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Goos-Hänchen shifts due to graphene when intraband conductivity dominates

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ABSTRACT

The conductivity of a monolayer graphene at intraband transitions is sensitive on the Fermi level and on the wavelength of the incident beam. Changing conductivity values through these parameters thus may offer better control of light impinging on graphene. In this paper, we investigate reflection, the simplest interaction of light on such surface, by looking at the Goos-Hänchen (GH) shift experienced by the incident light where the wavelength is at terahertz range. With this wavelength range, we assume that the carriers in graphene undergo intraband transition. We calculate that spatial and angular GH shifts can be present. For both GH shifts in general, we find that increasing the Fermi level changes the incident angle at which the maximum GH shifts arise. Moreover, we see that at higher frequencies, the amount of beam shift decreases with the Fermi level. At lower frequencies on the other hand, the shift becomes proportional to the Fermi level. Upon obtaining the measurable shifts, we find that the magnitude of the physical shifts can be easily detected given appropriate experimental parameters. Our results may increase the utility of graphene in optoelectronics devices and applications.

1. Introduction

Graphene, a two-dimensional atomic crystal has recently gained attention due to its extraordinary electronic and optical properties. The discovery of this one-atom thick material, more than a decade ago led to numerous research to characterize its very unique properties for practical electronic and device applications [1]. Graphene is found to have high carrier density and carrier mobility which are now utilized to enhance optoeletronic devices [2,3]. Due to the mentioned properties and graphene‘s flexibility, it greatly improves the energy capacity and charge rate of Li-based recheargable batteries [4]. Activation of graphene can also store remarkably high electrical energy [5]. Moreover, graphene‘s unique band structure enables an ultrawide range of operational wavelengths making it a promising candidate for optical communication and remote sensing [6] .

Many studies have also explored the optical properties of graphene in the visible region where graphene’s optical conductivity can be approximated as $\sigma = e^2/4\hbar$ assuming half-filling and clean graphene [7–9]. Graphene’s optical conductivity in the visible range is mainly attributed to the interband transition of carriers [7]. However, when the frequency is at terahertz (THz), contributions from intraband scattering will dominate leaving the conductivity purely complex [3]. In this region, the conductivity of graphene is seen to increase up to two orders of magnitude compared to the conductivity in the visible range. Moreover, the conductivity now depends on the free-carrier concentration thus by varying the Fermi level, we can control and enhance graphene’s optical and electronic properties in the terahertz range [10–13]. Similarly, we can also switch the reflected light by tuning the properties of graphene. Recent papers have experimentally demonstrated the broadband modulation of terahertz waves at room temperature using graphene [14–16]. In [14], graphene acts as a tunable impedance surface to control the phase of the modulated THz wave. In [15], Rodriguez et al., were able to actively tune THz wave transmission by varying the carrier concentration of graphene-based structures. With the fast-paced development of graphene-based terahertz modulators, one needs to account the beamshifts or minimize deviation to the law of reflection that the THz wave experienced due to the graphene layer.

A physical beam reflected on a surface of a material with an index gradient experiences a shift or deviation from the path predicted by geometrical optics. This effect is known as Goos-Hänchen (GH) shift [17,18]. GH shifts arise from the dispersion of the reflection or transmission coefficients [19]. Because the GH shift can be related to the different material and structure parameters due to the reflection and transmission coefficients, measurement of this shift offers an alternative method to characterize properties of materials. Numerous material surfaces have been investigated based on the GH shifts they impart on the impinging beam. These include metals [20,21], dispersive media [22], negatively refractive media [23], and in metamaterials [24–26]. However, the shift is generally extremely small that for practical applications, several models and experiments have been proposed to enhance the magnitude of shift either by using dispersive materials [22], surface plasmon

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resonances [26,27], transformation optics [25], beam shaping [28–32], and weak measurements [33].

