Amplification of the propagating plasmon in a periodical structure with an active graphene

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Abstract. The amplification of the unidirectionally propagating plasmon modes excited by the incident terahertz wave in a periodical structure with an active graphene is studied theoretically. The effective excitation of propagating plasmon mode occurs due to the simultaneous excitation of “radiative” and “nonradiative” plasmon modes at the same frequency. The amplification of propagating plasmon modes is due to radiative recombination in inverted graphene.

1. Introduction

The plasmon properties in graphene structures are a fruitful sphere of investigations [1-3]. It has been suggested to use the plasmon properties of a periodical graphene structure to amplify [4], detect [5], and transform terahertz (THz) waves [6]. The excitation of the plasmon in graphene demands the coupling element, which balances the difference of momenta between incident THz electromagnetic wave and plasmon [7,8]. Such balance of momenta can be achieved using wide area grating couplers [9]. These grating couplers enable to excite two oppositely travelling plasmons in graphene, which form the standing plasma wave. The excitation of the propagating plasmon in graphene was observed during the scattering of incident THz electromagnetic wave on the different single couplers [10-13]. The effect of attenuated total reflection was proposed for the excitation of travelling plasmon in graphene [14].

One of the unique properties of graphene is a possibility for the population inversion of charge carriers [15]. The population inversion reveals itself as negative conductivity in monolayer [15] and bilayer graphene [16]. The population inversion in graphene was observed at sub picosecond time-scale, which might be utilized at amplification THz radiations. A terahertz light emission was observed from graphene field-effect transistor with the current-injection inverted graphene.

In this work we investigate the excitation and amplification of unidirectionally propagating plasmon in periodic graphene structure. We theoretically demonstrate that normally incident THz wave can excite the propagating plasmon modes in asymmetric dual grating gate graphene (DGGG) structure, and these modes can be amplified due to recombination processes in inverted graphene.

2. Theoretical model

The DGGG structure is shown in Figure 1. The homogeneous graphene layer is separated from the grating gate by a thin dielectric slab with thickness d. The graphene layer is screened by spatially
homogeneous metallic back gate. The thickness of dielectric slab between graphene and the back gate is \( h \). The THz electromagnetic wave with the electric field polarized across the grating gate fingers is normally incident from the top onto the metal gratting gate. The dual gratting gate consists of two periodical interdigitated sub gratings. Two subgratins of the DGGG are laterally shifted in respect to each other in order to introduce an asymmetry into the unit cell of the periodic DGGG structure.

Figure 1. Schematic view of the DGGG-structure

3. Results and discussion

We solve the problem of the excitation of plasmon modes in the DGGG structure within a self-consistent electromagnetic approach using the full system of the Maxwell equations (similar approach see in [17]). The THz response of graphene is described by the inverted complex dynamic THz conductivity [18]:

\[
\sigma(\omega) = \frac{e^2}{4\hbar} \left\{ \frac{8k_B T \tau}{\pi \hbar (1 - i\omega \tau)} \ln \left[ 1 + \exp \left( \frac{E_F}{k_B T} \right) \right] \right. \\
+ \left. \tanh \left( \frac{\hbar \omega - 2E_F}{4k_B T} \right) \frac{4\hbar \omega}{i\pi} \int_0^\infty \frac{G(E, E_F) - G(h\omega + 2, E_F)}{(h\omega)^2 - 4E^2} dE \right\},
\]

where \( e \) is the electron charge, \( \hbar \) is the reduced Planck constant, \( k_B \) is the Boltzmann constant, \( \tau \) and \( T \) are the momentum relaxation time and temperature of the carriers in graphene, respectively, \( E_F \) is the quasi-Fermi energy in graphene determining the inversion of charge carriers (+\( E_F \) and −\( E_F \) for electrons and holes, respectively), and \( G(\xi, \psi) = \sinh \left( \frac{\xi}{k_B T} \right) / \cosh \left( \frac{\xi}{k_B T} \right) + \cosh \left( \frac{\psi}{k_B T} \right) \).

