Gain of terahertz plasmons in a double-layer graphene

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Abstract. Amplification of terahertz plasmons in a pair of parallel active graphene monolayers is studied theoretically. It is shown that symmetric mode increment of plasmons in the double-layer graphene may be greater than that in a single graphene layer by approximately two times of magnitude.

1. Introduction
Graphene, being natural two-dimensional material with zero band-gap [1], appears as a perfect platform for terahertz (THz) radiation amplification [2]. Justification of possibility of possessing negative conductivity of graphene at THz frequencies [3] along with the possibility of excitation of highly confined graphene plasmons [4] resulted in proposals of THz graphene lasers [5] and plasmonic amplifiers [6–8]. Double-layer graphene structure consists of two parallel graphene monolayers with a narrow dielectric gap (barrier layer) between them. 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]. In this paper, we study the amplification of THz plasmons in the double-layer graphene.

![Figure 1. Schematic view of the structure under consideration.](image)

2. Theoretical model
The structure under consideration is schematically shown in Fig. 1. We consider a symmetric structure with two coupled graphene layers with identical inverted population of free charge carriers in each graphene layer which are separated by a dielectric gap (barrier layer) of thickness d and covered by dielectric claddings. Dielectric permittivity of surrounding materials, εe, are equal for the top and bottom claddings while the value of dielectric permittivity of the barrier layer, εb, differs from εe.
Representing the spatio-temporal dependence of the plasmon fields in the form
\[ \propto \exp(-\imath \omega t + k_x x + k_y y) \]
in claddings (minus and plus sign stands for the top and bottom cladding, respectively) and
\[ \propto \exp(-\imath \omega t + k_x x) \left[ A_{b\alpha} \exp(k_y y) + A_{c\alpha} \exp(-k_y y) \right] \]
\((A_{b\alpha} \text{ and } A_{c\alpha} \text{ are the amplitudes of electric or magnetic fields of the forward and the counter waves})\) in the barrier layer, we write the dispersion relation as [9]
\[ \tanh(k_{yb} d) = -\frac{2\Psi}{1+\Psi^2} \]
(1)
with
\[ \Psi = \frac{k_{yb}}{\varepsilon_b} \left[ \frac{\varepsilon}{k_{yc}} + i \frac{\sigma(\omega)}{\varepsilon_\omega \omega} \right], \quad k_{ij} = \sqrt{k_i^2 - \varepsilon_j \omega^2/c^2}, \]
(2)
where \( j = b, c \) stands for the barrier layer and claddings, respectively, \( k_x \) and \( \omega \) are the wavevector and frequency of the plasmon, \( \varepsilon_b \) is the electric constant, \( \sigma(\omega) \) is the dynamic graphene conductivity [6]. In a symmetric structure the dispersion equation (1) splits into two branches:
\[ \tanh(k_{yb} d/2) = -1/\Psi \]
(3)
corresponding to the symmetric mode and
\[ \tanh(k_{yb} d/2) = -\Psi, \]
(4)
defining the antisymmetric mode. These modes are termed according to the tangential to graphene component of the plasmon electric field distribution across the symmetry plane of the structure under consideration, which is symmetric for symmetric mode and antisymmetric for the other one.

3. Results and discussion
In Fig. 2, one can see the symmetric mode increment (gain) of plasmons defined as \( \alpha = -2\text{Im}k_x \) as a function of the barrier layer thickness \( d \). With decreasing the barrier layer thickness \( d \), the plasmon wavelength monotonically increases (see curve 2 in Fig. 2) leading to increasing the localization length \( L_{loc} = 1/\text{Re}k_x = \lambda/2\pi \) of plasmon electric field. The dependence of symmetric mode increment on barrier layer thickness \( d \) has an extremum (see curve 1 in Fig. 2). Let us define the physical reasons of such behaviour. The power density, released from graphene layers
\[ P = -\text{Re} \sigma |E_{ygr}|^2, \]
where \( E_{ygr} \) is the tangential to graphene component of the plasmon electric field in graphene layers and plasmon energy flux in the \( x \) direction \( W = 1/2 \int_{-\infty}^{\infty} \text{Re} \left( E_y \cdot H_x \right) dy \) obey to a simple relationship representing the energy conservation law: spatial variation of energy flux \( W \) is defined by the value of power density released from graphene layers, \( P \), i.e. \( dW/dx = P \). Taking into account that \( P \) and \( W \) are proportional to \( \exp(-2\text{Im}k_x) \), the symmetric mode gain \( \alpha \) could be rewritten as \( \alpha = -2\text{Im}k_x = P/W \). In other words optical mode gain is power density, released from graphene layers at fixed plasmon energy flux \( W = 1 \text{W/m} \).

With decreasing the barrier layer thickness \( d \), the power density \( P \) initially increases due to constructive interference of the plasmon fields in both graphene monolayers. At large separation between graphene layers the plasmon energy flux \( W \) (that we assume to be fixed) is mainly concentrated in the barrier layer because the dielectric permittivity value of barrier layer is bigger than that of the claddings (see curve 1 in Fig. 3). At small barrier layer thicknesses the plasmon energy flux \( W \) is mainly concentrated in claddings (see curve 2 in Fig. 3). Thus, the decreasing of \( P \) is caused by
weaker localization of the plasmon electric field in the vicinity of graphene layers at small barrier layer thicknesses due to concentration of the plasmon energy flux in the claddings with small value of the dielectric permittivity.

In conclusion, we have studied the gain of the symmetric plasmon mode in the double-layer graphene heterostructure. It is shown that symmetric mode increment of plasmons in the double-layer graphene may be greater than that in a single graphene layer by approximately two times of magnitude. Amplified plasmons can be used in low-loss interconnects and active elements in the THz plasmonic graphene nanocircuits.

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Figure 2. The symmetric mode increment of plasmons (curve 1) and plasmon wavelength (curve 2) versus barrier layer thickness.

Figure 3. The plasmon energy flux $W$ in the barrier layer (curve 1) and in claddings (curve 2) versus barrier layer thickness $d$.

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