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Tunable lateral and angular shifts of a reflected beam from a graphene-based structure

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ABSTRACT

We discuss the lateral shift (LS) and the angular shift (AS) of a reflected Gaussian beam from the interface covered with a graphene sheet, which is modeled as an infinitesimally thin surface conductivity. In the two cases where the incident medium is optically rarer or denser than the refractive medium, the LS and AS are numerically analyzed for a TM-polarized beam by using the stationary-phase approach. It is found that both the LS and AS can be controlled by tuning graphene's chemical potential, the frequency or the angle of incidence of incident beam. In particular, when the incident medium is optically denser, since the total internal reflection takes place and the surface plasmon polaritons are excited, the larger AS can be achieved around the critical angle, the pseudo-Brewster angle or resonance angle. Also, a higher chemical potential can tune the directions of the LS (i.e., the positive or negative shifts). The results provide a way to tune flexibly the LS and AS by means of the graphene sheet.

1. Introduction

Light reflection and refraction at a plane dielectric interface is one of the most basic optical processes and occur at almost all practical optical systems. For a plane wave, the processes can be described by the well-known Snell's law and Fresnel formulas, which provide the geometrical-optics picture of light evolution. However, for an actual bound beam with finite width, the centers of the reflected and transmitted beams deviate from the geometrical-optics prediction and exhibit small shifts. Goos–Hänchen (GH) shift [1–3] is a sizable lateral shift (LS) which is undergone by a reflected beam and occurs in the plane of incidence when the total internal reflection appears. Practically, an angular shift (AS), i.e., a small angular deviation from the law of specular reflection, known as the Fresnel filtering [4,5], can appear in the case of partial reflection and transmission [6,7]. It has been demonstrated experimentally that for a dissipative surface, the LS and AS can occur simultaneously [6].

With the upsurge of nano-optics employing light evolution at subwavelength scales, a number of novel and interesting effects relevant to the LS have been exposed. As a result, the LS has attracted rapidly growing attention and been widely studied. It was shown that the LS and AS arise from the dispersion of the reflection or transmission coefficients [2,6]. The reflection or transmission coefficients depend strongly on the material interfaces as well as polarization of incident beam, so that altering the properties of an interface can modify the LS and AS. Up to now, a variety of interface systems have been examined, including weakly absorbing [8–10] and metallic interfaces [11,12], nonlinear Kerr material interfaces [13,14], anisotropic interfaces [15], photonic crystals [16], negative-index materials [17,18], and other heterogeneous materials [19,20], etc.

In recent years, graphene, a single two-dimensional plane of carbon atoms forming a dense honeycomb lattice, has risen to popularity in many areas of research and technology owing to its unique electronic [21], mechanical [22], optical [23], and thermal properties [24]. Despite being atomically thin, it can interact strongly with light in the frequency range from terahertz to mid-infrared [25–27]. Its high carrier mobility and conductivity at room temperature makes it a very promising building block for post-silicon electronics, as well as for photonic, plasmonic and opto-electronic devices [25,28–30]. More importantly, by either chemical doping or external gate voltage we can control graphene's chemical potential, which depends on its free-carrier (electron or hole) concentration, and hence its electromagnetic response. Consequently, the electromagnetic properties of a graphene-based system can be tunable and flexible. In this work, we employ graphene's tunability to control the LS and AS.

This paper is organized as follows. In Section 2, we give briefly the basic theory background, including the frequency-dependent surface conductivity of the graphene sheet, the reflection

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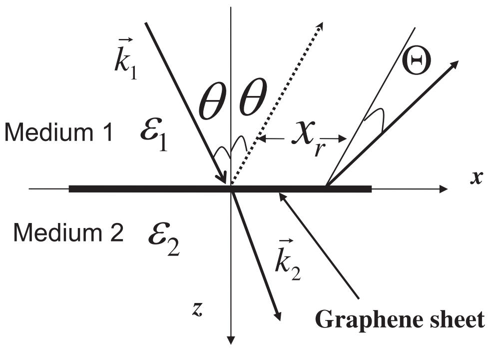

