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Tunable enhanced Goos–Hänchen shift in one-dimensional photonic crystals containing graphene monolayers

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ABSTRACT

Theoretically, the Goos–Hänchen effect at the interface of a one-dimensional photonic crystal containing graphene monolayers has been investigated. It was shown that the lateral shift of the reflected beam can be remarkably enhanced when the phase matching conditions are satisfied for the excitation of the surface polaritons at the interface of the structure in the graphene induced photonic band gap. The effect of the optical properties of the graphene sheets on the enhancement of the Goos–Hänchen shift was investigated and it was shown that the beam displacement can be controlled by the tuning of the chemical potential of graphene. This may have potential applications in the optical communication systems.

1. Introduction

The Goos–Hänchen (GH) shift refers to a lateral shift between the center of a reflected beam and that of the incident beam when a total reflection occurs at the interface between two media. This shift is due to the different phase change experienced by each plane wave composing the beam and was experimentally demonstrated by Goos and Hänchen in 1947 [1]. The GH shift usually has small values, much less than the beam width. However, it is known that much larger shifts may be occurred in the layered structures and photonic crystals (PCs). So, investigations have been extended to various multilayer structures [2–4].

For instance, the GH effect is investigated in the linear and nonlinear defective one-dimensional photonic crystals (1D PCs) and it is found that the lateral shifts of both reflected and transmitted beams are greatly enhanced near the defect mode of the 1D PC [5,6]. Also, the GH effect has been studied extensively in the presence of metamaterials and a large negative GH shift was obtained [7–11]. Moreover, tunable GH shift is investigated in the systems containing materials with tunable optical properties such as liquid crystals and polymers [12–14].

Among such materials, graphene, a single two-dimensional plane of carbon atoms forming a honey-comb lattice, is another alternative with tunable optical properties [15]. Beside the general features such as high mobility of carriers, flexibility, robustness and environmental stability [16,17], graphene has some properties which can make it a suitable option in designing photonic devices. Graphene has low dissipative loss in THz frequency range and its optical and electronic properties can be controlled by changing the chemical potential [18,19]. So, the optical properties of the graphene based

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structures can be easily tuned via a gate voltage. These characteristics may result in the tunable GH shift in the presence of the graphene monolayers [20].

In their recent works, the authors have been studied the photonic band gaps (PBGs) and surface polaritons (SPs) of a 1D PC containing graphene monolayers [21,22]. The investigations revealed that the mentioned structure has a new type of PBG in the THz region (i.e. graphene induced photonic band gap, (GIPBG)) which is different from the conventional Bragg gaps. It was shown that the GIPBG is omnidirectional and can support strongly localized SPs for both TM and TE polarizations which are tunable due to the controllable characteristics of the graphene monolayers. SPs are a kind of electromagnetic modes, which, after being excited, can propagate and transfer energy along the interface [23] and result in the enhanced lateral shift of the reflected and transmitted waves [24–26]. So, one can predict the occurrence of a large tunable GH shift in the graphene based 1D PCs.

In the present paper, we will study the GH effect at the interface of a 1D PC in which the graphene sheets are embedded between the adjacent dielectric layers as a controlling elements. In our numerical analysis, we use the well known transfer matrix method [23] to calculate the reflection of the structure. We show that the GH shift can be increased considerably at the incidence angle for which the SPs can be excited. The lateral shift is tunable due to the controllable optical properties of the graphene sheets. Finally, we represent a simulation of the electric field distribution in the investigated structure which verifies the enhancement of the GH shift due to the excitation of SPs.

