Physics Letters A 381 (2017) 2876–2881

Contents lists available at ScienceDirect

Physics Letters A

www.elsevier.com/locate/pla

Active control of Imbert–Fedorov shifts with graphene-coated chiral metamaterials

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ARTICLE INFO

Article history:
Received 3 April 2017
Received in revised form 1 July 2017
Accepted 1 July 2017
Available online 5 July 2017
Communicated by V.A. Markel

Keywords:
Imbert–Fedorov shift
Graphene
Chiral metamaterial
Chemical potential

ABSTRACT

We propose a method for controlling the Imbert–Fedorov (IF) shifts of a reflected beam at a graphene-coated chiral metamaterial (CMM) interface, where graphene's chemical potential, the CMM's chirality parameter and the permittivity of dielectric at interface serve as external tunable stimuli to control the IF shifts. The spatial IF (SIF) shift and angular IF (AIF) shift are formulated by the reflection coefficients. The numerical results indicate that for *p*-polarized incident beam, the IF shifts can be controlled efficiently near the pseudo-Brewster angle through the chemical potential, and that both the high-permittivity dielectric and low-chirality CMM can bring about a broad shift modulation. Actually, the existence of graphene reduces the SIF shifts, but it can play a crucial role in the shift modulation. The above results might be helpful in exploiting various tunable terahertz-wave devices.

1. Introduction

The reflection of a bound light beam at a planar dielectric interface has interesting characteristics that have long been the subject of study [1–4]. The interest has mainly focused on the Goos–Hänchen (GH) shift [1,4] and Imbert–Fedorov (IF) shift [2, 3], which occur in the directions parallel and perpendicular to the plane of incidence, respectively [5]. Although they were found long ago, the investigations on the shifts are still active in recent years. This is because of their extensive applications in areas such as optical microscopy [6], high-sensitivity temperature sensors [7], high-sensitivity chemical vapor detection [8], metrology [9] and plasmonics [10]. The relevant studies reveal not only the inherent physics behind the phenomena [5,11–14], but also the behaviors of the shifts at various reflecting surfaces [15–18]. Despite a long history for the studies of the IF shift, only in 2006 analytical expression for the shift of a polarized Gaussian beam was derived in the correct form [19]. Comparatively, the IF shift should be further explored because it is closely related to the spin angular momentum carried by a polarized beam and conservation of the total angular momentum in the system [19–21]. Generally, the IF shift is rather tiny and difficult to observe directly, but it may be detectable now by so-called weak measurement technique [9, 22], whereby the quantum version of the IF shift, i.e., the spin Hall effect of light (SHEL) has also been observed [19].

Similar to the GH shift, the IF shift is associated with the Fresnel reflection coefficients which are sensitive to the characteristics of materials constituting an interface. For example, the GH shift in total internal reflection is positive, but it is negative for *p*-polarized light in metallic reflection; for reflection from multilayers or grating or metamaterials, the optical beam shifts can be greatly enhanced [23]. Therefore, a controllable shift can be achieved by tuning the interface properties, e.g., by using a particular substrate. Technologically, the controllable shift is helpful in future applications and experiments, such as torsion pendulum readout, geodetic surveying, atomic force microscopy, machine-tool operation and gravitational wave detectors [24]. In this respect, the graphene-coated interface might be a suitable system.

Graphene, an atom thick sheet of carbon, has been identified as a befitting material in photonics and optoelectronic applications owing to highly flexible optical properties [25–32]. Graphene's surface conductivity and surface susceptibility rely on chemical potential, frequency and temperature [31], thus the physical properties of graphene can be controlled by changing these parameters. In particular, graphene's chemical potential, depending on the concentration of free-carriers (electrons or holes), can be easily controlled by either chemical doping or external gate voltage. Recently, the beam shifts (including the GH and IF shifts) have been intensely discussed at various graphene-coated interfaces [15, 23,33–39]. Comparatively, however, only a few studies of the IF shift at chiral metamaterial (CMM) interfaces have been examined

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http://dx.doi.org/10.1016/j.physleta.2017.07.002
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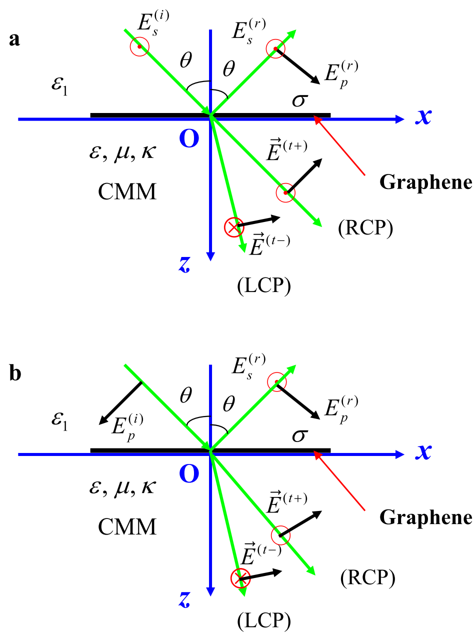

Fig. 1. Sketch of a light beam reflection at the graphene-coated CMM interface. (a) For s-polarized incident beam, and (b) for p-polarized incident beam.

[40,41]. Metamaterials are artificial effective media that can exhibit numerous extraordinary electromagnetic properties not existing in natural materials, including abnormal reflection or refraction [42,43], super-resolution imaging [44,45], electromagnetic cloaking [46,47] etc. In particular, a CMM displays tunable magnetoelectric coupling response, which can be tailored in unit-cell design by altering its chirality parameter. As a result, at the graphene-based CMM interface we can use two main means (i.e., altering graphene's chemical potential and CMM's chirality parameter) to achieve the more flexible modulation of the IF shifts.