Fig. 1. Schematic of a light beam reflection on the planar interface which delimits two nonmagnetic media and is covered with a graphene sheet. Here, the dotted line with arrow denotes the reflected beam predicted by the geometric optics, and the solid line with arrow stands for the practical reflected beam. x_r and Θ represent the LS and AS, respectively.

coefficient on the interface covered with a graphene sheet, and the formulae describing the LS and AS. In Section 3, aiming at two cases, we analyze numerically the dependences of the LS and AS on the chemical potential, the angle of incidence and the frequency of incident beam. Finally, we summarize the main conclusions in Section 4.

2. Basic theory

Consider a simple structure depicted schematically in Fig. 1, where a graphene sheet is coated on the $z=0$ interface separating two nonmagnetic isotropic dielectric media with their respective relative permittivity ε_1 and ε_2. Let a central plane-wave component of the Gaussian beam of angular frequency ω impinge on the interface at the angle of incidence θ; clearly, the z-axis is normal to the interface and the O–xz plane is the plane of incidence. The graphene sheet is modeled as an infinitesimally thin frequency-dependent surface conductivity, written as [31] $\sigma(\omega)=\sigma_{\text{intra}}+\sigma_{\text{inter}}$, where σ_{intra} and σ_{inter} arise from the intraband and interband contributions, respectively. From the Kubo formalism [32], we have [31,32]

$$\sigma_{\text{intra}}=\frac{2ie^2k_BT}{\pi\hbar^2\left(\omega+i\tau^{-1}\right)}\ln\left[2\cos h\left(\frac{\mu_c}{2k_BT}\right)\right], \tag{1}$$

and

$$\sigma_{\text{inter}}=\frac{e^2}{4\hbar}\left[G\left(\frac{\hbar\omega}{2}\right)+i\frac{4\hbar\omega}{\pi}\int_0^\infty\frac{G(\varepsilon)-G\left(\hbar\omega/2\right)}{(\hbar\omega)^2-4\varepsilon^2}\mathrm{d}\varepsilon\right], \tag{2}$$

where $G(\varepsilon)=\sin h(\varepsilon/k_BT)/[\cos h(\mu_c/k_BT)+\cos h(\varepsilon/k_BT)]$, μ_c is chemical potential, τ is the relaxation time from various electron scattering processes, and T is temperature.

In the frequency region satisfying $\hbar\omega<2\left|\mu_c\right|$, the interband absorption is blocked and the intraband contribution (1) dominates [33]. In the work, we restrict ourselves to this frequency region and hence σ_{inter} will not be considered hereinafter. Moreover, we discuss the transverse magnetic (TM) wave only, while the transverse electric (TE) wave can be analyzed similarly. Thus, the electric and magnetic fields in the media can be denoted by $\vec{E}=(E_x,0,E_z)e^{i(k_xx-\omega t)}$, $\vec{H}=(0,H_y,0)e^{i(k_xx-\omega t)}$. From Maxwell's equations, it follows easily that the components H_y and E_x satisfy the equations

$$\frac{\mathrm{d}^2H_{jy}}{\mathrm{d}z^2}+\left(k_0^2\varepsilon_j-k_x^2\right)H_{jy}=0, \tag{3a}$$

$$E_{jx}=\frac{1}{i\omega\varepsilon_0\varepsilon_j}\frac{\mathrm{d}H_{jy}}{\mathrm{d}z}, \tag{3b}$$

where $j=1,2$ corresponds to the quantities in the medium 1 (incident medium) and 2 (refractive medium), respectively, and ε_0 is the permittivity of vacuum. The solutions to Eq. (3) are given by

