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Realization of tunable Goos-Hänchen effect with magneto-optical effect in graphene

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ABSTRACT

Tunable Goos-Hänchen (GH) effect with magneto-optical (MO) effect in a prism-graphene coupling structure is proposed. Based on MO effect of graphene in terahertz region, GH effect can be modulated by applied magnetic fields. The GH shift is calculated by stationary phase method and verified by finite-element method (FEM). The physical mechanism of MO modulation for GH effect in the prism-graphene coupling structure is also analyzed based on the interaction between graphene and incident light. GH effect based on Kerr rotation may have great potential in the application of optical rotation displacement modulation and sensing. Meanwhile tunable GH effect in graphene shows a big potential in the measurement of Fermi energy or relaxation time of graphene. It provides us an effective method to facilitate its design and applications in terahertz devices and systems.

1. Introduction

When a light beam is totally reflected at an interface, a lateral shift of the reflected light beam occurs from the position predicted by geometrical optics. This phenomenon is demonstrated by Goos and Hänchen in 1947 and thus was named Goos-Hänchen (GH) effect [1]. In an ordinary case, the GH shift is of the order of one wavelength which impedes its direct observation in a single reflection. The enhancement and modulation of GH effect has attracted much attention of researchers for its potential applications in optical sensors [2–4]. In a heterostructure consisting of an electro-optic film and a magneto-electric film, both the spatial and the angular GH shifts can be controlled through a variation of the direction and the magnitude of the external electric field [5]. Meanwhile by inverting the direction of the external magnetic field, a non-symmetrical inversion of GH shift can be realized. GH effect in graphene can be electrically tuned by controlling the Fermi energy of the monolayer graphene in terahertz (THz) region [6]. The giant quantized GH effect on a graphene-on-substrate system was predicted and studied which provide a pathway for modulating the GH effect [7]. In terahertz region, the observation of graphene GH effect [8,9] will lead to significant new and interesting applications in various types of optical sensors. Meanwhile the prism-graphene coupling structure can also effectively control the transverse shift which is known as photonic spin Hall effect (PSHE) [10,11]. In a graphene-substrate system with the presence of an external magnetic field, PSHE in the quantum Hall regime holds great promise for detecting quantized Hall conductivity and the Berry phase [12]. Further study shows that PSHE shift is sensitive to the number of graphene layer which means PSHE can be used as a detection method for the number of graphene layer [13,14].

As a two-dimensional (2D) material, graphene has a permittivity tensor with nonzero diagonal and off-diagonal components in terahertz region. Due to the magnetic field applied perpendicular to graphene, the components of permittivity tensor depend both on the frequency of the impinging electromagnetic wave and cyclotron frequency of the electrons. Thus graphene shows a magneto-optical Kerr effect (MOKE) which causes the rotation of the linearly polarized light when reflected from surface of graphene layer. MOKE in graphene has been studied in theoretical works [15–17], which is not only a probe for study the properties of graphene, but also has a potential for THz applications based on graphene devices [18].

In this paper, we study the tunable GH effect in graphene of

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reflected light in prism-graphene coupling structure which can be modulated by magnetic field. As the MOKE effect in graphene layer brings Kerr rotation of incident light, the GH effect for different polarized beams of reflected light can be observed. Meanwhile the tunable GH effect in prism-graphene coupling structure can be modulated by external magnetic field which is applicable in terahertz devices.

2. Model and theory

In this paper, we consider a classic model of prism-graphene coupling structure as shown in Fig. 1. A p-polarized Gaussian beam is incident from air to prism-graphene coupling structure with an incident angle of θ and a frequency of F. A tunable magnetic field of B is applied on the prism-graphene coupling structure along z-axis. The reflected beam experiences a GH shift of L along x-axis. When a large GH shift is observed, the incident light is coupled into the waveguide as the insert of Fig. 1 shows.