Giant Goos-Hänchen shift was predicted and later experimentally observed in graphene under total internal reflection [27,34]. A large-scale lateral shift was observed when the incident light changes from transverse magnetic (TM or *p*-polarized) to transverse electric (TE or *s*-polarized) mode. Aside from the change in polarization states of the incident beam, large magnitude of the GH shifts is also achievable with the use of partially coherent light fields [35]. Furthermore, the tunability of the GH shifts due to graphene was theoretically calculated by Xu, et al. wherein they presented the dependence of beamshifts on graphene's chemical potential, and incident beam frequency and angle [36]. However, rarely any literature reports GH shifts due to graphene of THz beam in external reflection.

In this paper, we investigate theoretically the GH shift of an externally reflected *p*-polarized terahertz beam due to graphene's Fermi energy. We have used an incident light having frequency in the THz range to satisfy the condition at which intraband conductivity of the monolayer graphene dominates. The results presented here can aid in determining the optimal incident frequency and angle for a much easy detection of beamshift, which in turn, can be used to determine properties of materials. Furthermore, we show that by changing the Fermi energy by doping or potential gating, one could also control beam deflection for optoelectronic applications. We show that the shift is dominated by the angular GH shift whose effect are measurable with appropriate experimental parameters, while the spatial GH shift, although also easily measurable, is an order of magnitude smaller.

2. Theoretical framework

2.1. Goos-Hänchen effect

Consider a beam of light with a finite beam width impinging on a plane dielectric interface. This beam of light exhibits spatial and angular shifts. These shifts, known as the Goos-Hänchen shifts, rely on the polarization and frequency of the incident beam and the material properties of the interface [18,37]. The dimensionless spatial (Δ_{GH}) and angular (Θ_{GH}) Goos-Hänchen shifts are expressed as:

$$\Delta_{GH} = w_p \mathrm{Im}\left(\frac{\partial \ln r_p}{\partial \theta}\right) + w_s \mathrm{Im}\left(\frac{\partial \ln r_s}{\partial \theta}\right) \tag{1}$$

$$-\Theta_{GH} = w_p \mathrm{Re}\left(\frac{\partial \ln r_p}{\partial \theta}\right) + w_s \mathrm{Re}\left(\frac{\partial \ln r_s}{\partial \theta}\right) \tag{2}$$

where $w_{s/p} = \frac{R^2{}_{s/p} a^2{}_{s/p}}{R_p^2 a_p^2 + R_s^2 a_s^2}$, $a_{s/p}$ are the electric field components of the incident beam, and $r_{s/p}$ are expressed in Eq. (4) [18] where s and p represent the polarization state of the incident beam. Fig. 1 shows a cartoon representation of Δ_{GH} and Θ_{GH} shifts.

Both the dimensionless spatial and angular GH shifts discussed so far, are factors of how large the beamshift will be. It is useful therefore, to convert these shifts into physical units that we can be measured in the laboratory. The physical beamshift Γ_X is expressed as,

$$k_0 \Gamma_X = \Delta_{GH} + (z/L)\Theta_{GH} \tag{3}$$

where $k_0 = 2\pi/\lambda$, z is the distance of the detector from minimum beamwaist, and $L = k_0\omega_0^2/2$ is the Rayleigh wavelength where ω_0 is the beamwaist of the incident beam.

2.2. Fresnel coefficients

Eqs. (1) and (2) depend on the Fresnel coefficients, r_s and r_p. When a 2D material is sandwiched between two dielectric surfaces with permittivity constants ϵ_1 and ϵ_2, the modified reflection coefficients are,

$$r_s = \frac{\sqrt{\epsilon_1}\cos\theta_1 - \sqrt{\epsilon_2}\cos\theta_2 - \tilde{\sigma}}{\sqrt{\epsilon_1}\cos\theta_1 + \sqrt{\epsilon_2}\cos\theta_2 + \tilde{\sigma}} \quad \text{and} \quad r_p = \frac{\frac{\sqrt{\epsilon_2}}{\cos\theta_2} - \frac{\sqrt{\epsilon_1}}{\cos\theta_1} + \tilde{\sigma}}{\frac{\sqrt{\epsilon_1}}{\cos\theta_1} + \frac{\sqrt{\epsilon_2}}{\cos\theta_2} + \tilde{\sigma}}, \tag{4}$$

