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Reflection through a parallel-plate waveguide formed by two graphene sheets

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ABSTRACT

Reflection through a dielectric slab located between two graphene sheets is considered. The proposed parallel-plate waveguide is assumed to be symmetric with the substrate and cladding layers are air. The two graphene sheets are considered to be identical and having frequency-dependent surface conductivity σ(ω). The reflection through the proposed structure is investigated with the angle of incidence and the frequency of incident electromagnetic waves.

1. Introduction

Graphene is one-atom-thick two-dimensional material that is expected to play a significant role in the fabrication of recent opto-electronic devices. It is considered as the two-dimensional version of graphite. The carbon atoms in graphene are bonded to each other by covalent bonds in hexagonal structure. Graphene has gained considerable interest by physicist, chemists, and engineers due to many interesting features. It is stable and rigid. It can show ballistic transport over at least several hundred nanometers. Intrinsic graphene is a zero bandgap semiconductor. It's conductivity can be altered by many techniques. Electrostatic or magnetostatic gating and chemical doping can be used to alter its conductivity and transport properties.

Many interesting papers have been published recently to investigate the properties of slab waveguide structures comprising graphene sheets. Hajian et al. [1] presented the dispersion relations of transverse magnetic (TM) surface plasmons supported by a graphene parallel plate waveguide surrounded by self-focusing nonlinear claddings. They found many interesting features such as the decrease of surface plasmons localization length. Parallel-plate waveguide formed by two graphene sheets was shown to guide quasi-transverse electromagnetic modes with attenuation similar to structures composed of metals [2]. In 2013, it was shown that when both electric and magnetic biases are applied to a parallel-plate waveguide formed by two graphene sheets, a hybrid mode can be generated [3]. The electric and magnetic biases have a significant role in adjusting the intensity of the propagating modes. Moreover, it was shown that the confinement of the wave in the waveguide structure can be enhanced by decreasing the graphene plate separation. The propagation of surface waves along a spatially dispersive graphene sheet was investigated [4]. The analysis was based on the admittances of an equivalent circuit of graphene. C. Xu et al. presented a new electro-refractive Mach- Zehnder interferometer based on graphene-oxide-silicon waveguide structure using graphene as the active medium [5]. The optical properties of graphene were analyzed [6]. Reflectance and transmittance of graphene in the visible region were studied as a function of frequency and temperature. The interaction of electromagnetic waves with single graphene layer was investigated [7]. Moreover, the reflection and transmission from a multilayer of parallel graphene sheets was also studied [7].

In this work, reflection through symmetric waveguide with dielectric core layer and air as a cladding and substrate is considered. The dielectric core layer is assumed to sandwiched between two graphene layers. The graphene sheets have frequency-dependent surface conductivity. The reflection through the proposed structure is studied with the frequency and the incident angle.

2. Theory of reflection

Consider a structure consisting of two media with parameters (ε_1, μ_1) and (ε_2, μ_2) are separated by a graphene layer located

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at z = 0. The incident, reflected and transmitted wave vectors are given by, $\boldsymbol{k_{inc}} = -\hat{z}k_{1z} + \hat{x}k_x$, $\boldsymbol{k_r} = \hat{z}k_{1z} + \hat{x}k_x$, and $\boldsymbol{k_t} = -\hat{z}k_{2z} + \hat{x}k_x$. The magnitudes of $\boldsymbol{k_{inc}}$, $\boldsymbol{k_r}$ and $\boldsymbol{k_t}$ are given by $k_{inc} = k_r = k_1$ and $k_t = k_2$. For s-polarized light, the incident, reflected, and transmitted electric fields are given by

$$\boldsymbol{E_{inc}} = \hat{y}Ae^{-ik_{1z}z}e^{ik_x x} \quad (1)$$

$$\boldsymbol{E_r} = \hat{y}AR_{12}e^{ik_{1z}z}e^{ik_x x} \quad (2)$$

$$\boldsymbol{E_t} = \hat{y}AT_{12}e^{-ik_{2z}z}e^{ik_x x} \quad (3)$$

where A is the amplitude of the electric field.

The tangential component of the magnetic field can be obtained using

$$\boldsymbol{H_z} = \hat{z}\frac{i}{\omega\mu}\frac{dE_y}{dz} \quad (4)$$

$$\boldsymbol{H_{inc}} = \hat{z}\frac{k_{1z}}{\omega\mu_1}Ae^{-ik_{1z}z}e^{ik_x x} \quad (5)$$

$$\boldsymbol{H_r} = -\hat{z}\frac{k_{1z}}{\omega\mu_1}AR_{12}e^{ik_{1z}z}e^{ik_x x} \quad (6)$$

$$\boldsymbol{H_t} = \hat{z}\frac{k_{2z}}{\omega\mu_2}AT_{12}e^{-ik_{2z}z}e^{ik_x x} \quad (7)$$

Applying the boundary conditions at $z = 0$, we get

$$1 + R_{12} = T_{12} \quad (8)$$

The tangential component of the magnetic field is discontinuous due to the presence of graphene layer. The discontinuity in $\boldsymbol{H}$ is given by the surface current J_s. The surface current is related to the electric field through Ohm's law $J_s = \sigma E_y$, then

$$H_1 - H_2 = J_s = \sigma E_y(z = 0) \quad (9)$$

where σ is the conductivity of the graphene.

