терагерцевое излучение, усиление поверхностных плазмонов

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## Introduction

Graphene-based structures are currently being actively investigated to amplify and detect terahertz (THz) radiation, in particular due to graphene plasmonic properties [1, 2]. The amplification of THz plasmons in graphene with direct electric current (DC) has been studied theoretically [3, 4], and also demonstrated experimentally [5]. The dispersion of plasmon modes in graphene with a DC co-directed (oppositely directed) with the wave vector of plasmon was investigated in [6], which also shows plasmon amplification at THz frequencies associated with the Cherenkov effect.

## Materials and Methods

In this paper, the dispersion and amplification of THz plasmons in graphene with a DC current arbitrary directed relative to the direction of plasmon propagation is investigated. The structure under study consists of a graphene layer located in the *xoz*-plane between two semi-infinite dielectrics with dielectric constants $\varepsilon_1$ and $\varepsilon_2$ (Fig. 1). Graphene is described by the conductivity obtained in tensor form in the hydrodynamic approximation. The use of the hydrodynamic approximation is justified in the case when the momentum scattering frequency in interparticle collisions prevails over the collision frequency of charge carriers with inhomogeneities of the graphene crystal lattice and the frequency of the acting field [7]. The hydrodynamic conductivity of graphene is obtained as a result of solving the hydrodynamic equations for the momentum and energy balance of charge carriers, as well as the continuity equation [7, 8]:

$$\frac{\partial N}{\partial t}+\frac{\partial (NV)}{\partial x}=0, \tag{1}$$

$$\frac{\partial S}{\partial t}+\nabla\hat{\Pi}+eEN+\frac{e}{c}J\times B=-S\gamma, \tag{2}$$

$$\frac{\partial W}{\partial t}+V_{\mathrm{F}}^{2}\nabla S+eEJ=0 \tag{3}$$

where $N$ is the number of particles, $J$ is the current density, $S$ is the macroscopic momentum, $W$ is macroscopic energy, $\Pi$ is the stress tensor, $e$ is the electron charge, $c$ is the speed of light, $E$ and $B$ electric and magnetic fields, respectively. Here $\gamma = 1/\tau$, $\tau$ is the momentum relaxation time of charge carriers in graphene. The relations between the quantities entering Eqs. (1)–(3) can be written as [7]:

$$S=MV,\ \hat{\Pi}=P+S\otimes V,\ P=M(V_{\mathrm{F}}^{2}-V^{2})/3,\ W=MV_{\mathrm{F}}^{2}-P, \tag{4}$$

where $M$ is the effective fluid mass density, $P$ is the carrier pressure, $V_F$ is the Fermi velocity in graphene. The energy relaxation time is much longer than the oscillation period and the energy conversion process is adiabatic, which causes zero on the right side of Eq. (3). Hydrodynamic Eqs. (1)–(3) are solved using the perturbation approach by decomposing every variable over degrees of the amplitude of the acting electric field and retaining only the linear terms of the perturbation series. Taking into account the DC current in graphene, leads to the tensor form of graphene conductivity:

$$\sigma=\begin{pmatrix}\sigma_{xx} & \sigma_{xz}\\ \sigma_{zx} & \sigma_{zz}\end{pmatrix}. \tag{5}$$

The expressions for the elements of the graphene conductivity tensor obtained using the analytical solution software package are too bulky, so they are not explicitly given in the article.

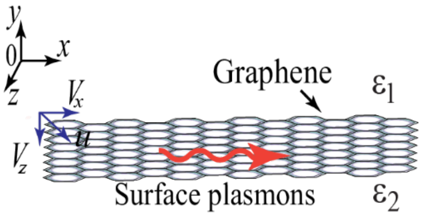

Fig. 1. Schematic view of structure

As a result of solving Maxwell's equations with electrodynamic boundary conditions, a dispersion equation was obtained for surface modes propagating along the ox-axis (the in-plane-of-graphene components of the wave vector is $k_z = 0$ and $k_x \neq 0$) in studied structure in the following form [8]:

$$\omega\varepsilon_0\left(\frac{\varepsilon_1}{k_{y1}}-\frac{\varepsilon_2}{k_{y2}}\right)+\sigma_{xx}+\frac{\sigma_{xz}\sigma_{zx}\mu_0\omega}{k_{y2}-k_{y1}-\sigma_{zz}\mu_0\omega}=0, \qquad (6)$$