In this paper, we mainly discuss the MO effect of graphene and its influence on GH effect. As graphene shows no MO effect in optical region we can only observe tunable GH in graphene in terahertz region. Especially, as graphene is a 2-dimensional material, it brings a greater MO modulation effect for GH shift. If graphene is replaced by other MO materials, GH effect in graphene can still be observed. However, the properties and possible applications of GH effect in graphene may be different for different MO materials.

Depending on the orientation of magnetization vector relative to the reflective surface and the incident plane, three types of MOKE in reflection are distinguished: the polar Kerr effect (PMOKE), longitudinal Kerr effect (LMOKE) and transverses Kerr effect (TMOKE). The magnetization vector of B is along z-axis, y-axis and x-axis in PMOKE, LMOKE and TMOKE, respectively.

For PMOKE or LMOKE, a rotation of the polarization plane occurs when linearly polarized light reflects from a sample surface. Intensity variations of linearly polarized reflected light are observed in both PMOKE and LMOKE configurations. On the other hand, TMOKE is manifested as intensity variations and a phase shift of linearly polarized light reflected from a magnetized material. The off-diagonal component of permittivity tensor leads to an additional nonreciprocal phase shift (NRPS) for TM waves.

As graphene is a two-dimensional material with nonzero off-diagonal components of ε_{gxy} and ε_{gyx}, we study the GH effect in a PMOKE configuration with an applied magnetic field in z-axis. In the prism-graphene coupling structure, the effective permittivity components of graphene are given by Ref. [19].

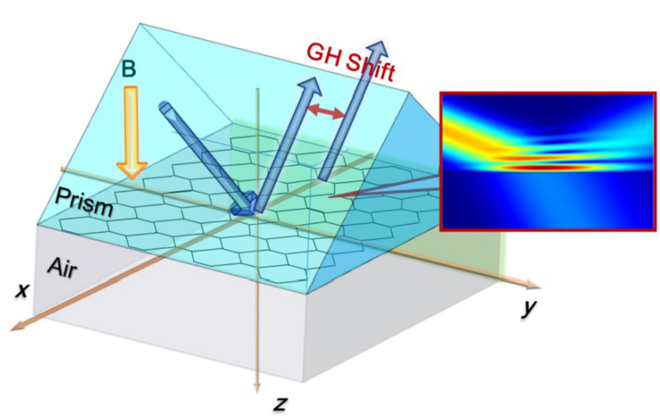

Fig. 1. Schematic of tunable GH effect in a prism-graphene coupling structure. (A colour version of this figure can be viewed online.)

$$\varepsilon_{gxx} = \varepsilon_{gyy} = \varepsilon_{gzz} = \varepsilon_0 - i\frac{e^2 E_F}{\hbar^2 \pi}\frac{1/\tau - i\omega}{\omega t_g\left[(i/\tau+\omega)^2 - \omega_c^2\right]} \tag{1}$$

and

$$\varepsilon_{gxy} = -\varepsilon_{gyx} = \varepsilon_0 - i\frac{e^2 E_F}{\hbar^2 \pi}\frac{\omega_c}{\omega t_g\left[(i/\tau+\omega)^2 - \omega_c^2\right]} \tag{2}$$

in which E_F is the Fermi energy, t_g is the effective thickness of graphene ($t_g = 0.5$ nm) and $\omega_c = eBv_F^2/|E_F|$ is the cyclotron frequency. Here v_F is the Fermi velocity ($v_F = 9.5 \times 10^5$ m/s) and e ($e = 1.6 \times 10^{-19}$ C) is the electronic charge.