Applying the discontinuity of H and multiplying by $\omega\mu_1/k_{1z}$, we get

$$1 - R_{12} = (\frac{\mu_1 k_{2z}}{\mu_2 k_{1z}} + \frac{\sigma\omega\mu_1}{k_{1z}})T_{12} \quad (10)$$

Substituting for T_{12} from Eq. (8) in Eq. (10)

$$1 - R_{12} = (\frac{\mu_1 k_{2z}}{\mu_2 k_{1z}} + \frac{\sigma\omega\mu_1}{k_{1z}})(1 + R_{12}) \quad (11)$$

Let $A_{12} = \frac{\mu_1 k_{2z}}{\mu_2 k_{1z}}$, Eq. (11) becomes

$$1 - R_{12} = A_{12} + \frac{\sigma\omega\mu_1}{k_{1z}} + A_{12}R_{12} + \frac{\sigma\omega\mu_1}{k_{1z}}R_{12} \quad (12)$$

$$R_{12}(1 + A_{12} + \frac{\sigma\omega\mu_1}{k_{1z}}) = 1 - A_{12} - \frac{\sigma\omega\mu_1}{k_{1z}} \quad (13)$$

$$R_{12} = \frac{1 - A_{12} - \frac{\sigma\omega\mu_1}{k_{1z}}}{1 + A_{12} + \frac{\sigma\omega\mu_1}{k_{1z}}} \quad (14)$$

Substituting from Eq. (14) into Eq. (8), we get

$$1 + \frac{1 - A_{12} - \frac{\sigma\omega\mu_1}{k_{1z}}}{1 + A_{12} + \frac{\sigma\omega\mu_1}{k_{1z}}} = T_{12} \quad (15)$$

$$T_{12} = \frac{2}{1 + A_{12} + \frac{\sigma\omega\mu_1}{k_{1z}}} \quad (16)$$

Consider three-layer waveguide with parameters (ε_1, μ_1), (ε_2, μ_2) and (ε_3, μ_3) with two graphene layers at z = 0 and z = d as shown in Fig. 1. The core layer and the two graphene sheets form a parallel plate capacitor. The electric field for TE case becomes

$$\boldsymbol{E_1} = \hat{y}Ce^{ik_{1z}z}e^{ik_x x} \quad (17)$$

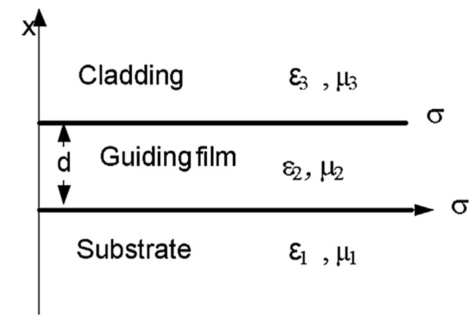

Fig. 1. A parallel-plate waveguide formed by two graphene sheets.

$$\boldsymbol{E_2} = \hat{y}[B_1e^{-ik_{2z}z} + B_2e^{-ik_{2z}z}]e^{ik_x x} \quad (18)$$

$$\boldsymbol{E_3} = \hat{y}De^{-ik_{3z}z}e^{ik_x x} \quad (19)$$

In a similar manner to the two-layer structure, one can write

$$R_{12} = \frac{1 - A_{12} - \frac{\sigma\omega\mu_1}{k_{1z}}}{1 + A_{12} + \frac{\sigma\omega\mu_1}{k_{1z}}} \quad (20)$$

$$R_{23} = \frac{1 - A_{23} - \frac{\sigma\omega\mu_2}{k_{2z}}}{1 + A_{23} + \frac{\sigma\omega\mu_2}{k_{2z}}} \quad (21)$$

Then the reflectance from the parallel plate waveguide is given by

$$R = \frac{R_{12} + R_{23}e^{2ik_{2z}d}}{1 + R_{12}R_{23}e^{2ik_{2z}d}} \quad (22)$$

In this paper, we consider only s-polarization (TE) because p-polarization (TM) is exactly the same with μ_j is replaced by ε_j of layer j.

It is worth mentioning that the graphene conductivity has many forms depending on the frequency range considered, doping, temperature and chemical potential. The low energy conductivity of graphene consists of two parts: intraband and interband contributions. In macroscopic volume, the thickness of the ultrathin graphene layers can be regarded as infinitesimally thin. The conductivity of graphene can be derived from Kubo formula. Ignoring the impact of magnetic field (without Hall conductivity), the Kubo formula is given by

$$\sigma(\omega, \mu_c, \Gamma, T) = -\frac{ie^2(\omega + i2\Gamma)}{\pi\hbar^2} \times [\frac{1}{(\omega + i2\Gamma)^2} \int_0^\infty E(\frac{\partial f(E)}{\partial E} - \frac{\partial f(-E)}{\partial E})dE - \int_0^\infty \frac{f(-E) - f(E)}{(\omega + i2\Gamma)^2 - 4(E/\hbar)^2}dE], \quad (23)$$

where μ_c is the chemical potential, Γ is the phenomenological scattering rate which is independent of energy E, and T is temperature.

We have $f(E) = \{1 + exp[(E - \mu_c)/k_BT]\}^{-1}$ is the Fermi distribution function, and $2\Gamma = \tau^{-1}$ with $\tau \approx \mu_m\mu/e\upsilon_F^2$ the electron relaxation time in graphene where μ_m is the carrier mobility and $\upsilon_F \approx 10^6$ m/s is the Fermi velocity. k_B is Botlzman constant. The first term and second term in Eq. (23) correspond to the intraband electron-phonon scattering process and interband electron transition respectively, i.e., $\sigma = \sigma_{intra} + \sigma_{inter}$.

It was found that the intraband contribution dominates in the THz and far-infrared region, while in near-infrared and visible region, the interband contribution is more dominant. In our calculations, we ignore losses and consider $\hbar\omega < 1.67\,\mu_c$ (Im σ > 0), also taking the conductivity for highly doped or gated graphene