Double frequency plasmonic amplification of terahertz radiation in a periodical double-layer graphene

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Abstract. The plasmon amplification spectrum of terahertz radiation in a double-layer graphene nanoribbon array is theoretically studied. It is shown that this graphene structure exhibits strong plasmon response and giant amplification at vicinity of the anticrossing regime between optical and acoustic plasmon modes at room temperature.

1. Introduction

Graphene, a two-dimensional monolayer of graphite, has received a great deal of interest recently due to its unique electronic properties stemming from a linear (Dirac-type) gapless carrier energy spectrum. Graphene is also remarkable for high free-carrier mobility (temperature independent carrier mobility about 250000 cm²/V·s was observed in multilayer epitaxial graphene on 4H-SiC substrate [1, 2]). Such carrier mobility corresponds to 1 ps carrier scattering times for the quasi-Fermi energy about 40 meV at room temperature and concentration of nonequilibrium electrons (holes) about \(1.2\times10^{11}\) cm\(^{-1}\). Carrier scattering times longer than 1 ps were observed recently in optically pumped graphene [3, 4].

Graphene exhibits strong plasmonic response at terahertz (THz) frequencies due to both high density and small “relativistic” effective mass of the charge carriers [5, 6]. Stimulated emission of near-infrared and THz photons from population inverted graphene was recently observed [7]. As compared with the stimulated emission of the electromagnetic modes (photons), the stimulated emission of plasmons by the interband transitions in the population inverted graphene exhibits a much higher gain due to a small group velocity of the plasmons in graphene and strong confinement of the plasmon field in the vicinity the graphene layer [8].

Double-layer graphene structure consists of two parallel graphene layers with a narrow dielectric barrier slab between them. The electromagnetic fields of plasmons propagating in these layers interact with each other giving rise to a single unified plasmon in the pair of parallel graphene monolayers surrounded by dielectric claddings [9]. Double-layer graphene structure is actively studied due to their fundamental importance and practical applications.

2. Theoretical model

In this paper, we consider the amplification of a THz wave by the stimulated generation of resonant plasmons in a patterned double-layer population inverted graphene structure. Consider two graphene microribbon arrays separated by a thin dielectric barrier slab and placed on the semi-infinite dielectric substrate (see inset on figure 1). External THz wave is incident normally to the plane of the structure along y-direction with the polarization of the electric field \(E_x^{(0)}\) across the graphene strips. The optical
problem of interaction between THz wave and the double-layer graphene structure has been solved by using a self-consistent electromagnetic approach and integral equations method. The system of two coupled integral equations for the surface current density \( j_x^{(w)}(x,y) \) on the graphene micro ribbon in both planes (at \( y=d \) and \( y=0 \)) are

\[
\int_0^w j_x^{(w)}(x',d) G_m^{(1)}(x,x',d) \, dx' \pm \int_{-w}^0 j_x^{(w)}(x',0) G_m^{(2)}(x,x',0) \, dx' \equiv \sigma_{w,d} Z_{m}^{(1)} E_x^{(0)} \delta_{m0},
\]

\[
\int_0^w j_x^{(w)}(x',d) G_m^{(1)}(x,x',0) \, dx' \pm \int_{-w}^0 j_x^{(w)}(x',0) G_m^{(2)}(x,x',0) \, dx' \equiv \sigma_{w,0} Z_{m}^{(2)} E_x^{(0)} \delta_{m0},
\]

where \( G_m^{(1)}(x,x',d) = \sigma_{w,d} \frac{1}{L} \sum_m Z_{m,d} \exp(iq_m(x-x')) \), \( G_m^{(2)}(x,x',0) = \sigma_{w,0} \frac{1}{L} \sum_m Z_{m,0} \exp(iq_m(x-x')) \) are the kernels of the integral equations, \( Z_{m,d}, Z_{m,0} \) are the explicit algebraic coefficients, calculated from the Maxwell equations. The response of optically pumped graphene is described by the complex dynamic surface conductivity \( \sigma_{w,d(0)} \) [8]. The system of Fredholm integral equations of the second kind (1) was solved numerically by the Galerkin method. In the results, the induced electric and magnetic fields at the any point of the structure can be found.

Because the period of the structure is much shorter than the electromagnetic wavelength, only zero-order spatial Fourier harmonics are the travelling waves emitted into the ambient medium and substrate while all higher-order Fourier harmonics are evanescent fields decaying for \( y \to \pm \infty \). Therefore, the reflection and transmission coefficients in the far-field zone can be calculated as \( R = \left| E_{\text{ref}}(d) \right|^2 / \left| E_x^{(0)} \right|^2 \) and \( T = \left| E_{\text{tr}}(0) \right|^2 / \left| E_x^{(0)} \right|^2 \), respectively, where \( E_{\text{ref}}(d) \) and \( E_{\text{tr}}(0) \) are the zero-order spatial Fourier harmonics of the x-component of the induced electric field in graphene planes \( y=0 \) and \( y=d \). The absorption/amplification coefficient is calculated as \( A = 1 - R - T \) ( \( A > 0 \) in the absorption regime and \( A < 0 \) in the amplification regime).

3. Results and discussion

Figure 1(a) shows the calculated spectrum of the plasmon resonances as a function of the dielectric barrier layer thickness values and frequency at room temperature. Calculations were performed for a small value of the quasi-Fermi energy equal to 20 meV.

![Figure 1(a, b, c)](image)

Figure 1(a, b, c). (a) Amplification spectrum of the considered double-layer graphene structure with period \( L=500 \text{ nm} \), strip width \( w=0.25 \text{ nm} \), quasi-Fermi energy 20 meV, dielectric constant of the
substrate and barrier layer 11.7. The electron scattering time in graphene is 1 ps for temperature 300K. Schematic view of the double-layer graphene nanoribbon array and the coordinate system is shown in the inset at the top right. (b) Amplification coefficient of the considered graphene structure with \( d=40 \) nm. (c) Amplification coefficient of the considered graphene structure with \( d=25 \) nm. The insert in (c) shows the fragment for the lower values of the ordinate-axis.

However, such a low pumping is sufficient for the interband transitions in graphene prevail over Drude losses. Consequently a real part of graphene conductivity becomes negative \( \Re(\sigma_{\omega,d(0)}) < 0 \), that corresponds to the energy gain (negative absorbance) in graphene. Solid black line on Figure 1(a) corresponds to transparent inverted graphene \( \Re(\sigma_{\omega,d(0)}) = 0 \), and the real part of the inverted graphene conductivity is positive (negative) to the left (right) of this line.

The system under consideration supports the optical and acoustic plasmon modes. The figure 1(a) shows (from left to right) the fundamental acoustic, fundamental optical and first higher acoustic modes. The resonant frequencies of the optical and acoustic modes vary in the opposite way with the change of the thickness of the insulating dielectric layer \( d \), which makes possible the anticrossing regime. The maximum amplification is achieved in the vicinity of the anticrossing regime (figure 1(c)) due to interaction of the optical and acoustic plasmon modes.

4. Conclusions
It is shown that THz amplification has a broad dynamic range and a wide range of dielectric barrier layer thickness values. Largest amplifications are achieved at lower dielectric barrier layer thickness values at the two resonant frequencies in the vicinity of the anticrossing regime, even for small quasi-Fermi energy 20 meV at room temperature.

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