Plasmonic absorption of THz radiation in graphene structure with a metal grating

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Plasmonic absorption of THz radiation in graphene structure with a metal grating

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Abstract. The plasmonic absorption spectrum of THz radiation in the graphene with periodic metal grating is theoretically studied. It is shown that graphene exhibits strong plasmon absorption resonances at the frequencies of plasma oscillations in graphene for narrow-slit metal grating and a thin barrier layer.

1. Introduction

In recent years, studies of graphene, a two-dimensional graphite monolayer, have been of great interest on account of the unique electronic properties of this material following from the linear (Dirac) gapless energy spectrum of charge carriers [1]. Graphene possesses a strong plasmonic response at terahertz (THz) frequencies due to both a high density and low collective effective mass of free charge carriers [2, 3]. Using the plasma oscillations of charge carriers in graphene is attractive because it allows for concentrating the electromagnetic field near the graphene layer, which considerably enhances the efficiency of the interaction between THz radiation and graphene.

Nanoperiodic graphene-based plasmon structures are physically interesting objects. Since the wavelength of the plasma wave excited in such a structure is comparable with the structure period, this structure forms a planar plasmonic crystal. On the other hand, since the spatial period of the metal grating is shorter than the wavelength of the incident THz radiation by two or three orders of magnitude, this structure may be considered as a planar resonant THz metasurface strongly coupled with THz radiation. In this case, the entire structure can be characterized by the effective surface impedance that experiences resonances at the excitation frequencies of plasma waves in graphene [4]. This allows one to find the conditions for perfect matching of the structure with the incident THz radiation which ensures the most effective excitation of plasmons in graphene [5].

2. Theoretical model

In this paper, we consider the absorption of a THz wave by the resonant plasmons in a homogeneous graphene sheet located in x-z plane on the surface of a dielectric substrate (see figure 1). A one-dimensional planar metal grating is isolated from the graphene sheet by a thin dielectric barrier slab. Each ideally conducting strip of the planar metal grating is infinite in the z direction and has zero thickness in the y-direction. External THz wave is incident normally to the plane structure along y-direction with the polarization of the electric field E_0 across the metal grating contacts.

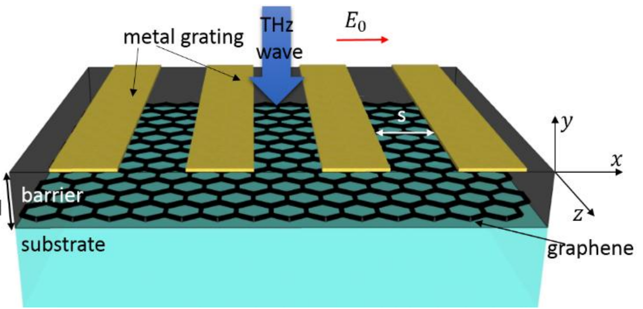

Figure 1. Schematic view of the graphene sheet with the metal grating and the coordinate system. The dielectric constant for the substrate and the barrier are the same, $\varepsilon_s = \varepsilon_b = 11.7$.

The optical problem of interaction between THz wave and the graphene structure with metal grating has been solved by using a self-consistent electromagnetic approach based on a plane wave decomposition of the full system of the Maxwell equations, similar to that described in [6].

The response of graphene is described by the complex dynamic surface conductivity [7]:

$$\frac{\sigma_{Gr}(\omega)}{\sigma_0} = \frac{8ik_BT}{\pi\hbar(\omega+\mathrm{i}\gamma)}\ln\left[2\cosh\left(\frac{E_F}{2k_BT}\right)\right] + G\left(\frac{\hbar\omega}{2}\right) + \frac{4i\hbar\omega}{\pi}\int_0^\infty \frac{G(\varsigma)-G(\hbar\omega/2)}{(\hbar\omega)^2-4\varsigma^2}d\varsigma, \qquad (1)$$

where

$$G(\varsigma) = \frac{\sinh(\varsigma/k_BT)}{\cosh(E_F/k_BT)+\cosh(\varsigma/k_BT)},$$

$\sigma_0 = e^2/4\hbar$, E_F is the Fermi energy, the temperature T is set to 300K, e is the electron charge, k_B is the Boltzmann constant, and $\hbar$ is the reduced Planck constant. The first term describes a Drude-like response due to the intraband processes involving the phenomenological intraband electron scattering rate γ. The rest terms describe the interband transitions in graphene. The real part of the conductivity equation (1), which is responsible for energy dissipation and takes into account both (intraband and interband) scattering mechanisms, is presented in figure 2 (a). The main contribution to the conductivity originates from the Drude losses, which increases with increasing the Fermi energy and decreases with increasing the frequency (as seen in figure 2 (a)). Losses due to the interband transitions contribute to the conductivity only for small values of the Fermi energy (figure 2 (b)).

