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Surface wave-induced enhancement of the Goos–Hänchen shift in single negative one-dimensional photonic crystal

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ABSTRACT

The Goos–Hänchen (GH) shift in one-dimensional photonic crystal (1DPC), composed of alternate ε-negative and μ-negative materials, is theoretically investigated. It is demonstrated that larger shifts can be obtained when surface modes are excited. It is also found that the magnitude of the lateral GH shift is closely related to intrinsic loss factor. The results show that for a definite value of loss and for values larger than that, backward surface waves which lead to negative lateral GH shifts can be excited. On the other hand, there are large positive GH shifts for small loss factor less than aforementioned definite loss. The GH shift is very sensitive to the thickness of air gap which is necessary to excitation of the surface waves.

1. Introduction

When a light beam illuminates the interface between two homogeneous media, under total internal reflection, the barycenter of the reflected beam does not coincide with that of the incident one. This is the so called GH effect which has been analyzed theoretically and experimentally in literatures [1–3]. The amount of GH shift is usually much less than the beam width. However, the larger shifts can occur in layered structures, supporting surface waves, which are able to transfer energy along the interface [4]. Surface modes are special type of localized waves at the interface separating two different media [5,6]. The existence of electromagnetic surface waves was suggested by Kosswl [7] and later considered in an approximate manner by Arnaud [8]. To do an exact analysis of the optical surface waves the band theory of periodic media can be used [9]. In periodic systems, the modes that are localized at the surfaces are known as Tamm states [10]. Tamm states, at first time, have been found as the localized electronic states at the edge of a truncated periodic potential. These states have been studied in different fields of physics, including optics, in which the waves are confined within the interface of periodic and homogeneous media [9,11].

Recently, the double-negative (DNG) material (material with both negative permittivity and permeability, also called left-handed material) and the single-negative (SNG) material (material with the ε-negative (ENG) or the μ-negative (MNG) material) have attracted a great deal of attention because of their unique properties and useful applications [12–15]. The GH shift has been studied in various situations, for example, dielectric slab systems [16], left-handed materials [17] and one-dimensional photonic crystals (1DPCs) [18]. It has been also calculated for the cases of a single interface [19–21] and a periodic structure consisting of alternating right-handed and left-handed materials [22].

In the present work, we have investigated the GH shift of a Gaussian beam reflected from a layered structure composed of the alternating ENG and MNG materials. The paper is organized as follows. In Section 2, the proposed structure is introduced and the GH shift of a Gaussian beam is investigated. The surface wave excitation and its effect on the GH shift are discussed in Section 3. Finally, in Section 4, the paper is concluded.

2. Theory and calculations

Let us consider the propagation of a Gaussian beam through a 1DPC structure composed of alternate ENG and MNG layers with thicknesses of d_1 and d_2, respectively. The structure is capped by an ENG layer of width d_c (used to control the surface states [6]),

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and separated from dielectric by an air layer of width L which we will call it gap layer (see Fig. 1). The electric permittivity, ε, and magnetic permeability, μ, of the ENG and MNG layers are given by, respectively [23]

$$\varepsilon_{ENG} = 1-\frac{\omega_{ep}^2}{\omega^2+i\omega\Gamma_e}, \quad \mu_{ENG}=3 \tag{1}$$

and

$$\varepsilon_{MNG}=3, \quad \mu_{MNG}=1-\frac{\omega_{mp}^2}{\omega^2+i\omega\Gamma_m} \tag{2}$$

First, we neglect the damping terms (loss effects) in permittivity and permeability (i.e., $\Gamma_e=\Gamma_m=0$) for simplicity. The loss effects will be taken into account later. Both ω_{ep} and ω_{mp} are set to be 1×10^{10} (rad/s) [24]. Also, we take the electric permittivity and magnetic permeability of the dielectric layer as $\varepsilon_d=12.25$ and $\mu_d=1$, respectively.

The amount of GH shift is given by: $\Delta=d\phi/dk_x$, where ϕ is the phase of the beam reflection coefficient, $r=|r|\exp(i\phi)$. This relation is obtained under the assumptions that the beam experiences the total internal reflection, and the phase of the reflection coefficient ϕ is a linear function of the wave-vector component k_x across the spectral width of the beam [25]. Meanwhile, in the case where the phase ϕ is not a linear function of the wave vector component, k_x, this relation for the shift of beam is not totally valid [26].

