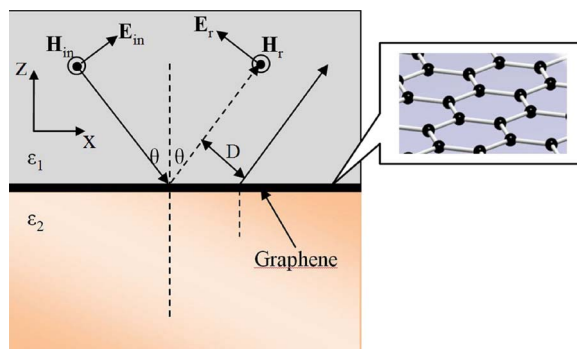


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Volume 5, Number 3, June 2013

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DOI: 10.1109/JPHOT.2013.2260530
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Electrically Tunable Goos–Hänchen Shift of Light Beam Reflected From a Graphene-on-Dielectric Surface

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DOI: 10.1109/JPHOT.2013.2260530
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Manuscript received March 29, 2013; revised April 17, 2013; accepted April 18, 2013. Date of publication April 29, 2013; date of current version May 30, 2013. This work was supported in part by the National 973 Program of China under Grant 2012CB315701, by the National Natural Science Foundation of China under Grant 11004053, by Hunan Provincial Natural Science Foundation of China under Grant 12JJ7005, and by the Young Teacher Development Plan of Hunan University. Corresponding author: X. Dai (e-mail: xiaoyudai@126.com).

Abstract: We have theoretically investigated the Goos–Hänchen (GH) shift of the TM-polarized beam reflected from a graphene-on-dielectric surface near the Brewster angle. It is shown that even a single-layer graphene allows for notable variation of the GH shift. The GH shift can be enlarged and switched from positive to negative or vice versa. Importantly, the GH shift depends on the Fermi energy, and thus, it can be electrically controlled through electrical or chemical modification of the charge carrier density of the graphene. Furthermore, the relationship between the GH shift and the electron–phonon relaxation time and the number of graphene layers is clarified.

Index Terms: Goos–Hänchen (GH) shift, graphene, pseudo-Brewster angle.

1. Introduction

The Goos–Hänchen (GH) effect was discovered by Goos and Hänchen [1] and theoretically explained by Artmann in the late 1940s [2]. It is highly desirable in many applications, e.g., optical waveguide switch [3], optical temperature sensing [4], and high-resolution surface plasmon sensors [5]. Hence, the GH effect has received extensively attention in recent years; the research on GH effect extends from total reflection regime to different circumstances such as multilayered structures [6], absorptive media [7], [8], photonic crystals [9], and negative-index metamaterials [10]. Besides, it is known that the tunability of the GH shift is intrinsically important for the applications in the optical devices; some methods have been put forward to make the GH shift tunable. For instance, Pflöghaar *et al.* [11] observed the transition of the lateral shift of a probe light beam totally reflected by changing the detuning of the probe beam; Wang *et al.* [12] presented a proposal to manipulate the GH shift of a light beam via a coherent control field, which is injected into a cavity configuration containing the two-level atomic medium; and Ziauddin *et al.* [13] reported a coherent control of the GH shift in a fixed configuration or device via superluminal and subluminal wave propagation. Zhao and Gao [14] investigated the temperature-dependent GH shift for an electromagnetic wave reflected from a metal/dielectric composite material, etc.

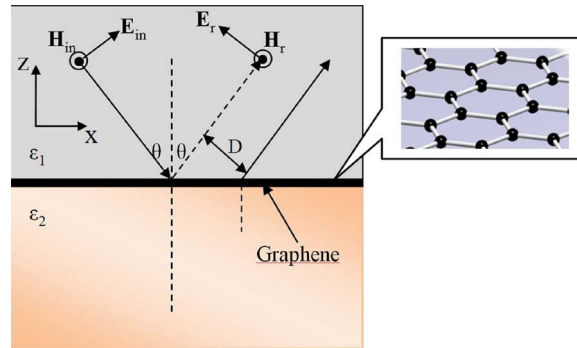


Fig. 1. Schematic diagram of the lateral shifts of the reflected beams from graphene-on-dielectric surface (TM polarization). The incident and reflected beams are schematically represented by their respective beam axes.

Recently, graphene, a single atomic sheet of graphite, has attracted intensive scientific interest owing to its incredible physical properties. It shows great potential applications in nanoelectronic devices and optoelectronic devices with ultrahigh electron mobility and ultrafast relaxation time for photo-excited carriers [15]–[17]. Different kinds of novel photonic and optoelectronic applications have been presented, such as optical modulator [18], broadband polarizer [19], transformation optics [20], and light emission devices [21]. More importantly, the conductivity properties of graphene can be tuned simply by adjusting the gate voltage, and this could provide an effective route to achieving electrical tunable plasmons [22], bandgap [23], [24], etc.

