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Large tunable negative lateral shift from graphene-based hyperbolic metamaterials backed by a dielectric

Yong-qiang Kang[a], Wenyi Ren[b], Qizhi Cao[c,*]

[a] Institute of Solid State Physics, Shanxi Datong University, Datong, Shanxi 037009, China
[b] School of Science, Northwest A&F University, Yangling 712100, China
[c] School of Physics and Electronic Information Science, Guangxi Teachers Education University, Nanning 530023, China

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ABSTRACT

Large negative lateral shift from the graphene-based hyperbolic metamaterials (GHMM) backed by a dielectric is theoretically predicted. It is demonstrated that large negative lateral shift for TM polarized reflected beam can be thousands of wavelengths near the Brewster angle. The lateral shift can be tunable by Fermi energy. Numerical simulation results for Gaussian incident beams coincide with the theoretical results from the stationary phase method. The result may have potential application in the design of photoelectronic device and optical communication systems.

1. Introduction

The Goos-Hänchen (GH) effect shift refers to lateral shift of the reflected beam on the interface for different media when a total reflection occurs, which is firstly observed by Goos and Hänchen [1,2]. Recently, the GH shifts have extensively investigated such as indefinite medium [3], photonic crystals [4], negative refractive media [5], lossless dielectric slab [6], and others. Meanwhile, some other lateral shifts also exist, in which total internal reflection does not take place but the partial reflection does [4–7]. Li found negative lateral shift when an incident light beam transmitted through an optically denser dielectric slab from air [6]. Lai et al. discussed GH effect near the Brewster resonance angle when light beam reflected on weakly absorbing medium [7]. Most recently, the manipulation of GH shift in various schemes are reported [8–10]. For instance, Wang and Zhu et al. demonstrated the GH shift by coherent control with electric field [8]. Zhao and Gao et al. reported the temperature tunable GH shift for an light beam reflected from the surface of metal/dielectric composites materials [9]. Luo et al. proposed the metal-insulator-semiconductor structure to manipulate the GH shift [10]. Besides, large lateral shift are vital for the applications on photoelectric devices [11–15]. Liu et al. demonstrated that lateral shift of the millimeter order can occur in waveguide coupling system [13]. Cheng et al. give a discussion that GH shifts could be positive or negative on a metamaterial slab [14].

Hyperbolic metamaterials (HMM) that have hyperbolic shape of the dispersion relation has been demonstrated for potential applications in optical waveguide, negative refraction and imaging hyperlens [16–20]. Biehs et al. demonstrated that hyperbolic materials can be made as the perfect black body [21]. Xiang et al. reported that the critical coupling can be realized and controlled with GHMM at the near-infrared frequency range [22]. Ning et al. demonstrated that a wideband absorber by GHMM with Fibonacci quasiperidic at the mid-infrared frequency range [23]. Considering that graphene has the characteristic behavior of the conductivity as a function of the chemical potential, and GHMM has the properties of near-perfect light absorption, in this paper, we theoretically predict a large negative lateral shift of the GHMM backed by a dielectric As expected, the conditions of resonance for the GHMM structure are altered significantly with the Fermi energy of the graphene changed. Therefore it is anticipated that the GH shift can be

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[*] Corresponding author.
E-mail address: qzhcao77@163.com (Q. Cao).

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easily manipulated by adjusting the Fermi energy. More importantly, the GH shift can be significantly enhanced and reach the thousands of wavelengths near the resonance angle (Brewster angle). We believe that the GH shift from the GHMM backed by dielectric may open up a new way for potential photoelectronic device application in future.

2. Model and method

2.1. Graphene based hyperbolic metamaterial

The graphene conductivity σ can be shown by the Kubo formula [9,10,20], and can be expressed as $\sigma = \sigma_{\text{intra}} + \sigma_{\text{inter}}$, where the intra-band σ_{intra} and inter-band σ_{inter} are given by

$$\sigma_{\text{intra}} = \frac{ie^2 k_B T}{\pi\hbar^2(\omega + i/\tau)}\left(\frac{E_f}{k_B T} + 2\ln\left(e^{-\frac{E_f}{k_B T}} + 1\right)\right), \tag{1}$$

$$\sigma_{\text{inter}} = \frac{ie^2}{4\pi\hbar}\ln\left|\frac{2E_f - \hbar(\omega + i/\tau)}{2E_f + \hbar(\omega + i/\tau)}\right|, \tag{2}$$

where $\hbar$, ω, k_B and τ are the Planck constant, incident light frequency, Boltzman constant and the electron-phonon relaxation time, respectively. e, T and E_f are an electron charge, the temperature and Fermi energy, respectively. The permittivity of the graphene sheet ε_G can be denoted as [10,20,21].

$$\varepsilon_G = 1 + i\frac{\sigma}{d_G\omega\varepsilon_0}, \tag{3}$$

where ε_0 and d_G is the permittivity in vacuum and thickness of graphene, respectively.

In the sub-wavelength limit, the GHMM is a homogeneous effective medium with anisotropic permittivity tensor components [20,22,23],

$$\varepsilon = \begin{pmatrix} \varepsilon_x & & \\ & \varepsilon_y & \\ & & \varepsilon_z \end{pmatrix}, \tag{4}$$

Where $\varepsilon_x = \varepsilon_y = \varepsilon_{\|}$, $\varepsilon_z = \varepsilon_{\perp}$. $\varepsilon_{\perp}$ and $\varepsilon_{\|}$ are the vertical and parallel parts of the permittivity, respectively, and expressed as [20,22,23].

$$\varepsilon_{\|} = \frac{d_G\varepsilon_G + d_C\varepsilon_C}{d_G + d_C}, \qquad \varepsilon_{\perp} = \frac{\varepsilon_G\varepsilon_C(d_G + d_C)}{d_G\varepsilon_C + d_C\varepsilon_G}, \tag{5}$$

where d_c and ε_C are the thickness and permittivity of dielectric, respectively. The spatial dispersive curve for TM polarization is deduced by

$$\frac{k_z^2}{\varepsilon_x} + \frac{k_x^2}{\varepsilon_z} = k_0^2, \tag{6}$$

where k_0 is wave vector in air, k_x and k_z are the wave vector in x and z direction, respectively. The dispersive curve of graphene-dielectric composite is hyperbolic while $\varepsilon_x\varepsilon_z < 0$.

2.2. GH shift of the GHMM backed a dielectric

The geometric problem is illustrated in Fig. 1. The GHMM slab is assumed with the thickness d_1 backed by a dielectric $\varepsilon_2 = 1.5$ with the thickness d_2 in air. A plane wave with incident angle θ incoming from air into the structure, the transfer matrix can be

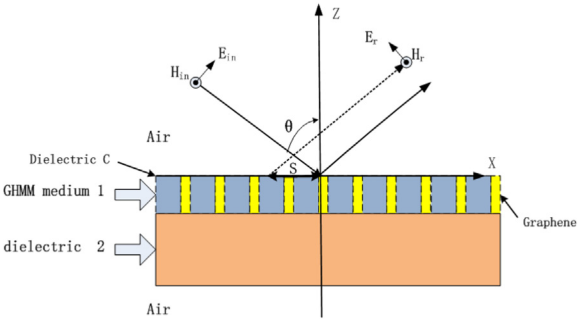

Fig. 1. Schematic diagram of light beam propagating through a GHMM backed by a dielectric in air.