2. Theoretical model

In this paper we only consider the TE-polarized waves in our calculations but the study can be extended to the TM-polarized waves, too. The GH shift, Δ_r of a beam reflected by a multilayer structure can be defined as $\Delta_r = -d\phi_r/dk_x$ [27], when the phase ϕ_r of the reflection coefficient is a linear function of the wave vector component k_x across the spectral width of the beam. However, if the phase ϕ_r is not a linear function of the wave vector k_x across the spectral width of the beam (e.g., for narrow beams with wide spectrum), this approximate formula for the GH shift of the beam is not completely valid. In such cases, the field profile of the reflected beam should be obtained from that of the incident beam:

$$E_r(x) = \frac{1}{2\pi}\int_{-\infty}^{+\infty} R(k_x)\bar{E}_i(k_x)e^{ik_x x}\,dk_x \tag{1}$$

where $R(k_x)$ and $\bar{E}_i(k_x)$ are the reflection coefficient and Fourier spectrum of the incident beam, respectively. The relative shift of the reflected beam is defined as the normalized first momentum of the electric field of the beam, $\Delta_r = \Delta_1$, where

$$\Delta_n = \frac{1}{a^n}\frac{\int_{-\infty}^{+\infty} x^n |E_r(x)|^2\,dx}{\int_{-\infty}^{+\infty} |E_r(x)|^2\,dx}. \tag{2}$$

Here, a is the width of the incident beam. In most cases, the reflected beam can have a complicated field profile and the GH shift defined by Eq. (2) may have different values from that of the approximate formula. $\Delta_1 \ll 1$ represents the GH shift much smaller than the width of the incident beam while $\Delta_1 \geqslant 1$ corresponds to the large lateral shifts which are observed in the experiments. The second moment of the reflected beam, calculated from Eq. (2), characterizes the relative width of the reflected beam, $W_r = \sqrt{\Delta_2}$. In this paper, we consider a Gaussian incident beam with the width a and the electric field:

$$E_i(x) = exp[-(x^2/4a^2) + ik_{xi}x]. \tag{3}$$

Here, $k_{xi} = k_i sin\theta$ is the parallel to the interface component of the incident field and $k_i = \omega\sqrt{\varepsilon_i\mu_i}/c$ is its corresponding wave number.

We consider a one-dimensional multilayer structure as depicted in Fig. 1. The input beam is incident from an optically dense medium with $\varepsilon_i\mu_i > \varepsilon_0\mu_0$ at an incident angle larger than the angle of total internal reflection. The 1D PC consists of two types of isotropic nonmagnetic dielectric materials with the permittivity of ε_1 and ε_2 and the thicknesses of d_1 and d_2, which is separated from the dense dielectric medium by a gap layer of air with the thickness d_0, permittivity $\varepsilon_0 = 1$ and permeability $\mu_0 = 1$. The PC is capped with a layer of the material with the permittivity of ε_1 but different width d_c. Here the period number is considered to be $N = 15$. The graphene monolayers are embedded between adjacent dielectric layers of the 1D PC and $\sigma_g(\omega)$ represents the surface conductivity of the graphene which is governed by Kubo formula [18,19] including the intraband and interband transition contributions as $\sigma_g(\omega) = \sigma_g^{intra}(\omega) + \sigma_g^{inter}(\omega)$, where

$$\begin{aligned}
\sigma_g^{intra}(\omega) &= \frac{e^2}{4\hbar}\frac{i}{2\pi}\left\{\frac{16k_BT}{\hbar\omega}ln\left(2\,cosh\left(\frac{\mu_c}{2k_BT}\right)\right)\right\},\\
\sigma_g^{inter}(\omega) &= \frac{e^2}{4\hbar}\left\{\frac{1}{2} + \frac{1}{\pi}arctan\frac{\hbar\omega - 2\mu_c}{2k_BT} - \frac{i}{2\pi}ln\frac{(\hbar\omega + 2\mu_c)^2}{(\hbar\omega - 2\mu_c)^2 + (2k_BT)^2}\right\}
\end{aligned} \tag{4}$$

Here, e is the charge of electron, k_B is the Boltzmann constant, T is the temperature in K and μ_c is the chemical potential which can be controlled via a gate voltage. In its general form, σ_g has both the real and imaginary parts and the equivalent permittivity of grahene monolayers is obtained by $\varepsilon_g = 1 + (i\sigma_g\eta_0/k_0d_g)$ where η_0 is the vacuum impedance, k_0 is the vacuum