Graphene plasmonic terahertz detector with high responsivity

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Abstract. Rectification of terahertz radiation in a spatially periodic graphene structure with dual grating gate is theoretically studied. The calculated current responsivity is an order of magnitude greater than the responsivity of conventional plasmonic detector based on the field-effect-transistor array.

1. Introduction
Unique properties of graphene [1] such as high mobility and drift velocity of charge carriers allows for utilizing graphene plasmons for detecting terahertz (THz) radiation in graphene micro- and nanostructures [2]. Due to nonlinear properties of plasma waves in graphene [3] there are two different physical mechanisms of THz plasmonic rectification which are caused by the effects of differential plasmonic drag and electron-hole plasmonic ratchet [4].

2. Results and discussion
Let us consider a graphene monolayer screened by an interdigitated metal dual-grating gate (figure 1). Graphene is located on SiO₂ substrate and separated from the dual-grating gate (DGG) by Al₂O₃ barrier.

![Figure 1. Schematic view of the DGG graphene structure.](image)

Two sub-gratings of the DGG are laterally shifted in respect to each other in order to introduce asymmetry into the unit cell of the periodic DGG-graphene structure. Applying the constant voltage between DGG and graphene allows for controlling the equilibrium carrier density in gated areas of graphene. Type of carriers in gated areas of graphene depends on the gate voltage sign.
Nonlinear dynamics of the charge carriers in graphene is considered in the hydrodynamic approximation [5]. We solved the hydrodynamic equations in the perturbation approach [6] by expanding carrier velocity, Fermi energy and current density in powers of the electric field amplitude and keeping only linear and quadratic terms in this expansion. We used approximations of zero temperature and small carrier hydrodynamic velocity. Plasmon field induced by normally incident THz wave in graphene was calculated by using the self-consistent electromagnetic approach [7].

For the harmonic electric field $E(x,t) = E_0(x)\exp(-i\omega t)/2 + \text{c.c.,}$ with $\omega$ being the frequency of the incident wave, the total rectified DC current density in spatially periodic graphene can be written as [4]

$$j_0 = -\frac{|e|^2 v_F^2}{2\hbar^2 \pi \omega \gamma^2} \left( \text{sgn}(e) \text{Re} \left( \left( \omega - i \frac{\gamma}{2} \right) \frac{E_0}{\epsilon_x} \frac{\partial (E_0^*)}{\partial x} \right) \right),$$

where $|e|$ is the elemental charge ($e < 0$ for electrons and $e > 0$ for holes), $\gamma$ is the carrier relaxation rate, $v_F$ is the Fermi velocity of charge carriers in graphene, and angular brackets denote the space averaging.

We assume that, in the graphene regions under the metal strips of width $w_2$, there is a conductivity of one (for example, hole) type while the conductivity of another (electronic) type is in the rest of the unit cell. Such a spatial distribution of carriers in graphene is described by the distribution of the equilibrium Fermi energy $\epsilon_{F_1}^{(0)} = \epsilon_{F_2}^{(0)} = \epsilon_{E_{1}}^{(0)}$ and $\epsilon_{F_2}^{(0)} = \epsilon_{E_{2}}^{(0)}$. For a periodic structure with a given distribution of charge carriers, equation (1) transforms into the form $j_0 = j_0^d + j_0^\sigma$, where

$$j_0^d = \frac{|e|^2 v_F^2}{2\hbar^2 \pi \omega \gamma^2} \left( \text{sgn}(\epsilon_{F_1}) \left( 1 - \frac{w_2}{l} \right) + \text{sgn}(\epsilon_{F_2}) \frac{w_2}{l} \right) \sum_p q_p |E_{s,o,p}|^2,$$

$$j_0^\sigma = \frac{|e|^2 v_F^2}{2\hbar^2 \pi \omega \gamma^2} \frac{4}{\gamma l} \left( \text{sgn}(\epsilon_{F_2}) - \text{sgn}(\epsilon_{F_1}) \right) \text{Re} \left[ \left( \frac{i\omega + \frac{\gamma}{2}}{2} \right) \sum_p \sum_{p' \neq p} E_{s,o,p}^* E_{s,o,p'}^* \frac{p'}{p-p'} \sin \left( \pi \left( p-p' \right) \frac{w_2}{l} \right) \exp \left( i\pi \left( p-p' \right) \frac{s_1-s_2}{l} \right) \right],$$

where the expansion of the electric field in the Fourier space series $E_{s,o}(x) = \sum_p E_{s,o,p} \exp(iq_p x)$ is used, $q_p = 2\pi p/l$, and $p, p'$ are integer. Rectification of THz radiation in a periodic graphene structure can occur due to two different physical mechanisms [4]: the effect of differential plasmon drag of charge carriers in graphene described by equation (2) and the effect of the plasmon electron-hole ratchet described by equation (3).