where θ_1 is the incident angle, θ_2 is the transmitted angle, and $\tilde{\sigma}$ is the conductivity of the material as $\tilde{\sigma} = \frac{\sigma}{\epsilon_0 c}$ where ϵ_0 and c is the permittivity and the speed of light in vacuum, respectively. The Fresnel coefficients can be derived by imposing the boundary conditions: $\mathbf{n}\times(\mathbf{E_2}-\mathbf{E_1})|_{\mathbf{z=0}} = \mathbf{0}$ and $\mathbf{n}\times(\mathbf{H_2}-\mathbf{H_1})|_{\mathbf{z=0}} = \mathbf{J}$ where $\mathbf{n}$ is the unit surface normal, $\mathbf{E_{1,2}}$ and $\mathbf{H_{1,2}}$ are the electric field and magnetic fields at the interface, respectively and $\mathbf{J}$ is the surface current density of material [38].

2.3. Graphene

The Goos-Hänchen effect relies on the Fresnel coefficients, which in return depend on the conductivity of the material interface. In this study, we investigate the Goos-Hänchen effect due to a monolayer graphene when its intraband conductivity dominates. The optical conductivity of graphene in the random phase approximation and at finite temperature T can be written as [7,39],

$$\sigma(\omega) = \frac{2e^2 k_B T}{\pi\hbar^2}\frac{i}{\omega + i\tau^{-1}}\log\left[2\cosh\left(\frac{E_F}{2k_BT}\right)\right] + \frac{e^2}{4\hbar^2}\left[H\left(\frac{\omega}{2}\right) + \frac{4i\omega}{\pi}\int_0^\infty d\epsilon \frac{H(\epsilon) - H(\frac{\omega}{2})}{\omega^2 - 4\epsilon^2}\right] \tag{5}$$

where the first and second terms correspond to the intraband and interband transitions, respectively. This frequency dependence of the complex conductivity of homogeneous materials arises from the Drude model [3]. However, when the frequency goes down as in the THz range and the temperature T is below E_F/k_B which is usually the case at room temperature, the conductivity is reduced to,

$$\sigma(\omega) = \frac{2e^2}{\pi\hbar^2}\frac{iE_F}{\omega + i\tau^{-1}} \tag{6}$$

and becomes solely dependent on the scattering time τ, Fermi level E_F and angular frequency ω [3]. In this range, the interband transition is usually negligible due to the Pauli exclusion principle and as a result, the intraband scattering dominates the highly doped graphene [3,27]. For short-range scattering, the scattering rate τ is proportional to the Fermi level, $\tau = \mu E_F/ev_F^2$ where μ is the mobility and v_F is the Fermi velocity [40]. At room temperature, the mobility and the Fermi velocity have values in the order of 10000 $\mathrm{cm^2/Vs}$ and 1×10^6 m/s, respectively [41]. This conductivity affects light as it impinges on its interface.

In this study, we used Eqs. (1) and (2) to calculate the shifts with Eqs. (4) and (6) which are material dependent.

3. Results and discussion

The conductivity of graphene in the THz range is dependent on several factors namely the incident beam frequency, graphene's Fermi level, and scattering time as seen in Eq. (6). In our calculations, a Polymethylpentene (TPX) substrate with permittivity of 2.1196 is used because it has a dielectric response to a THz beam. We assign values of the Fermi level from 0.1 eV to 0.2 eV which are experimentally realizable [42]. We have investigated the external reflection of a *p*-polarized THz beam for practicality and simplicity.

Fig. 2 shows the reflectivity, phase jumps, and the Goos Hänchen shifts after the incident beam at an incident angle θ is reflected on an air-graphene-TPX interface. The reflectivity due to graphene never reaches zero: it attains a minimum value of reflectivity at certain incident angle referred to as the pseudo-Brewster angle θ_{pB}. In general, the slope of each R_p curve becomes steeper after passing θ_{pB}. This behavior of reflectivity results to an angular GH shift, Θ_{GH} shown in Fig. 2c.