There are some papers that discussed the quantum or electronic GH effect in graphene [25]–[28]. Beenakker *et al.* investigated that the GH effect at a p-n interface in graphene depends on the pseudospin degree of freedom of the massless Dirac fermions and found a sign change of GH shift at the critical angle for total reflection [25]. Wu *et al.* demonstrated theoretically that a strain-induced gauge field can lead to valley-dependent transport phenomena, e.g., the Brewster angles and the GH effect [27]. Song *et al.* reported giant GH shifts for electron beams tunneling through graphene double-barrier structures [28]. Recently, Chen *et al.* gave a brief overview of the electronic GH shifts in semiconductor and graphene-based nanostructures, including single and double barriers and superlattices [26]. However, only a few papers discussed the optical GH effect in graphene. For example, Martinez and Jalil introduced the current into the electromagnetic boundary conditions and discussed the GH shift at the interface of two media of different permittivity, with graphene at their interface. It was found that the presence of surface charge at the graphene interface significantly altered the GH shift for the TE polarization, while in the TM polarization case, the charge and current could have opposing effects on the GH shift [29]. Different from this work, in this paper, we will investigate theoretically the GH shift of the TM-polarized beam reflected from a graphene-on-dielectric surface near the Brewster angle. It is found that the GH shift can be electrically controlled by changing electrical or chemical modification of the charge carrier density of the graphene. Moreover, we also point out that the GH shift depends on the electron–phonon relaxation time and the number of the layers of the graphene sheet. Therefore, electrical tunability of GH shift from the graphene-on-dielectric surface could potentially open a new possibility of SPR imaging detection, biosensor, flexible optical-beam steering and alignment, and optical devices in information processing.

2. Model and Method

We illustrate the geometric problem in Fig. 1. Media 1 and 2 are characterized by permittivity values ϵ_1 and ϵ_2 , respectively. In the following analysis, we assume that medium 1 is vacuum ($\epsilon_1 = 1$) and medium 2 is dielectric ($\epsilon_2 = 2.25$). Artmann has proposed the stationary-phase method [2] to calculate the GH shift, who recognizes that the light beam is a collection of plane waves of slightly different transverse wave vectors. After the total internal reflection, these component waves will

undergo different phase changes and sum to form a reflection beam with a lateral shift. In our structure, as shown in Fig. 1, a light beam (TM polarization) of angular frequency ω is incident from a medium at an angle θ on the interface of medium 2. The electric field of the plane-wave component of the incident beam is denoted by $\mathbf{E}_{in}(z) = \mathbf{E}_0 \exp(j\mathbf{k}_i \cdot \mathbf{z})$, where $\mathbf{k}_i = k_x \hat{e}_x + k_{z1} \hat{e}_z$, $k_x = k_1 \sin \theta$, and $k_{z1} = k_1 \cos \theta$; $k_1 = k_0 \sqrt{\varepsilon_1}$ is the wave vector in medium 1 and $k_0 = \omega/c$. The field is assumed to be uniform in the y -direction. The GH shift of TE polarization is usually much smaller. However, for the TM polarization, when the light beam reflected from a weakly absorbing semi-infinite medium, a large GH shift can be observed due to the abrupt change of phase across the Brewster dip (the angle of minimum reflection).

If the graphene layers are absent, the reflection coefficients for incident beams are obtained as

$$r(\theta, \omega) = \frac{k_{z1}/\varepsilon_1 - k_{z2}/\varepsilon_2}{k_{z1}/\varepsilon_1 + k_{z2}/\varepsilon_2} \quad (1)$$

for TM waves, and

$$r(\theta, \omega) = \frac{k_{z1} - k_{z2}}{k_{z1} + k_{z2}} \quad (2)$$

for TE waves, where $k_{z2} = k_0 \sqrt{\varepsilon_2 - \varepsilon_1 \sin^2 \theta}$.

