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Transverse shifts of a light beam reflected from a uniaxially anisotropic chiral slab

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ABSTRACT

We study for the first time the transverse shifts of a Gaussian beam reflected from a uniaxially anisotropic chiral (UAC) slab, where the chirality appears only in one direction and the host medium is a uniaxial crystal or an electric plasma. The results indicate that the transverse shifts are closely related to the propagation behaviors of the eigenwaves in the slab. Specifically, when one or both of the eigenwaves are totally reflected at the second interface of the slab, the spatial transverse shift becomes resonances but is not enhanced; when one eigenwave is totally reflected at the first interface and the other is transmitted at the second interface, the larger and negative transverse shifts can be obtained. The propagation behaviors of the eigenwaves in the UAC slab provide more abundant information about the transverse shifts than in a single interface structure.

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1. Introduction

It is known that a bound light beam experiences transverse shifts on reflection and transmission at a dielectric interface, which differs from the geometric-optics prediction. There exist two types of transverse shifts, i.e., the spatial transverse shift (STS) and the angular transverse shift (ATS) [1].

The STS occurs in the direction perpendicular to the plane of incidence. In the case of total reflection, it is usually called the Imbert-Fedorov shift [2]. When the incident beam is linearly polarized, the STS is also regarded as the spin Hall effect of light (SHEL) [3–7], which is, in essence, the split of a linearly polarized beam of light into its two right- and left-circularly polarized components (or spin components). The effect is, albeit very tiny, detectable with the current state-of-the-art measure technique and can find its potential applications in metrology and (bio)sensor.

The STS has been discussed by use of different methods. Physically, the most satisfying approach may utilize the fundamental law of conservation of angular momentum [6–9]. Based on the Noether's theorem, the total (spin and orbital) angular momentum must be conserved along the axis of symmetry of the system which is, for an obliquely incident beam on a planar optical interface, the normal to the interface. To conserve total angular momentum, the centroids of the reflected and transmitted components of an incident polarized beam undergo the shifts along the direction perpendicular to the plane of incidence. A more typical method to determine the STS consists in decomposing the incident, reflected, and transmitted beams of finite cross section into their plane wave constituents and applying the Fresnel relations to the *s* and *p* components of the individual plane waves. The spatial dependence of the reflected and transmitted beams is retrieved by summing over all partial plane waves which can be done analytically by using the paraxial approximation [3,10–13].

The ATS appears when the incident beam is elliptically polarized, because in the case the reflection (transmission) coefficients of the *s*- and *p*-polarized plane wave are different. The expression for such an ATS of the reflected beam has been obtained by Nasalski [14]. Bliokh et al. [7] have performed explicit calculations of such ATSs for both reflected and transmitted beams. The ATS also appears when the intensity distribution inside the incident beam is of no axial symmetry, that is, this distribution has an antisymmetric part relative to the plane of incidence as well as to the plane perpendicular to the former, because in the case the reflection (transmission) coefficients of the plane wave depend on the angle of incidence. Such ATSs of the reflected and transmitted beams have been discussed in Refs. [15–17].

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Clearly, the reflection and the transmission coefficients have a great impact on the transverse shifts, while the reflection and the transmission coefficients usually depend on the electromagnetic parameters of materials constituting the interface, such as the permittivity and the permeability. Therefore, a number of studies have been performed for various interface circumstances, including air–glass interface [3,18], metamaterial interfaces [5,19], isotropic–uniaxial interfaces [20,21], isotropic–chiral [22], anisotropic interfaces [23–25], etc. However, so far, almost all the studies of the transverse shifts have only focused on a single dielectric interface, viz., the interface between two semi-infinite media. The report has been relatively scant on the transverse shifts of a beam reflected on a slab or a multilayered structure. Actually, the two interfaces of a slab structure behave like the mirrors of a Fabry–Perot-type cavity to provide multiple reflections and interference effects; meanwhile, the slab structure act as a waveguide to offer waveguide modes, which might affect the properties of the transverse shifts. In addition, the structured parameters of a slab affect the transverse shifts as well. More importantly, a slab structure has potential applications in thin film metrology and biochemical sensors. A chiral medium can possesses artificially tunable electromagnetic parameters which are not realized in a conventional isotropic medium because it can be fabricated artificially by using miniature wire spirals or conducting springs, which provide additional interaction of electric and magnetic fields inside it. Recently, a uniaxially anisotropic chiral medium has been investigated [26], where the chirality appears only in one direction and the host medium is a uniaxial crystal or an electric plasma. Owing to its flexibility in design, such a uniaxially anisotropic chiral (UAC) slab might be a desirable candidate in the control of the transverse shifts.

The organization of this paper is as follows. In Section 2, using an eigenvalue method, we derive the reflection matrix of the electromagnetic wave on the UAC slab within the framework of the 4×4 matrix. With the reflection matrix, we give the expressions for the STS and the ATS. In Section 3, we examine the effects of the propagation behaviors of the two eigenwaves in the slab on the transverse shifts, and discuss numerically the dependences of the transverse shifts on the angle of incidence for three cases with different electromagnetic parameters, which provide some interesting electromagnetic properties. Finally, in Section 4 the main conclusions are summarized.