We consider an incident beam with the Gaussian shape of $E_i=\exp[-(x/a)^2-ik_{x_0}x]$, where a is the width of incident beam, k_{x_0} determines the angle of incidence θ by $k_{x_0}=k_d\sin\theta$, and $k_d=\omega\sqrt{\varepsilon_d\mu_d}/c$ is the wave number in the medium into which the transmitted beam propagates. Each plane wave which composes the beam, experiences a different phase change and the reflected field can be found as

$$E_r(x)=\frac{1}{2\pi}\int r(k_x)\overline{E}_i(k_x)e^{ik_xx}dk_x, \tag{3}$$

where $\overline{E}_i$ is the Fourier spectrum of the incident beam and $r(k_x)$ is the reflection coefficient. Using the well-known transfer matrix method [27], the reflection coefficient for the TE-polarized wave, illustrated in Fig. 1(a), is given by: $r=-M_{12}/M_{11}$, where M_{12} and M_{11} are the elements of the total transfer matrix of the structure, $M=\prod_{j=1}^{N}M_j$. Here $M_j=\begin{pmatrix} A & B \\ B^* & A^* \end{pmatrix}$ is the transfer matrix between the adjacent (j and $j+1$) layers and can be obtained by satisfying the continuity conditions of the tangential components of the electric and magnetic fields at the interfaces of the adjacent layers where

$$A=e^{-ik_{jz}d_j}(1+(k_{(j+1)z}\mu_j/k_{jz}\mu_{(j+1)})),$$
$$B=e^{-ik_{jz}d_j}(1-(k_{(j+1)z}\mu_j/k_{jz}\mu_{(j+1)})). \tag{4}$$

In Eq. (4), k_j is defined as: $k_j=\omega\sqrt{\varepsilon_j\mu_j-\beta^2}/c$, β is the normalized wave number component along the interface and N is the total number of layers [27].

The relative shift of the beam, Δ, is defined by use of the normalized first momentum of the reflected electric field as $\Delta=\Delta_1$, and its relative width is expressed by the second momentum as $W=\sqrt{\Delta_2}$, where Δ_n is the nth momentum of the reflected beam is given by

$$\Delta_n=a^{-n}\int x^n|E_r(x)|^2dx\left(\int|E_r(x)|^2dx\right)^{-1} \tag{5}$$

$\Delta\ll1$ corresponds to a beam shift much smaller than the beam width, while $\Delta\gg1$ corresponds to a giant GH shift.

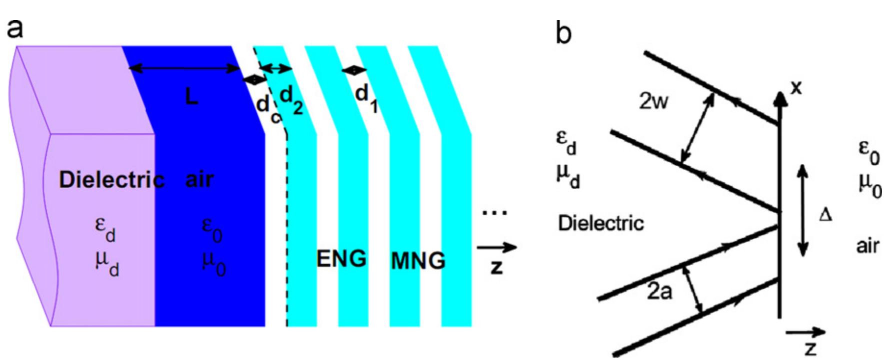

Fig. 1. The geometry of the proposed structure, (a), which consists of alternate ENG and MNG layers separated from optically dense semi-infinite dielectric by an air gap of width L and single negative ENG layer. Shows the incident Gaussian beam of width a reflected from the structure with lateral shift of Δ and reflected beam width of W, (b).

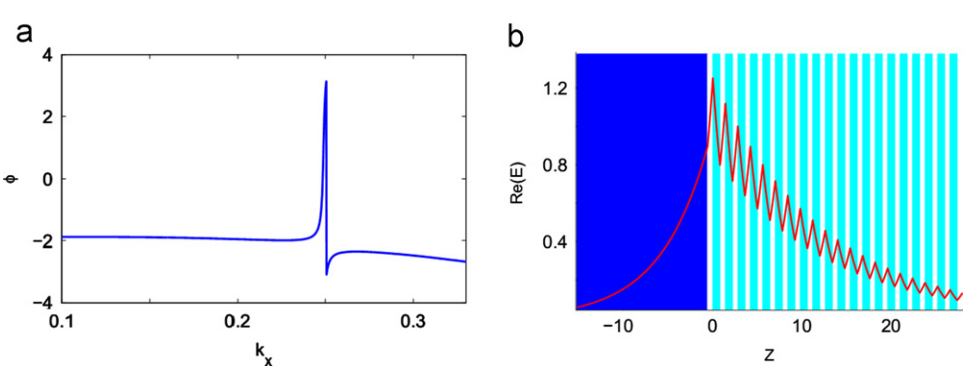

Fig. 2. The variation of the total phase shift with respect to k_x, (a). The electric field profile, (b) corresponding to the resonance wave number depicted in (a).