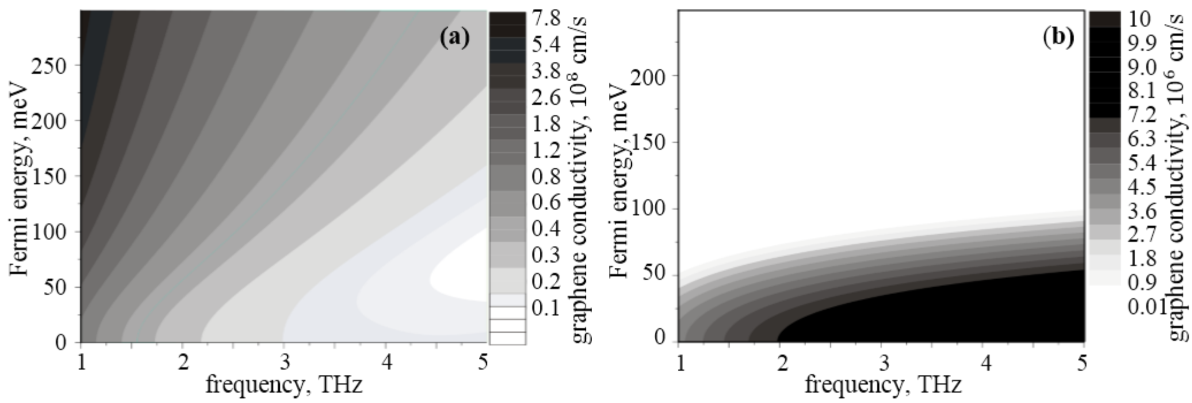

Figure 2 (a, b). (a) the real part of graphene conductivity as a function of the frequency and Fermi energy for $\gamma = 10^{12}\ \mathrm{s}^{-1}$ and $T = 300$ K; **(b)** the real part of graphene conductivity for $\gamma = 0$.

3. Results and discussion

Figure 3 shows the absorption spectrum calculated for realistic parameters of the graphene structure as a function of the Fermi energy and frequency at room temperature. As can be seen in figure 3, graphene exhibits strong plasmon response at the frequencies of the fundamental and higher plasmon resonances in graphene.

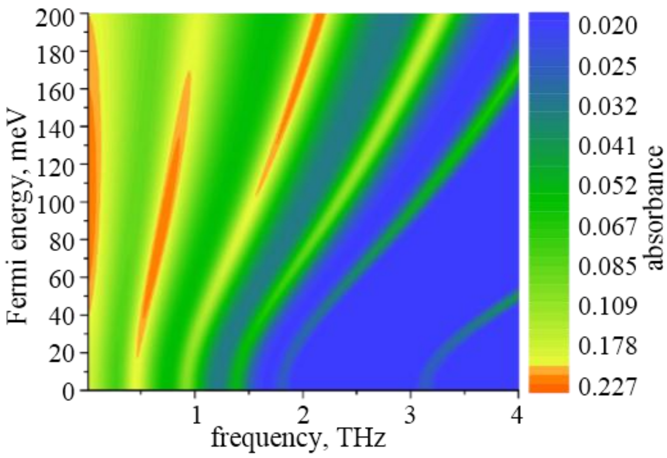

Figure 3. Absorption spectrum of the graphene structure with metal grating with period 2 μm and metal strip width 1.5 μm, and the barrier layer is 20 nm thick. The phenomenological intraband electron scattering rate is $\gamma = 10^{12}\,\mathrm{s}^{-1}$. for temperature 300K. The red colour shows the area in which the absorption is maximal.