Then if the graphene layers are coated on medium 2, the reflection coefficients should be modified as [30], [31]

$$r(\theta, \omega) = \frac{k_{z1}/\varepsilon_1 - k_{z2}/\varepsilon_2 + \hat{\sigma}(k_{z1}/\varepsilon_1)(k_{z2}/\varepsilon_2)}{k_{z1}/\varepsilon_1 + k_{z2}/\varepsilon_2 + \hat{\sigma}(k_{z1}/\varepsilon_1)(k_{z2}/\varepsilon_2)} \quad (3)$$

for TM waves, and

$$r(\theta, \omega) = \frac{k_{z1} - k_{z2} - k_0 \hat{\sigma}}{k_{z1} + k_{z2} + k_0 \hat{\sigma}} \quad (4)$$

for TE waves, where $\hat{\sigma} = \sigma/\varepsilon_0 \omega$, and σ is the surface conductivity of graphene sheet. Within the random-phase approximation (RPA) and at zero temperature, the surface conductivity of graphene in the local limit reduces to [32]–[34],

$$\sigma(\omega) = \frac{e^2 E_F}{\pi \hbar^2} \frac{i}{\omega + i\tau^{-1}} + \frac{e^2}{4\hbar} \left[\theta(\hbar\omega - 2E_F) + \frac{i}{\pi} \log \left| \frac{\hbar\omega - 2E_F}{\hbar\omega + 2E_F} \right| \right] \quad (5)$$

where ω is the frequency of incident light, and e and \hbar are universal constants related to the electron charge and reduced Planck's constants, respectively. E_F and τ are the Fermi energy (or chemical potential) and electron–phonon relaxation time, respectively. $\theta(x)$ is the Heaviside step function. The first and second terms on the right side of (5) stem from the intraband and interband contributions, respectively. Fermi energy E_F can be straightforwardly obtained from carrier density n_{2D} in a graphene sheet; $E_F = \hbar\nu_F \sqrt{\pi n_{2D}}$, where $\nu = 10^6$ m/s is the Fermi velocity of electrons. Here, carrier density n_{2D} can be electrically controlled by an applied gate voltage, thereby leading to a voltage-controlled Fermi energy E_F and the voltage-controlled surface conductivity $\sigma(\omega)$; this could provide an effective route to achieve electrical control GH shift in graphene-on-dielectric surface.

In general, the reflection coefficients can be expressed as

$$r(\theta, \omega) = |r(\theta, \omega)| \exp[i\phi_r(\theta, \omega)] \quad (6)$$

where $\phi_r(\theta, \omega)$ is the phase of the reflection coefficient. According to the stationary-phase method [2], for the incident beam with a sufficiently large beam waist (i.e., the beam with a narrow angular spectrum, $\Delta k \ll |k|$), the lateral shift of the reflected beam is [2], [6], [7]

$$D(\theta, \omega) = -\frac{\lambda}{2\pi} \frac{d\phi_r}{d\theta}. \quad (7)$$

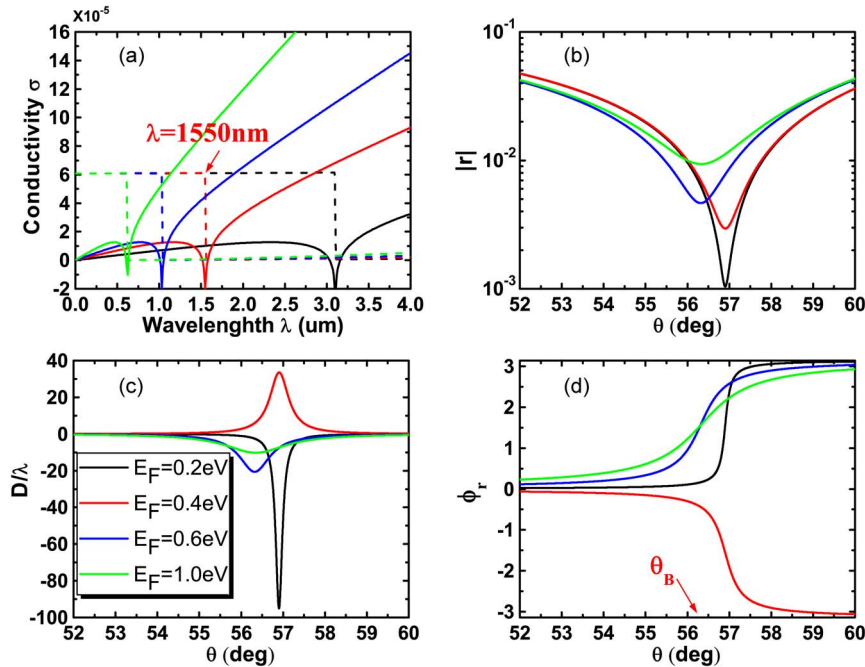


Fig. 2. (a) The dependencies of the optical conductivity of graphene sheet on the wavelength at the different Fermi energy, the dashed line and the solid line are the real part and imaginary part of optical conductivity, respectively; (b), (c), and (d) are the dependence of the reflectivity, GH shift, and reflection phase on the incident angle, respectively. Here, $\tau = 100$ fs, the Brewster angle θ_B in the absence of the graphene has been indicated, and the pseudo-Brewster angles shifts to larger incident angle due to the effect of the graphene.

