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Spin Hall effect of light in one-dimensional photonic crystal

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ABSTRACT

We established a general propagating model to investigate the spin Hall effect of light in one-dimensional photonic crystal. A polarized (spin dependent) Gaussian beam which was incident obliquely through one-dimensional photonic crystal was demonstrated. Having decomposed a polarized Gaussian beam into different plane wave components charactering individual wave vectors, we revealed the transmission coefficient and reflection coefficient of each plane wave which propagates through the one-dimensional photonic crystal. It enabled us to obtain exact solution to the electric field of transmitted and reflected beams, and the analytical formula of light intensity, accordingly. A method based upon the partial differentials with the intensity distribution of the transmitted and reflected Gaussian beams was presented to determine the transverse and longitude shifts explicitly. Spin dependent shifts in one-dimensional photonic crystal provide alternative evidence for the spin Hall effect of light.

1. Introduction

The spin Hall effect has been widely concerned since it was put forward in 2004 [1]. Theories based on geometric phase (Berrys phase) and spin–orbit interaction were proposed to describe SHEL [2–7], and experiments were carried out to measure the TSs for the special case of linearly polarized incident Gaussian beam [8–10]. And, these works were focused on reflection and refraction at the interface between air and glass [3–7] or propagation in effective inhomogeneous and anisotropic medium [2]. These works confirmed previous theories on Fedorov–Imbert shift [11–13] and Goos–Hänchen shift [14]. Recently, it has been reported that SHEL occurred in spherical geometry, left-hand and other materials, research into the influence of optical materials on the spin Hall effect of light (SHEL) have become a hot topic [15–18]. However, as one of the hot topics of research on optical materials, the influence of one-dimensional photonic crystal (1D PC) on the SHEL has not yet been studied. One-dimensional photonic crystal is a structure where dielectric arranges periodically in one direction [19–21], and whose photonic omnidirectional band gap feature [22–24] has made research into SHEL a great difference theoretically and practically from previous studies. However, two difficulties have presented themselves in the research into the spin Hall effect in 1D PC. Firstly, how to settle the band gap for the wave packet propagating obliquely through 1D PC? And secondly, how to apply the transfer matrix equations extensively adopted for plane wave to Gaussian wave packet?

In view of these difficulties, we treated each plane wave component of the Gaussian wave packet as the composition of s-polarization and p-polarization according to optical theory. Applying the method of transfer matrix to s-polarization and p-polarization propagating through the 1D PC, we obtained the reflection coefficient and transmission coefficient, as well as the eigen equation of the photonic crystal. According to the eigen equation, considering that the angles of the wave packet is distributed in the area $\pm 5^{\circ}$ round the center wave vector, we plotted the frequency band diagram of 1D PC in the direction of the central vector for optical and geometry parameters of selected photonic crystals, and thus confirmed the range of the band gap. In the light of transmission coefficient and reflection coefficient, we obtained corresponding analytic formula of light intensity by calculating the electric field of transmitted and reflected beams on the basis of inverse Fourier transform and derivative theorem to Fourier transform. By means of selecting a certain polarized incident Gaussian beam with corresponding frequency within the frequency band range, we plotted the figure of light intensity distribution that is perpendicular to the propagating direction of transmitted and reflected beams, and it showed that the central position of light intensity undergoes spin-dependent transverse shift (TS) and longitude shift (LS), namely spin Hall effect of light. Also, applying the method of partial differential with analytic formula of light intensity horizontally and vertically, we derived the exact expression of TS and LS explicitly. According to the

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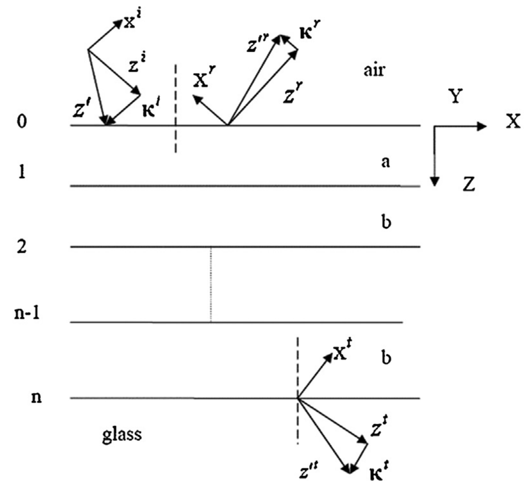

Fig. 1. Coordinate systems (x^a, y, z^a) attached to the central wave vector $\mathbf{k}_c^a (a = i, r, t)$, ($x'^a$, Y'^a, z'^a) attached to the individual plane wave vector, (X, Y, Z) established on the medium layer and $z = 0$ at interface.

expression, the amount of SHEL affected by angle of incidence and the number of photonic crystal dielectric layers were discussed through numerical analysis. Furthermore, taking for a special case of linearly polarized incident Gaussian beam, transmitted and reflected beams occurred with splitting into two circularly polarized beams due to different TS and LS respectively. These findings are widening the field of research on SHEL in 1D PC.