The efficiency of rectification of THz radiation due to the effect of the nonlinear plasmonic effects is affected by both the geometric asymmetry of the graphene structure and by the interaction of the spatial harmonics of the electric field of different orders. Effective interaction of spatial harmonics of the electric field of different orders becomes stronger when “hybrid” plasmonic resonances are excited in the structure due to interaction of plasmon modes in different plasmon resonators in the unit cell of the graphene structure [7, 8]. In addition to the "radiative" plasmon modes in spatially symmetrical graphene structure, the "nonradiative" plasmon modes (having zero net dipole moment in spatially symmetrical structures) can be also excited [8] in a spatially asymmetric structure.

The current responsivity of THz rectification is calculated by the expression $R = j_0 / Pl$, where $P = 1$ W/cm$^2$ is the incident THz wave power density and $l = 1$ mm is the width of graphene structure (along the z-axis).
Plasmon rectification of THz radiation has been investigated for a graphene structure with a double grating gate (Figure 1) with parameters $w_1=1\,\mu m$, $w_2=0.25\,\mu m$ and $\gamma=0.2\cdot10^{-12}\,s^{-1}$ for the distribution of the Fermi energy $\varepsilon_{Fw_1}=\varepsilon_{Fw_2}=\varepsilon_{Fw_3}=-\varepsilon_{Fw_0}=39\,meV$. The widths of the gaps between the gate electrodes $s_1$ and $s_2$ vary, while their sum remains the same, $s_1+s_2=0.375\mu m$. The electric fields of plasmons excited by the incident THz wave and the absorbance of the graphene structure are calculated in the framework of a self-consistent electromagnetic approach based on the integral equation method [7]. The absorption spectra and current responsivities are calculated for different coefficients of the structure asymmetry $K=1-\frac{s_1}{s_2}$, $0<K<1$.

Figure 2 demonstrates the calculated absorption and current responsivities of DGG graphene structure with the Fermi energy distribution of charge carriers in graphene unit cell as. The resonant peaks correspond to the excitation of gated fundamental and second-order plasmon modes under wider gate electrodes. Each of these plasmon modes weakly interact with the other plasmon modes. In this case, the plasmon fields is almost symmetric [8], and therefore the plasmon rectification effect is determined mainly by the spatial geometric asymmetry of the graphene structure.

The effect of the asymmetry of the electric field on the plasmon rectification is seen in figure 3 for the third and fourth plasmon resonances at 2.4 THz and 2.7 THz. Resonances at these frequencies are the "nonradiative" plasmon mode (not excited in a symmetric structure with $K=0$) and the "radiative" plasmon mode at higher frequency. As the geometric asymmetry of the structure increases, the influence of the "nonradiative" plasmon mode increases (figure 3), which leads to the increase in the asymmetry of the electric field at the hybrid resonance and to a significant increase in the rectified current (figure 3(b)).

At the hybrid resonances in the frequency range 3.1-3.5 THz (figure 4), the maximum rectified current arises for the asymmetry coefficient 0.4 (figure 4(b)). The "nonradiative" mode (with a higher frequency) in the weakly asymmetric structure has a small dipole moment and therefore weakly interacts with the other modes and weakly excited by the incident THz wave (figure 4). As the asymmetry of the structure increases, the dipole moment of the "nonradiative" mode increases. As a result, this mode can be efficiently excited by the incident THz wave. In this case, the "nonradiative" mode becomes optically active and the effect of anti-crossing of the "radiative" and "nonradiative" plasmonic modes occurs (figure 4). For a strong asymmetry of the structure, the interaction of these modes decreases, as a result of which the asymmetry of the spatial distribution of the field decreases, which leads to decreasing rectified current (figure 4(b)). The greatest rectification effect is achieved in

![Figure 2](image1.png)
Figure 3 (a, b). Dependence of (a) the absorbance spectrum and (b) responsivity of the DGG graphene structure on the asymmetry coefficient $K$ for the third- and fourth-order plasmon resonances.

Figure 4 (a, b). Dependence of (a) the absorption spectrum and (b) responsivity of the DGG graphene structure on asymmetry coefficient $K$ for the fifth- and sixth-order plasmon resonances.

the case when the "radiative" and "nonradiative" modes effectively interact (figure 4), leading to the formation of a hybrid mode with a Fano-type resonance.

In conclusion, in this work we have investigated the asymmetry dependence of the current responsivity of plasmonic DGG graphene structure. It is shown that the responsivity of THz rectification of hybrid plasmon modes is an order of magnitude higher than for weakly interacting plasmonic modes. Due to high current responsivity, the DGG graphene structure can be used as an effective THz resonant detector.

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