We define the absorption coefficient as

$$A = P_{\mathrm{abs}} / P_{\mathrm{in}},$$

where

$$P_{\mathrm{abs}} = \frac{1}{2L}\mathrm{Re}\left[\sigma_{\mathrm{Gr}}(\omega)\right]\int_{-L/2}^{L/2}\left|E_x(x,0)\right|^2 dx,$$

is the absorbed power of the THz wave per unit area of the graphene structure and P_{in} is the power density of the incident THz wave. The maximal possible absorption is given as [8]

$$A^{\max} = 0.5\left(1-\sqrt{R_0}\right), \text{ where } R_0 = \left(\sqrt{\varepsilon_s}-1\right)^2\left(\sqrt{\varepsilon_s}+1\right)^{-2}$$

is the reflectance of the structure without metal grating and graphene. In our case $A^{\max} = 0.227$ (for the substrate dielectric constant $\varepsilon_S = 11.7$ and dielectric constant of the ambient medium equals 1) which is consistent with the calculated results (red color lobe in Figure 3).

The total width of the absorption line is composed of the Drude dissipative damping (intraband processes involving the phenomenological intraband electron scattering rate γ), damping due to interband transition, and radiative damping. The radiative damping increases proportionally to the concentration of the charge carriers [8], which is defined by the value of the Fermi energy in graphene. On the other hand, the Drude dissipative damping of the plasmons is $\gamma/2$ and does not depend on the concentration of charge carriers in graphene [10]. The absorption of THz radiation in the structure becomes maximal when the sum of the Drude dissipative and interband transition damping is equal to radiative damping.

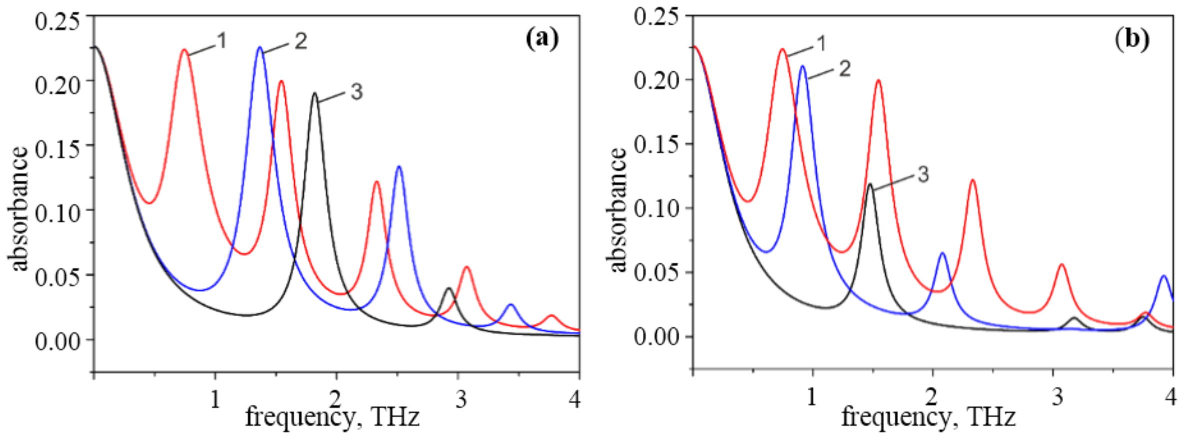

Figure 4 (a, b). (a) Absorption spectrum for different widths of the gaps between the metal strips of the metal grating: 1 – 0.5 μm; 2 – 1 μm; 3 – 1.5 μm. The metal grating period is 2 μm, Fermi energy is 100 meV, and the thickness of the barrier layer is 20 nm. **(b)** Absorption spectrum for different barrier thicknesses: 1 – 20 nm; 2 – 80 nm; 3 – 200 nm. The Fermi energy is 100 meV, the metal grating period is 2 μm, and the metal strip width is 1.5 μm.

As can be seen in figure 4, graphene exhibits strong plasmon response for a narrow-slit metal grating and small thickness of the barrier layer. Reducing the thickness of the barrier layer or the width of the gaps between the metal strips result in increased screening of graphene. Since the screening lowers the frequency of plasmons [9], plasmon resonances of the same orders are excited at lower frequencies (for the same values of the Fermi energy in graphene).

Because the positions of the plasmon absorption resonances can be tuned electrically by applying the electrostatic potential to the metal grating strips, the results of this paper can be used for creating tunable THz resonant absorbers.

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