With this relation, the lateral shift of the reflected beam for the absorption materials is given by [8]

$$D = -\frac{\lambda}{2\pi} \frac{1}{|r(\theta)|^2} \left\{ \text{Re}[r(\theta)] \frac{d\text{Im}[r(\theta)]}{d\theta} - \text{Im}[r(\theta)] \frac{d\text{Re}[r(\theta)]}{d\theta} \right\}. \quad (8)$$

The light beam is incident from an optically thinner medium to an optically denser medium, and the total reflection condition cannot be satisfied; hence, the GH effects do not occur. If the monolayer graphene is coated on the dielectric, then the GH shift occurs near the Brewster angle for a TM-polarized beam due to an abrupt change of phase across the Brewster angle, opposite to that in total internal reflection. Compared with the TM polarization, the GH shift for the TE-polarized beam is tiny and therefore will not be considered in this paper. In the absence of the graphene, the Brewster angle $\theta_B = \tan^{-1}(\sqrt{\epsilon_2})$, which has been indicated in Figs. 2–4. Lai and Chan [7] showed that a large negative GH shift exists near the Brewster angle for a weakly absorbing semi-infinite medium; Wang *et al.* [8] theoretically showed that the negative GH shift of TE- and TM-polarized reflected beams from the weakly absorbing dielectric slab can be very large near resonance angle. However, in these investigations, the GH shift cannot be manipulated in a fixed configuration or device. The situation will be changed if we introduce the electrically controlled graphene into the fixed configuration.

3. Results and Discussions

We discuss the GH shift with a communication wavelength $\lambda = 1550$ nm. Fig. 2(a) is the calculated optical conductivity of graphene sheet at the different Fermi energy; the dashed line and the solid line are the real part and the imaginary part of optical conductivity, respectively. It is indicated that the optical conductivity is dependent strongly on the Fermi energy. The imaginary part of the optical conductivity $\text{Im}(\sigma)$ exhibits some complex behavior: It has a dip near the wavelength λ_{dip} for

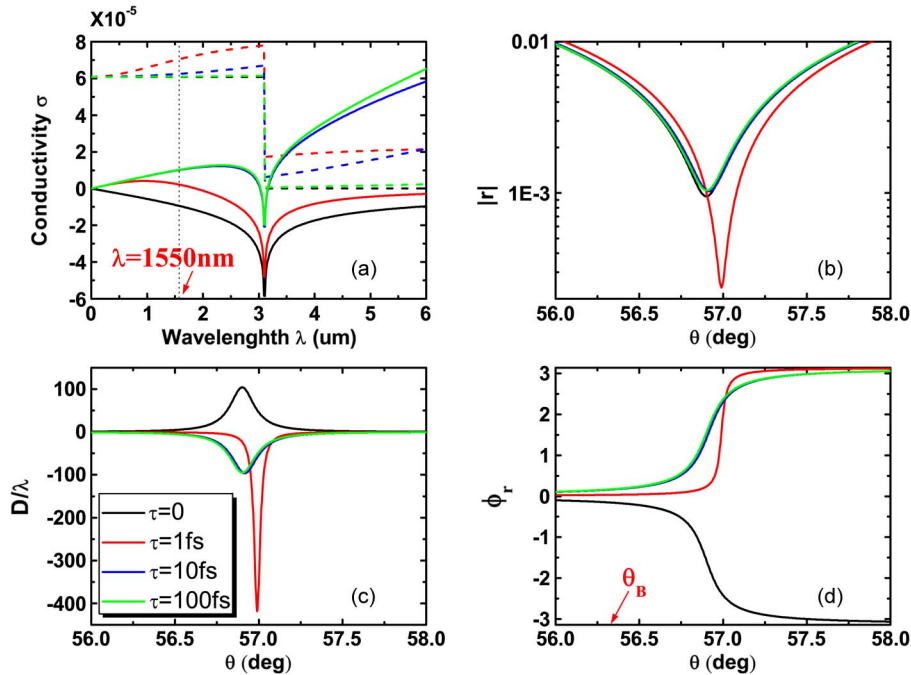


Fig. 3. (a) The dependencies of the optical conductivity of graphene sheet on the wavelength at the different relaxation time, the dashed line and the solid line are the real part and imaginary part of optical conductivity, respectively; (b), (c), and (d) are the dependence of the reflectivity, GH shift, and reflection phase on the incident angle, respectively. Here, $E_F = 0.2$ eV, the Brewster angle θ_B in the absence of the graphene has been indicated, and the pseudo-Brewster angles shifts to larger incident angle due to the effect of the graphene.