A plane wave propagating in the n th ($n = 1, 2, 3$) layer satisfies the equation of

$$\boldsymbol{\gamma}^{(n)2}\boldsymbol{E}_0^{(n)} - \boldsymbol{\gamma}^{(n)}\left(\boldsymbol{\gamma}^{(n)}\cdot\boldsymbol{E}_0^{(n)}\right) = \frac{\omega^2}{c^2}\overleftrightarrow{\varepsilon}^{(n)}\mu^{(n)}\boldsymbol{E}_0^{(n)} \tag{3}$$

where $\boldsymbol{\gamma}^{(n)} = \omega(\hat{x}N_x + \hat{z}N_z)/c$ is wave vector and $\boldsymbol{E}_0$ is amplitude of electric field in the nth layer. According to the boundary conditions of electromagnetic field, the parallel components (x component) of the wave vector in each layer are equal. By solving Equation (3), we can obtain the vertical components of each wave vector. In an isotropic layer, we suppose $N_{zj}^{(n)} = N_{z0}^{(n)} (j = 1, 3)$ in which $N_{z0}^{(n)} = N^{(n)2} - N_x^2$ and $N^{(n)2} = \mu^{(n)}\varepsilon_0^{(n)}$. In the graphene layer, we assume $\varepsilon_{20} = \varepsilon_{gxx} = \varepsilon_{gyy} = \varepsilon_{gzz}$ and $\varepsilon_{21} = \varepsilon_{gxy}$. The elements of the dynamic matrix is

$$\mathbf{D}^{(2)} = \begin{bmatrix} D_{11} & -D_{11} & D_{13} & -D_{13} \\ D_{21} & D_{21} & D_{23} & D_{23} \\ D_{31} & D_{31} & D_{33} & D_{33} \\ D_{41} & -D_{41} & D_{43} & -D_{43} \end{bmatrix} \tag{4}$$

In which $D_{11} = i\varepsilon_{21}N_xN_{z1}$, $D_{13} = i\varepsilon_{21}N_xN_{z2}$, $D_{21} = D_{11}N_{z1}$, $D_{23} = D_{13}N_{z2}$, $D_{31} = (\varepsilon_{20} - N_x^2)(\varepsilon_{20} - N_x^2 - N_{z1}^2) + \varepsilon_{21}^2$, $D_{33} = (\varepsilon_{20} - N_x^2) \times (\varepsilon_{20} - N_x^2 - N_{z2}^2) + \varepsilon_{21}^2$, $D_{41} = N_{z3}[\varepsilon_{20}(\varepsilon_{20} - N_x^2 - N_{z1}^2) + \varepsilon_{21}^2]$ and $D_{43} = N_{z4}[\varepsilon_{20}(\varepsilon_{20} - N_x^2 - N_{z2}^2) + \varepsilon_{21}^2]$.

The propagation matrix of each layer can be written as

$$\mathbf{P}^{(n)} = \begin{bmatrix} e^{i(\omega/c)N_{z1}^{(n)}d^{(n)}} & 0 & 0 & 0 \\ 0 & e^{i(\omega/c)N_{z2}^{(n)}d^{(n)}} & 0 & 0 \\ 0 & 0 & e^{i(\omega/c)N_{z3}^{(n)}d^{(n)}} & 0 \\ 0 & 0 & 0 & e^{i(\omega/c)N_{z4}^{(n)}d^{(n)}} \end{bmatrix} \tag{5}$$

in which $d^{(n)}$ is the thickness of nth layer. Combining the D matrix and P matrix of each layer, a Q matrix which connects the electric field amplitudes of incident and reflected light is

$$\mathbf{Q} = \mathbf{D}^{(1)^{-1}}\mathbf{D}^{(2)}\mathbf{P}^{(2)}\mathbf{D}^{(2)-1}\mathbf{D}^{(3)} \tag{6}$$

Then the reflection coefficients of a multilayer structure can be calculated by

$$r_{ss} = \frac{Q_{21}Q_{33} - Q_{23}Q_{31}}{Q_{11}Q_{33} - Q_{13}Q_{31}} \tag{7}$$

$$r_{ps} = \frac{Q_{41}Q_{33} - Q_{43}Q_{31}}{Q_{11}Q_{33} - Q_{13}Q_{31}} \tag{8}$$

$$r_{sp} = \frac{Q_{11}Q_{23} - Q_{21}Q_{13}}{Q_{11}Q_{33} - Q_{13}Q_{31}} \tag{9}$$