This paper is organized as follows. We give in Section 2 the model and theoretical framework in some detail. Here, according to Maxwell's equations and the boundary conditions associated with graphene's conductivity, we utilize a 4×4 matrix method to derive the reflection coefficients for p- and s-polarized incident beams at the graphene-coated CMM interface; then, we present the formulas describing the IF shifts, which hereafter refer to the spatial IF (SIF) and angle IF (AIF) shifts. In Section 3, choosing the four-folded rotated Ω-particle CMM [48] as an example, we numerically analyze and discuss the tunability of the IF shifts by the incident angle, chemical potential, the dielectric permittivity and the CMM's chirality. Finally, we summarize the main conclusions in Section 4.

2. Model and theoretical framework

The interface under consideration and the coordinate system are sketched in Fig. 1, where a graphene sheet is sandwiched between an isotropic nonmagnetic dielectric with relative permittivity ε_1 and a CMM with effective relative permittivity ε, permeability μ and chirality parameter κ; the z-axis is normal to the interface and points to the CMM; the plane of incidence lies in the O–xz plane. Let a central plane-wave component of a Gaussian beam of angular frequency ω impinge on the $z=0$ interface at the incident angle θ.

2.1. Wave propagation in CMM

The constitutive relations in the CMM are usually written as [48]

$$\begin{pmatrix}\mathbf{D}\\ \mathbf{B}\end{pmatrix}=\begin{pmatrix}\varepsilon_0\varepsilon & i\kappa/c_0\\ -i\kappa/c_0 & \mu_0\mu\end{pmatrix}\begin{pmatrix}\mathbf{E}\\ \mathbf{H}\end{pmatrix}, \tag{1}$$

where ε_0 and μ_0 are the permittivity and permeability of vacuum; c_0 is the speed of light in vacuum. Based on the Ω-particle resonator model, the effective permittivity, permeability and chirality parameter of the four-folded rotated Ω-particle CMM are determined, respectively, by [48]

$$\varepsilon=\varepsilon_b-\frac{\Omega_\varepsilon\omega_0^2}{\omega^2-\omega_0^2+i\omega\gamma}, \tag{2a}$$

$$\mu=\mu_b-\frac{\Omega_\mu\omega^2}{\omega^2-\omega_0^2+i\omega\gamma}, \tag{2b}$$

$$\kappa=-\frac{\Omega_\kappa\omega_0\omega}{\omega^2-\omega_0^2+i\omega\gamma}, \tag{2c}$$

where ω_0 is the resonance frequency; γ is the damping coefficient; ε_b and μ_b are the permittivity and permeability of a background material, respectively, and Ω_ε, Ω_μ and Ω_κ are the coefficients of the resonance terms in ε, μ and κ. They describe the strength of the resonance and obey the relation $\Omega_\kappa^2=\Omega_\varepsilon\Omega_\mu$.

It follows from Maxwell's equations and the constitutive relations (1) that the electromagnetic tangential field components in the CMM satisfy the matrix ordinary differential equation

$$\frac{d\psi}{dz}=ik_0M\psi, \tag{3}$$

where ψ is a four-component column vector defined as $\psi(z)=(E_x,E_y,H'_x,H'_y)^T$ with $H'_{x,y}=\eta_0H_{x,y}$; the superscript 'T' stands for the transpose operator and $\eta_0=\sqrt{\mu_0/\varepsilon_0}$ is the wave impedance in vacuum; M is a 4×4 matrix in the form

$$M=\begin{pmatrix}0 & -i\kappa(A+1) & 0 & -\mu(A-1)\\ i\kappa & 0 & -\mu & 0\\ 0 & \varepsilon(A-1) & 0 & -i\kappa(A+1)\\ \varepsilon & 0 & i\kappa & 0\end{pmatrix}, \tag{4}$$

with $A=\beta^2/k_0^2(\varepsilon\mu-\kappa^2)$, $k_0=\omega/c_0$ and $\beta=k_0\sqrt{\varepsilon_1}\sin\theta$.

The general solution of Eq. (3) can be written as [49]

$$\psi(z)=Ve^{ik_0\Gamma z}\psi_0, \tag{5}$$

where ψ_0 is a 4×1 constant column vector determined by the boundary conditions; Γ and V are the 4×4 matrices that consist of the four eigenvalues and eigenvectors of M, respectively. For the geometry shown in Fig. 1, we arrange the eigenvalues and eigenvectors such that the first two columns correspond to the forward (incident or transmitted) waves and the last two columns to the backward (reflected) waves. Then, we have the diagonal matrix $\Gamma=\mathrm{diag}(q_1,q_2,-q_1,-q_2)$, where q_1 and q_2 are the two roots of the eigenvalue equation $q^2=n_\pm^2-\beta^2/k_0^2$ and satisfy $\mathrm{Re}(q_1,q_2)>0$, i.e., their real parts are positive, and $n_\pm=\sqrt{\varepsilon\mu}\pm\kappa$ are the refractive indices of the right and left circularly polarized (RCP and LCP) waves in the CMM, respectively. The matrix V reads

$$V=\begin{pmatrix}-ic_+ & ic_- & ic_+ & -ic_-\\ 1 & 1 & 1 & 1\\ -c_+m & -c_-m & c_+m & c_-m\\ -im & im & -im & im\end{pmatrix}, \tag{6}$$

with $c_+=q_1/n_+$, $c_-=q_2/n_-$, $m=\sqrt{\varepsilon/\mu}$.

To employ the boundary condition, we need the field components in the isotropic dielectric occupying the $z<0$ region. It follows from Maxwell's equations that the field components satisfy