$\hbar\omega = 2E_F$, and at this dip, $Im(\sigma)$ can become negative; λ_{dip} shifts to shorter wavelength with the increasing Fermi energy E_F . The real part of the optical conductivity $Re(\sigma)$ is large if $\lambda < \lambda_{dip}$, and it almost disappears if $\lambda > \lambda_{dip}$. The electrically tunable optical conductivity will provide us a method to manipulate the reflectivity, GH shift, and phase, as shown in Fig. 2(b)–(d), respectively. First, we can find from Fig. 2(b) and (d) that the Brewster angles occur even when the graphene exhibits absorption behavior; the Brewster angle in the low-loss dielectric is called a pseudo-Brewster angle. Obviously, pseudo-Brewster angles shift to larger incident angle due to the effect of the graphene. However, reflectivity still has a tiny value near the pseudo-Brewster angles due to the nonvanishing imaginary part of the reflectivity caused by the complex optical conductivity. Also, the reflectivity has been greatly enhanced by increasing the Fermi energy [see Fig. 2(b)], which is induced by the increasing $Im(\sigma)$ at $\lambda = 1550$ nm. Meanwhile, the angle for the minimum reflectivity (Brewster angle) shifts to smaller incident angle. Significantly, we find that the GH shift can be large negative near the Brewster angle; here, $D \approx -100\lambda$ has been obtained for $E_F = 0.2$ eV, as shown in Fig. 2(c). However, increasing Fermi energy E_F can depress the negative GH shift. It should be noted that GH shift becomes positive at $E_F = 0.4$ eV; this phenomenon is quite unique, and we can realize the switching of GH shift from negative to positive or from positive to negative easily by tuning the Fermi energy, chemical modification, or the applied voltage. These novel behaviors of the GH shift can be explained by the relation of the reflection phase and the incident angle, as shown in Fig. 2(d); here, the slope of the reflection phase on the incident angle decreases with increasing Fermi energy E_F , which leads to the decrease in the absolute value of the GH shift. From Fig. 2(a), we can see that $Im(\sigma)$ is positive for $E_F = 0.2, 0.6,$ and 1.0 eV at $\lambda = 1550$ nm, and $Im(\sigma)$ is increasing with increasing Fermi energy E_F ; hence, we always have a positive $Im(r)$ near the Brewster angle and a change of $Re(r)$ from positive to negative across that angle. The phase $\phi_r(\theta) = \tan^{-1}|Im(r)/Re(r)|$ is monotone increasing with the incident angle and is limited in the range $[0, \pi]$. Hence, the positive slope $d\phi_r/d\theta$ can be obtained, which leads to the negative GH

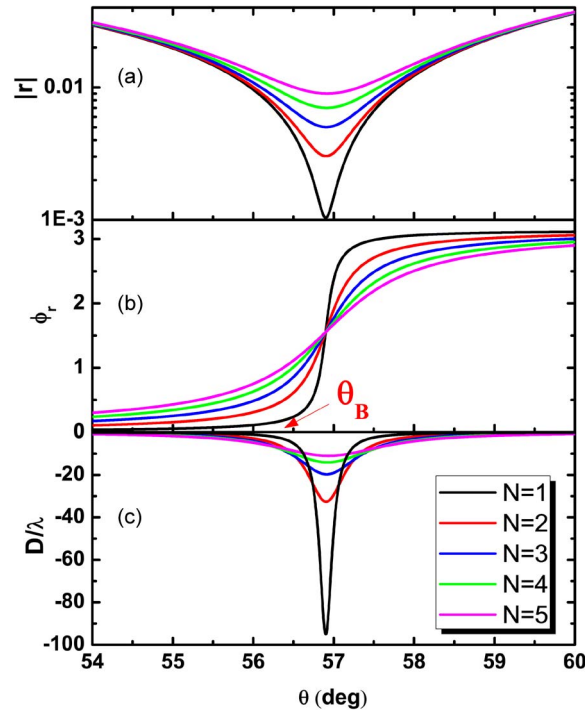


Fig. 4. The dependence of the reflectivity (a), reflection phase (b), and GH shift (c) on the incident angle at the different number of layers, respectively. Here, $E_F = 0.2$ eV and $\tau = 100$ fs, the Brewster angle θ_B in the absence of the graphene has been indicated, and the pseudo-Brewster angles shifts to larger incident angle due to the effect of the graphene.

shift. In addition, increasing the Fermi energy E_F decreases the slope of reflectivity phase and leads to the weakness of the GH shift. However, at $E_F = 0.4$ eV, $Im(\sigma)$ is negative at $\lambda = 1550$ nm, which makes the reflectivity have the negative $Im(r)$; however, $Re(r)$ still changes from positive to negative. Hence, the phase $\phi_r(\theta)$ is monotone decreasing with the incident angle and is limited in the range $[0, -\pi]$. The negative slope $d\phi_r/d\theta$ leads to the occurrence of the positive GH shift.