$$H_{1y}=Ae^{ik_{1z}z}+Be^{-ik_{1z}z} \tag{4a}$$

$$E_{1x}=\frac{k_{1z}}{\omega\varepsilon_0\varepsilon_1}\left(Ae^{ik_{1z}z}-Be^{-ik_{1z}z}\right), \tag{4b}$$

in medium 1, and

$$H_{2y}=Ce^{ik_{2z}z}, \tag{5a}$$

$$E_{2x}=\frac{k_{2z}}{\omega\varepsilon_0\varepsilon_2}Ce^{ik_{2z}z}, \tag{5b}$$

in medium 2, where A, B and C are the wave amplitudes, and $k_{jz}=\sqrt{k_0^2\varepsilon_j-k_x^2}$, $k_0=\omega/c$, $k_x=k_0\sqrt{\varepsilon_1}\sin\theta$.

Because the graphene sheet is modeled as an infinitesimally thin surface conductivity, the current induced in the sheet is purely superficial and it is related to the tangential field components through the surface conductivity. In this way, the boundary conditions at the $z=0$ interface are

$$E_{1x}=E_{2x},\quad H_{1y}-H_{2y}=\sigma E_{2x} \tag{6}$$

Applying Eq. (6) to (4) and (5), we acquire the reflection coefficient of the TM-polarized wave

$$r_p=\left|r_p\right|e^{i\phi_p}=1-\frac{2\varepsilon_1k_{2z}/\varepsilon_2k_{1z}}{1+\sigma k_{2z}/\omega\varepsilon_0\varepsilon_2+\varepsilon_1k_{2z}/\varepsilon_2k_{1z}}, \tag{7}$$

which can obviously reduce to the familiar Fresnel reflection coefficient for an insulating interface, i.e., $\sigma=0$. In terms of r_p, the LS and the AS can be determined, respectively, by [6]

$$x_r=\frac{\lambda}{2\pi\sqrt{\varepsilon_1}\cos\theta}Im(D),\quad \Theta=-\frac{\theta_0^2}{2}Re(D), \tag{8}$$

where λ and $\theta_0(=\lambda/\pi w_0)$ are the wavelength and the angular spread of the incident beam of the waist w_0, respectively, Im(D) and Re(D) mean the imaginary and real parts of D, and D is expressed as

$$D\equiv\frac{\partial\ln r_p}{\partial\theta}=\frac{1}{\left|r_p\right|}\frac{\partial\left|r_p\right|}{\partial\theta}+i\frac{\partial\phi_p}{\partial\theta}. \tag{9}$$

It is clear from Eqs. (8) and (9) that the LS is caused by the angular gradient of the phase ϕ_p of reflection coefficient, and the AS by the angular gradient of the amplitude $\left|r_p\right|$ of reflection coefficient and is inversely proportional to $\left|r_p\right|$, which can thus be observed in the case of partial reflection or reflection with real coefficients [34]. We can also see from Eqs. (8) and (9) that the LS and the AS depend on the surface conductivity via the reflection coefficient, while the surface conductivity can be tuned by altering graphene's chemical potential μ_c and the frequency of incident beam; therefore, the LS and AS can be adjusted by tuning these tunable parameters.

3. Numerical results and discussion

It is well known that the reflection on an interface can display very distinct properties, depending on whether the medium 1 is optically rarer or denser relative to the medium 2. Thus, in the following numerical calculations, we check two cases, i.e., $\varepsilon_1<\varepsilon_2$, and $\varepsilon_1>\varepsilon_2$. We choose the waist of incident beam $w_0=50\lambda$ to meet the paraxial approximation requirement [35], and assume the relaxation time $\tau=0.35$ps for the room temperature $T=300$ K (i.e., $k_BT=0.026$ eV).

We begin with the case $\varepsilon_1<\varepsilon_2$, where no total internal reflection can occur. Setting $\varepsilon_1=1$ (air) and $\varepsilon_2=2.28$ (BK7 glass), we plot in Fig. 2 the dependence of $\left|r_p\right|$, ϕ_p, Θ and x_r on the angle of incidence θ