2. Calculation on electric field of transmitted and reflected beams

Considering one-dimensional photonic crystal, with the periodic structure of lossless dielectric layers a and b and total number of layers is n, grown on a substrate of glass, a polarized Gaussian beam being incident on the surface of the photonic crystal obliquely from air in the present propagating model (see Fig. 1), we established three kinds of coordinate systems: central coordinate system (x^a, y, z^a) attached to the central wave vector $\mathbf{k}_c^a$ ($a = i, r, t$ represent incident, reflected and transmitted beams respectively), keeping z^a-direction along geometry optical propagating direction, paraxial coordinate system (x'^a, Y'^a, z'^a) attached to the individual plane wave vector ($\mathbf{k}^a$), with the direction of Y'^a changing along with the direction of $\mathbf{k}^a$, laboratory coordinate system (X, Y, Z) established on the medium layer and the Y-direction kept up with the Y'^a-direction all the time. According to Fourier transform to spatial electric field of polarized incident Gaussian beam $\mathbf{E}_i^{(0)}(\mathbf{r})$, the individual incident plane wave vector $\tilde{\mathbf{E}}_i^{(0)}$ in the coordinate system (x^i, y, z^i)is known as [4,7],

$$\tilde{\mathbf{E}}_i^{(0)} = \pi A_0 w_0 \exp\left(-\frac{\kappa_{x^i}^2 + \kappa_y^2}{2k^{(0)} D_0}\right) \frac{1}{\sqrt{1 + |m_c|^2}} \{\mathbf{u}_{x^i} + m_c \mathbf{u}_y - (\nu_{x^i} + m_c \nu_y)\mathbf{u}_{z^i}\} \exp(i\kappa_{x^i} x^i + i\kappa_y y + ik_{z^i}^{(0)} z^i) \tag{1}$$

Herein, the parameter $D_0 = (\lambda/2.2\pi) \times 10^8/\mathrm{m}^2$ or $w_0 = \sqrt{2/k^{(0)} D_0}$ characterizes the width and phase front curvature of the beam at $z^i = 0$. $\nu_{x^i} = \kappa_{x^i}/k^{(0)}$, $\nu_y = \kappa_y/k^{(0)}$, $k^{(0)}$ and is equal to the magnitude of central wave vector $k_c^{(0)}$ approximately. κ_{x^i}, κ_y present dimensionless magnitude of wave vector component transverse to the incident central propagation direction, m_c characterizes polarization of the central plane wave of the incident beam.

By the transform connection between central coordinate system (x^i, y, z^i) and paraxial coordinate system (x', Y', z') [4],

$$\begin{aligned} \mathbf{u}_{x^i} &= \mathbf{u}_{x'} - \nu_y \cot\theta \mathbf{u}_{Y'} + \nu_{x^i} \mathbf{u}_{z'} \\ \mathbf{u}_y &= \mathbf{u}_{Y'} + \nu_y \cot\theta \mathbf{u}_{x'} + \nu_y \mathbf{u}_{z'} \\ \mathbf{u}_{z^i} &= \mathbf{u}_{z'} - \nu_{x'} \mathbf{u}_{x'} - \nu_y \mathbf{u}_{Y'} \end{aligned} \tag{2}$$

we expressed the individual incident plane wave in the coordinate system (x', Y', z') as,

$$\tilde{\mathbf{E}}_i^{(0)} = \frac{(1 + m_c \nu_y \cot\theta)\mathbf{u}_{x'} + (m_c - \nu_y \cot\theta) u_{Y'}}{\sqrt{1 + |m_c|^2}} \pi A_0 w_0 \exp\left(-\frac{\kappa_{x^i}^2 + \kappa_y^2}{2k^{(0)} D_0}\right) \exp(ik_{z'}^{(0)} z') \tag{3}$$

According to optical theory [25], expression $\tilde{\mathbf{E}}_i^{(0)}$ in Eq. (3) is equivalent to composition of s-polarization along $u_{Y'}$ direction and p-polarization along $\mathbf{u}_{x'}$ direction, i.e., $\tilde{\mathbf{E}}_i^{(0)} = \tilde{\mathbf{E}}_{is}^{(0)} + \tilde{\mathbf{E}}_{ip}^{(0)}$.