From the analyses made above, it is clear that the GH shift can be controlled by the suitable adjustment of the applied voltage. Thus it is a very useful and powerful way to manipulate the GH shift. From (3), we find that the relaxation time τ is an important parameter because the actual value of the optical conductivity of graphene is strongly dependent on τ . Hence, the GH shift is also sensitive to the relaxation time τ . Fig. 3(a) shows the optical conductivity as a function of the wavelength; the dashed line and the solid line are the real part and the imaginary part of optical conductivity, respectively. Fig. 3(b)–(d) gives the reflectivity, GH shift, and reflectivity phase as a function of incident angle for various values of τ at the fixed Fermi energy $E_F = 0.2$ eV, respectively. It is obvious that the GH shifts are influenced strongly by the relaxation time τ . If $\tau = 0$, $Im(\sigma)$ is always negative, which leads the positive GH shift. $Im(\sigma)$ increases as τ increases, gradually becomes the positive value in most wavelengths, and leads to the negative GH shift, as shown in Fig. 3(c). Here, GH shift can be switched from positive to negative by controlling the relaxation time τ . The negative GH shift can be enhanced to $D \approx -400\lambda$ for $\tau = 1$ fs and be reduced to -100λ for $\tau = 10$ and 100 fs. It cannot be reduced further even if we increase the relaxation time greatly. Fig. 3(b) and (d) shows the corresponding changing of the reflectivity and phase for different relaxation times, which can be used to explain the behaviors of the GH shift. However, it is difficult to vary the relaxation time τ in real prepared graphene sample; hence, the dependence of the GH shift on τ is not related to the tunability of the GH shift for the fixed configuration.

For the few-layer graphene, the individual graphene sheet can be considered as a noninteracting monolayer; the optical conductivity of the few-layer graphene can be calculated as $N\sigma$ [35], [36], where N is the number of the layers. Then we can discuss the influence of the number of layers on

the GH shift, as shown in Fig. 4. It is apparent that increasing the number of layers of graphene can enhance the reflectivity due to the increased $Im(r)$ and $Re(r)$, as shown in Fig. 4(a). The slope of the phase of the reflected light beam is also decreasing [see Fig. 4(b)], and this will lead to the decreases in the GH shift, as shown in Fig. 4(c). As a consequence, the number of the graphene sheets N plays an important role in determining the GH shift near the pseudo-Brewster angle.

4. Conclusion

In this paper, we have investigated theoretically the GH shift of the TM-polarized beam reflected from a graphene-on-dielectric surface. It is found that the large negative GH shift occurs near the Brewster angle. Important is that the GH shift can be electrically controlled through electrical or chemical modification of the charge carrier density of the graphene. Specially, the GH shift can be switched from positive to negative or vice versa. Moreover, we also point out that the GH shift depends on the electron–phonon relaxation time and the number of the layers of the graphene sheet. The electrical tunability of GH shift from the graphene-on-dielectric surface could potentially open a new possibility of SPR imaging detection, biosensor, and flexible optical-beam steering and alignment, etc.