2. Basic theory

2.1. The reflection matrix

In a general anisotropic or chiral medium s and p waves are not the eigenmodes of Maxwell's equations; hence we must use the so-called reflection matrix to describe the reflection properties of a wave. Below, we derive the reflection matrix.

Assuming a Gaussian beam of angular frequency ω impinges from an isotropic medium with refractive index n_i on a UAC slab occupying the $0 \le z \le L$ region, as sketched in Fig. 1(a). Clearly, the z-axis is normal to the interface. Let $O-xz$ be the plane of incidence, and then the fields can be expressed as $\mathbf{F}=\mathbf{F}(z)e^{i(k_x x-\omega t)}$, where $\mathbf{F}$ represents the electric field $\mathbf{E}$ or the magnetic field $\mathbf{H}$; $k_x=k_0 n_i \sin\theta$, $k_0=\omega/c$ and θ is the angle of incidence of the central plane-wave component of the Gaussian beam. If the chiral particles in the UAC slab are aligned with the z-axis, the constituent relations which describe the electric displacement $\mathbf{D}$ and the magnetic induction $\mathbf{B}$ in the slab can be written as [26]

$$\mathbf{D}=\varepsilon_0(\overleftrightarrow{\varepsilon}\cdot\mathbf{E}+i\gamma\hat{z}\hat{z}\cdot\eta_0\mathbf{H}), \tag{1a}$$

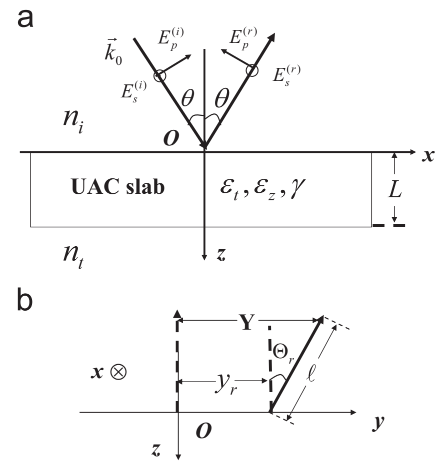

Fig. 1. (a) Schematic of a light beam reflection on the UAC slab. (b) An illustration of the transverse shifts. Here, the dashed line with arrow denotes the reflected beam predicted by the geometric optics, and the solid line with arrow stands for the practical reflected beam. y_r, Θ_r and $Y=y_r+\ell\Theta_r$ represent the STS, the ATS and the total transverse shift of a reflected beam, respectively. In this figure, both y_r and Θ_r are positive.

$$\mathbf{B}=\sqrt{\varepsilon_0\mu_0}(\overleftrightarrow{\mu}\cdot\eta_0\mathbf{H}-i\gamma\hat{z}\hat{z}\cdot\mathbf{E}), \tag{1b}$$

where $\eta_0=\sqrt{\mu_0/\varepsilon_0}$ is the wave impedance of vacuum and γ is the chirality parameter. For a nonmagnetic uniaxial host medium, the permeability tensor $\overleftrightarrow{\mu}$ is the 3×3 identity matrix, and the permittivity tensor $\overleftrightarrow{\varepsilon}$ can be cast in the form

$$\overleftrightarrow{\varepsilon}=\begin{pmatrix}\varepsilon_t & 0 & 0\\ 0 & \varepsilon_t & 0\\ 0 & 0 & \varepsilon_z\end{pmatrix}, \tag{2}$$

where ε_t and ε_z are the permittivity in the transversal and the longitudinal directions, respectively, and they can be either positive or negative, depending on the host medium.

According to the continuity of the tangential field components across the boundary, we can introduce a four-component column vector $\psi(z)=(E_x, E_y, \eta_0 H_x, \eta_0 H_y)^T$, where the superscript 'T' stands for the transpose operator. From Maxwell's equations and Eqs. (1) and (2), it follows that ψ obeys the matrix ordinary differential equation [22]

$$\frac{d\psi(z)}{dz}=ik_0 M\psi(z), \tag{3}$$

where M is a 4×4 matrix in the form

$$M=\begin{pmatrix}0 & -i\gamma a & 0 & 1-a\\ 0 & 0 & -1 & 0\\ 0 & a\varepsilon_z-\varepsilon_t & 0 & -i\gamma a\\ \varepsilon_t & 0 & 0 & 0\end{pmatrix}, \tag{4}$$

with $a=n_i^2\sin^2\theta/(\varepsilon_z-\gamma^2)$.

The general solution to Eq. (3) is straightforward and expressible as [22,27,28]

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

where ψ_0 is a 4×1 constant column vector determined by the boundary conditions; Q 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(a), we arrange the eigenvalues and eigenvectors such that the first two columns correspond to the reflected waves and the last two columns to the transmitted waves. Then, we have [22]

$$Q=\begin{pmatrix}-Q_4 & O\\ O & Q_4\end{pmatrix}, \quad V=\begin{pmatrix}V_1 & V_2\\ V_3 & V_4\end{pmatrix}, \tag{6}$$

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