The energy fluxes in the structure is described by the temporal-averaged Poynting vector \( S = 0.5 \Re \{ \mathbf{E} \mathbf{H}^* \} \), where \( \mathbf{E} \) is the total electric field and \( \mathbf{H} \) is the total magnetic field. We investigate the excitation of the plasmons in DGG graphene structure by the TM electromagnetic wave of the DGGG and, therefore, the energy flux has two components: incident flux of THz wave \( S_i = 0.5 \Re \{ E_z H_y \} \) and lateral plasmon flux \( S_x = -0.5 \Re \{ E_z H_y \} \). The lateral energy flux of the plasmon in the \( x \)-direction is given by averaged over the spatial period of the structure and integrated over \( z \)-coordinate the \( x \)-component of the Poynting vector

\[
S_x^P = \frac{1}{L} \int_{-\infty}^\infty S_x dxdz,
\]
where \( L \) is the spatial period of the structure. The Poynting flux of the plasmon in DGGG can be separated into two opposite fluxes as \( S^x = S^+ + S^- \), where \( S^+ \) is the Poynting flux in positive direction of \( x \)-axes (to the right at Figure 1), and \( S^- \) is the Poynting flux in negative direction of \( x \)-axes (to the left at Figure 1).

Similarly, we introduce the two coefficients of transformation of the incident wave into the left and right propagating plasmons as

\[
T_p^+ = \frac{S^+}{S_{inc}}
\]

\[
T_p^- = \frac{S^-}{S_{inc}}
\]

where \( S_{inc} = LS_{inc} \) and \( S_{inc} \) is the Poynting flux of THz wave incident onto one unit cell of the periodic DGG structure. The total transformation coefficient is \( T_p = T_p^+ + T_p^- \).

We made calculation for DGG structure with parameters: \( w_2 = 500 \, \text{nm}, S_1 = 250 \, \text{nm} \), \( S_2 = 80 \, \text{nm} \), \( d = 120 \, \text{nm}, h = 7.2 \, \mu\text{m}, E_F = 60 \, \text{meV}, \tau = 0.5 \, \text{ps} \), dielectric constant of the dielectric slabs is 7.5. At such parameters the dynamic conductivity of graphene has a negative real part at the THz frequencies greater than 2.8 THz. At these frequencies due to the radiative recombinations in graphene it can be possible to amplify THz radiation. Optimizing the DGG structure on every geometrical parameter in order to increase the transformation on incident THz wave unidirectionally propagating plasmon we find the regimes of significant amplifications of propagating plasmon in DGGG structure. In DGGG structure with the relatively far removed grating gate \((d \sim w_1, w_2)\) it is possible to excite the plasmon modes with wave vectors \( k_x = \frac{2\pi p}{L} \) \((p \) is a positive integers) quantized with length of DGGG structure period \( L \). Depending on filing factor \((w_1 + w_2)/L\) the frequencies of such plasmon modes lie between square root and linear dependence on wave vector. In the spatially asymmetrical structure it is possible to excite (in addition to ordinary “radiative” plasmons) the “nonradiative” plasmon modes. The excitation efficiency of “nonradiative” plasmons are rather low due to small net dipole moment of such modes. In order to increase the excitation efficiency of “nonradiative” modes it is possible to combine simultaneous excitation of “radiative” and “nonradiative” plasmon modes by tuning the different geometrical parameters of the DGGG structure (the point near frequency 4.45 THz with \( w_1 = 800 \, \text{nm} \) on Figure 2(a)).

**Figure 2(a, b).** (a) The dependence of the absorbance spectrum of DGGG structure on widths of gate finger \( w_1 \). The charge momentum relaxation in graphene is 0.5 ps for temperature 300K. (b) The dependence of the transformation coefficients \( T_p^+ \), \( T_p^- \) and \( T_p^+ \) of the incident wave into the travelling plasmon on the frequency with the width of the gate electrode \( w_1 = 800 \, \text{nm} \).
At such point the transformation coefficient $T_P^+$ prevails coefficient $T_P^-$ in order of values (Figure 2(b)), which means the excitation of the unidirectionally propagating plasmon. The transportation of the point of this combination of “radiative” and “nonradiative” plasmon modes into the frequency region with negative real-part conductivity leads to amplification of the unidirectionally propagating plasmon (Figure 2(b)).

4. Conclusions
We found out the conditions of the amplification of the unidirectionally propagating plasmon modes excited by the incident terahertz wave in a periodical structure with an active graphene. The effective excitation of propagating plasmon mode occurs due to the simultaneous excitation of “radiative” and “nonradiative” plasmon modes at the same frequency. Proposed periodical graphene structure can be used as a transformer of normally incident THz wave into propagating plasmon in graphene.

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