References

- [1] F. Goos and H. Hänchen, “Ein neuer und fundamentaler versuch zur totalreflexion,” *Ann. Phys.*, vol. 436, no. 7/8, pp. 333–346, Dec. 1947.
- [2] K. Artmann, “Berechnung der seitenversetzung des totalreflektierten strahles,” *Ann. Phys.*, vol. 437, no. 1, pp. 87–102, Jan. 1948.
- [3] T. Sakata, H. Togo, and F. Shimokawa, “Reflection-type 2×2 optical waveguide switch using the Goos–Hänchen shift effect,” *Appl. Phys. Lett.*, vol. 76, no. 20, pp. 2841–2843, May 2000.
- [4] C. W. Chen, W. C. Lin, L. S. Liao, Z. H. Lin, H. P. Chiang, P. T. Leung, E. Sijercic, and W. S. Tse, “Optical temperature sensing based on the Goos–Hänchen effect,” *Appl. Opt.*, vol. 46, no. 22, pp. 5347–5351, Aug. 2007.
- [5] X. Yin and L. Hesselink, “Goos–Hänchen shift surface plasmon resonance sensor,” *Appl. Phys. Lett.*, vol. 89, no. 26, pp. 261108-1–261108-3, Dec. 2006.
- [6] C. F. Li, “Negative lateral shift of a light beam transmitted through a dielectric slab and interaction of boundary effects,” *Phys. Rev. Lett.*, vol. 91, no. 13, pp. 133903-1–133903-4, Sep. 2003.
- [7] H. M. Lai and S. Chan, “Large and negative Goos–Hänchen shift near the Brewster dip on reflection from weakly absorbing media,” *Opt. Lett.*, vol. 27, no. 9, pp. 680–682, May 2002.
- [8] L. G. Wang, H. Chen, and S. Y. Zhu, “Large negative Goos–Hänchen shift from a weakly absorbing dielectric slab,” *Opt. Lett.*, vol. 30, no. 21, pp. 2936–2938, Nov. 2005.
- [9] J. He, J. Yi, and S. He, “Giant negative Goos–Hänchen shifts for a photonic crystal with a negative effective index,” *Opt. Exp.*, vol. 14, no. 7, pp. 3024–3029, Apr. 2006.
- [10] L. Ju, B. Geng, J. Horng, C. Girit, M. Martin, Z. Hao, H. A. Bechtel, X. Liang, A. Zettl, and Y. R. Shen, “Graphene plasmonics for tunable terahertz metamaterials,” *Nat. Nanotechnol.*, vol. 6, no. 10, pp. 630–634, Oct. 2011.
- [11] E. Pfeleghaar, A. Marseille, and A. Weis, “Quantitative investigation of the effect of resonant absorbers on the Goos–Hänchen shift,” *Phys. Rev. Lett.*, vol. 70, no. 15, pp. 2281–2284, Apr. 1993.
- [12] L. G. Wang, M. Ikram, and M. S. Zubairy, “Control of the Goos–Hänchen shift of a light beam via a coherent driving field,” *Phys. Rev. A, At. Mol., Opt. Phys.*, vol. 77, no. 2, pp. 023811-1–023811-5, Feb. 2008.
- [13] Ziauddin, S. Qamar, and M. S. Zubairy, “Coherent control of the Goos–Hänchen shift,” *Phys. Rev. A, At. Mol., Opt. Phys.*, vol. 81, no. 2, pp. 023821-1–023821-9, Feb. 2010.
- [14] B. Zhao and L. Gao, “Temperature-dependent Goos–Hänchen shift on the interface of metal/dielectric composites,” *Opt. Exp.*, vol. 17, no. 24, pp. 21 433–21 441, Nov. 2009.
- [15] K. S. Novoselov, S. V. Geim, A. K. Morozov, D. Jiang, Y. Zhang, S. V. Dubonos, I. V. Grigorieva, and A. A. Firsov, “Electric field effect in atomically thin carbon films,” *Science*, vol. 306, no. 5696, pp. 666–669, Oct. 2004.
- [16] A. H. Castro Neto, N. M. R. Guinea, F. Peres, K. S. Novoselov, and A. K. Geim, “The electronic properties of graphene,” *Rev. Mod. Phys.*, vol. 81, no. 1, pp. 109–162, Jan. 2009.
- [17] S. D. Sarma, S. Adam, E. Hwang, and E. Rossi, “Electronic transport in two dimensional graphene,” pp. 1–69, Nov. 2010, arXiv:1003.4731v1.
- [18] M. Liu, X. Yin, E. Ulin-Avila, B. Geng, T. Zentgraf, L. Ju, F. Wang, and X. Zhang, “A graphene-based broadband optical modulator,” *Nature*, vol. 474, no. 7349, pp. 64–67, Jun. 2011.
- [19] Q. Bao, H. Zhang, B. Wang, Z. Ni, C. H. Y. X. Lim, Y. Wang, D. Y. Tang, and K. P. Loh, “Broadband graphene polarizer,” *Nat. Photon.*, vol. 5, no. 7, pp. 411–415, Jul. 2011.
- [20] A. Vakil and N. Engheta, “Transformation optics using graphene,” *Science*, vol. 332, no. 6035, pp. 1291–1294, Jun. 2011.
- [21] T. H. Han, Y. Lee, M. R. Choi, S. H. Woo, S. H. Bae, B. H. Hong, J. H. Ahn, and T. W. Lee, “Extremely efficient flexible organic light-emitting diodes with modified graphene anode,” *Nat. Photon.*, vol. 6, no. 2, pp. 105–110, Feb. 2012.
- [22] J. Chen, M. Badioli, P. Alonso-González, S. Thongrattanasiri, F. Huth, J. Osmond, M. Spasenovi, A. Centeno, A. Pesquera, P. Godignon, A. Z. Elorza, N. Camara, F. Javier García de Abajo, R. Hillenbrand, and F. H. L. Koppens, “Optical nano-imaging of gate-tunable graphene plasmons,” *Nature*, vol. 487, no. 7405, pp. 77–81, Jul. 2012.

