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Electromagnetic waves reflection, transmission and absorption by graphene–magnetic semiconductor–graphene sandwich-structure in magnetic field: Faraday geometry☆

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Abstract

Electrodynamic properties of the graphene–magnetic semiconductor–graphene sandwich-structure have been investigated theoretically with taking into account the dissipation processes. Influence of graphene layers on electromagnetic waves propagation in graphene–semi-infinte magnetic semiconductor and graphene–magnetic semiconductor–graphene sandwich-structure has been analyzed. Frequency and field dependences of the reflectance, transmittance and absorbtance of electromagnetic waves by such structure have been calculated. The size effects associated with the thickness of the structure have been analyzed. The possibility of efficient control of electrodynamic properties of graphene–magnetic semiconductor–graphene sandwich-structure by an external magnetic field has been shown.

Keywords: Graphene; Magnetic semiconductor; Nanostructures; Absorptance; Microwaves; THz

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1. Introduction

Nowadays graphene (two dimensional lattice of carbon atoms) attracts researchers' attention with their special properties [1–4], including electrodynamical ones. So, for example, exciting of the surface plasmons in the graphene layers has been investigated theoretically [5–11] and experimentally [12,13]. These studies showed that both TE- and TM- polarized plasmons can exist in graphene. What is more, it is possible to control their dispersion characteristics by applying a voltage. Recently, the possibility of control of the hybrid surface waves in graphene placed between two dielectrics by applying an external magnetic field [14] and the waveguide properties of the sandwich-structure graphene-dielectric-graphene [15] have been studied, the existence of TE- and TM- polarized plasmon modes of THz frequencies, which are mixed in the presence of a magnetic field, has been shown. The

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☆ The article belongs to the special section Metamaterials.

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possibility of existence of waveguide modes with the negative group speed has been demonstrated as well. In work [16] the potential of creating of the hyperbolic metamaterial based on graphene–dielectric multilayer structure has been shown. The authors also noted that such metamaterial cannot be attributed to an elliptical or hyperbolic type in the presence of magnetic field due to the Hall effect in graphene, that allows one to control its properties. Reflection and transmission of electromagnetic waves by the graphene layer and graphene superlattice have been investigated in details in [17,18].

Despite the large number of studies, the authors are usually limited by investigation of a non-magnetic dielectric medium, where graphene is placed. It is very interesting to study the dynamic characteristics of graphene-based structures with more complex materials. Recently, metamaterial composed of periodic stacking of graphene–liquid crystal layers has been proposed for far-infrared frequencies [19]. The permeability of the liquid crystal and the surface conductivity of the graphene sheets are the tunable parameters. So, the optical properties of the structure can be controlled and the metamaterial is able to show both the elliptic and hyperbolic dispersions. A magnetic semiconductor could be another example of material with tunable permeability and permittivity. Semiconductor superlattices studied for a long time (see, for example, [20] and Refs. therein); however, they are still of the interest [21,22]. Frequency dispersion of the permittivity is one of the significant differences of semiconductor from dielectrics; the plasma waves can be excited in the semiconductor structures. When the semiconductor is placed in an external magnetic field, the helicons can to propagate in the material. Their properties depend on the magnetic field value. In its turn, the magnetic semiconductors have a number of specific features. For example, they may have a large magnetoresistance [23,24], magnetooptical properties [25,26], etc. Thus, the electrodynamic properties of graphene-magnetic semiconductor-based structures can be quite interesting. This paper is devoted to investigation of the reflection, transmission and absorption of electromagnetic waves by graphene–magnetic semiconductor–graphene sandwich-structure placed in an external magnetic field. All over the paper CGS units are used.

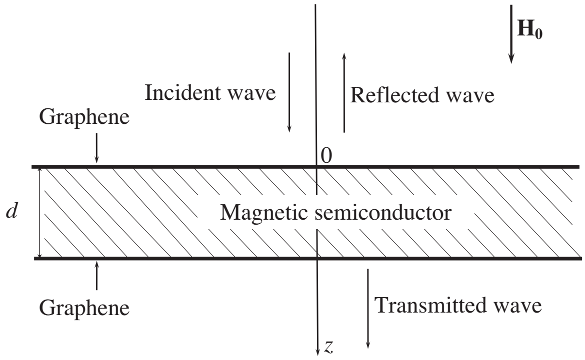

Fig. 1. Geometry of the problem.

2. Theory

Let us consider the graphene–magnetic semiconductor–graphene sandwich-structure placed in an external magnetic field $\mathbf{H}_0$, which is directed perpendicular to the structures' surface, in vacuum. Suppose that linearly polarized plane harmonic electromagnetic wave with time dependence of $\exp(-i\omega t)$ ($\omega = 2\pi f$ is an angular frequency, f is a linear frequency in Hz; we will use f in figures) is normally incident in the surface of the structure, shown in Fig. 1 (Faraday geometry). It is sufficient to consider an electromagnetic wave polarized along only one axis due to the axial symmetry of the problem. The coordinate axes are chosen so that the z-axis coincides with the direction of the external magnetic field, e.g., $\mathbf{H}_0 = (0, 0, H_0)$. The thickness of the magnetic semiconductor is denoted d.

For solving this problem, one has to know the characteristics of each component of the structure. For the magnetic semiconductor such characteristics are the tensors of the permeability $\hat{\mu}$ and the permittivity $\hat{\varepsilon}$. The permeability tensor of the magnetic semiconductor placed in an external magnetic field can be described as following:

$$\hat{\mu} = \begin{pmatrix} \mu_\perp & i\mu_a & 0 \\ -i\mu_a & \mu_\perp & 0 \\ 0 & 0 & \mu_\parallel \end{pmatrix}; \quad \mu_\perp = 1 + \frac{\omega_M(\omega_H - i\alpha\omega)}{\omega_H^2 - (1+\alpha^2)\omega^2 - 2i\alpha\omega\omega_H}; \quad \mu_a = \frac{-\omega_M\omega}{\omega_H^2 - (1+\alpha^2)\omega^2 - 2i\alpha\omega\omega_H}; \quad \mu_\parallel = 1 - \frac{i\alpha\omega_M}{\omega + i\alpha\omega_H}. \qquad (1)$$

In (1) we used the following notation: $\omega_H = gH_0$, $\omega_M = 4\pi g M_0$, g is the gyromagnetic ratio, M_0 is the saturation magnetization, α is the damping parameter.