where $k_{y1,2}=\pm\sqrt{\omega^2\varepsilon_{1,2}/c^2-k_x^2}$ are the out-of-plane-of-graphene components of the wavevectors in different media, ω is the angular frequency, $\varepsilon_1$ and $\varepsilon_2$ are the dielectric constants of the media above and below graphene, respectively, and $c$ is the speed of light, $\varepsilon_0$ and $\mu_0$ are the electric and magnetic constants, respectively. The signs of $k_{y1,2}$ are chosen from the condition of exponential decay of surface wave field away from the graphene layer.

## Results and Discussion

In the case of a directed DC current and a plasmon wave vector, the real part of graphene conductivity can be negative at THz frequencies, which leads to an amplification of plasmons in this frequency range due to the Cherenkov effect [6]. Let us consider how the dispersion and amplification of surface plasmons in graphene with a DC current will change depending on its direction. Fig. 2 shows the real part of the plasmon wave number as a function of frequency for different directions of charge carriers drift, while the value of the drift velocity remains constant $u = 0.5V_F$, where $V_F = 10^6$ m/s is the Fermi velocity in graphene. The charge carriers drift velocity along the ox-axis is defined as $V_{x0}=\sqrt{u^2-V_{z0}{}^2}$. With increasing of the deviation of the charge carriers drift direction from the direction of plasmon propagation, their localization increases at a fixed frequency (Fig. 2), which is associated with a decrease in the projection of the drift velocity of charge carriers on the *ox*-axis and a decrease influence of the Doppler shift on the dispersion of plasmons. Despite the increasing localization of plasmons, the efficiency of their amplification decreases (Fig. 3). This is due to a decrease of the interaction efficiency of drifting electrons with the tangential electric field of plasmons.

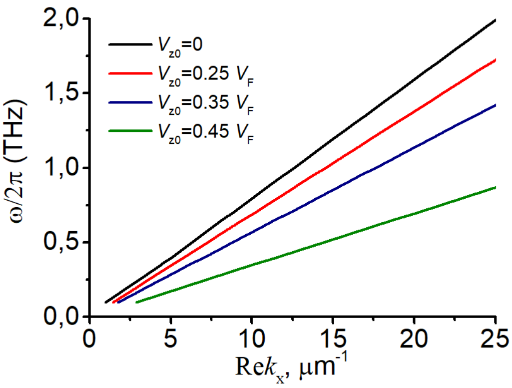

Fig. 2. Plasmon dispersion for different directions of charge carrier drift in graphene at the charge carrier drift velocity $u = 0.5V_F$. The direction of drift of charge carriers is determined from the expression $V_{x0}=\sqrt{u^2-V_{z0}{}^2}$. Graphene parameters: momentum relaxation time of the charge carrier is $\tau = 0.5$ ps, the Fermi energy is $\varepsilon_F = 200$ meV.

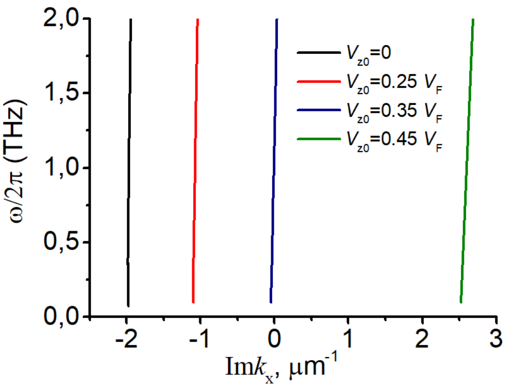

Fig. 3. Imaginary part of the plasmon wave number as a function of frequency for different directions of charge carrier drift in graphene at the charge carrier drift velocity $u = 0.5V_F$. Graphene parameters as in Fig. 2

## Conclusion

Thus, the dispersion and amplification of plasmon eigen mode in graphene with a DC current directed arbitrarily relative to the direction of plasmon wave wector is investigated. The possibility of amplification of plasmons in graphene in a certain range of DC current directions at THz frequencies is shown. The most effective amplification is achieved when the charge carrier drift and plasmons propagate co-directionally due to the most effective interaction of the terahertz wave field with the drifting charge carriers.

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