- [23] C. H. Lui, Z. Li, K. F. Mak, E. Cappelluti, and T. F. Heinz, "Observation of an electrically tunable band gap in trilayer graphene," *Nat. Phys.*, vol. 7, no. 12, pp. 944–947, Dec. 2011.
- [24] Y. Zhang, T. T. Tang, C. Girit, Z. Hao, M. C. Martin, A. Zettl, M. F. Crommie, Y. R. Shen, and F. Wang, "Direct observation of a widely tunable bandgap in bilayer graphene," *Nature*, vol. 459, no. 7248, pp. 820–823, Jun. 2009.
- [25] C. W. J. Beenakker, R. A. Sepkhanov, A. R. Akhmerov, and J. Tworzydło, "Quantum Goos–Hänchen effect in graphene," *Phys. Rev. Lett.*, vol. 102, no. 14, pp. 146804-1–146804-4, Apr. 2009.
- [26] X. Chen, X. J. Lu, Y. Ban, and C. F. Li, "Electronic analogy of the Goos–Hänchen effect: A review," *J. Opt.*, vol. 15, no. 3, pp. 033001-1–033001-12, Mar. 2013.
- [27] Z. Wu, F. Zhai, F. M. Peeters, H. Q. Xu, and K. Chang, "Valley-dependent Brewster angles and Goos–Hänchen effect in strained graphene," *Phys. Rev. Lett.*, vol. 106, no. 17, pp. 176802-1–176802-4, Apr. 2011.
- [28] Y. Song, H. C. Wu, and Y. Guo, "Giant Goos–Hänchen shift in graphene double-barrier structures," *Appl. Phys. Lett.*, vol. 100, no. 25, pp. 253116-1–253116-4, Jun. 2012.
- [29] J. C. Martinez and M. B. A. Jalil, "Theory of giant Faraday rotation and Goos–Hänchen shift in graphene," *Europhys. Lett.*, vol. 96, no. 2, pp. 27008-1–27008-6, Oct. 2011.
- [30] B. Sensale-Rodriguez, T. Fang, R. Yan, M. M. Kelly, D. Jena, and L. Liu, "Unique prospects for graphene-based terahertz modulators," *Appl. Phys. Lett.*, vol. 99, no. 11, pp. 113104-1–113104-3, Sep. 2011.
- [31] T. Zhan, Y. Shi, X. Dai, X. Liu, and J. Zi, "Transfer matrix method for optics in graphene layers," pp. 1–8, Dec. 2012, arXiv:1212.5763.
- [32] E. H. Hwang and S. D. Sarma, "Dielectric function, screening, and plasmons in two-dimensional graphene," *Phys. Rev. B, Condens. Matter*, vol. 75, no. 20, pp. 205418-1–205418-6, May 2007.
- [33] M. Polini, R. Asgari, G. Borghi, Y. Barlas, T. Pereg-Barnea, and A. MacDonald, "Plasmons and the spectral function of graphene," *Phys. Rev. B, Condens. Matter*, vol. 77, no. 8, pp. 081411-1–081411-4, Feb. 2008.
- [34] F. H. Koppens, D. E. Chang, and F. Javier Garcia de Abajo, "Graphene plasmonics: A platform for strong light-matter interactions," *Nano. Lett.*, vol. 11, no. 8, pp. 3370–3377, Aug. 2011.
- [35] C. Casiraghi, A. Hartschuh, E. Lidorikis, H. Qian, H. Harutyunyan, T. Gokus, K. S. Novoselov, and A. C. Ferrari, "Rayleigh imaging of graphene and graphene layers," *Nano. Lett.*, vol. 7, no. 9, pp. 2711–2717, Sep. 2007.
- [36] H. Yan, X. Li, B. Chandra, G. Tulevski, Y. Wu, M. Freitag, W. Zhu, P. Avouris, and X. Xia, "Tunable infrared plasmonic devices using graphene/insulator stacks," *Nat. Nanotechnol.*, vol. 7, no. 5, pp. 330–334, May 2012.