Enhanced and switchable spin Hall effect of light near the Brewster angle on reflection

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(Received 21 August 2011; published 5 October 2011)

We theorize an enhanced and switchable spin Hall effect (SHE) of light near the Brewster angle on reflection and demonstrate it experimentally. The obtained spin-dependent splitting reaches 3200 nm near the Brewster angle, which is 50 times larger than the previously reported values in refraction. We find that the amplifying factor in weak measurement is not a constant, which is significantly different from that in refraction. As an analogy of SHE in an electronic system, a switchable spin accumulation in SHE of light is detected. We were able to switch the direction of the spin accumulations by slightly adjusting the incident angle.

DOI: 10.1103/PhysRevA.84.043806 PACS number(s): 42.25.−p, 42.79.−e, 41.20.Jb

I. INTRODUCTION

The spin Hall effect (SHE) of light can be regarded as a direct optical analogy of SHE in an electronic system where the spin electrons and electric potential are replaced by spin photons and refractive index gradient, respectively [1–3]. Recently, the SHE of light has been intensively investigated in different physical systems, such as high-energy physics [4,5], plasmonics [6], optical physics [7–10], and semiconductor physics [11]. The SHE of light is generally believed to be a result of an effective spin-orbital interaction, which describes the mutual influence of the spin (polarization) and the trajectory of the light beam. In general, the spin-dependent splitting in these physical systems is limited by a fraction of the wavelength, which is a disadvantage for potential application to nanophotonic devices.

The SHE in an electronic system offers an effective way to manipulate the spin particles, which promises potential applications in semiconductor spintronic devices [12–14]. The generation and manipulation of spin-polarized electrons in semiconductors define the main challenges of spin-based electronics [15]. In semiconductor systems, the spin accumulation can be switched by altering the directions of an external magnetic field [16,17]. By rotating the polarization plane of the exciting light, the directions of spin current can be switched in a semiconductor microcavity [18,19]. Now a question arises: Is there a similar phenomenon in SHE of light? In this paper, we reveal an enhanced and switchable SHE of light near the Brewster angle on reflection.

The SHE of light has been studied in reflection both in theory [20–22] and in experiments [23]. From the viewpoint of Fourier optics, we know that the incident beam can be expressed in terms of the angular spectrum components, which are incident at different angles. The requirement in the paraxial propagation model is that the angular width of the beam should be small, and therefore the higher-order terms of Fresnel reflection coefficients can be ignored. When the beam is incident near the Brewster angle, the reflection coefficients of different angular spectrum components are sensitive to its incident angle and the higher-order terms should be taken into account. Hence, the developed paraxial propagation model cannot be applied, and the experimental evidence still does not describe the SHE of light near the Brewster angle.

The paper is organized as follows. First, we develop a general propagation model to describe the SHE of light near the Brewster angle on reflection. Next, we attempt to reveal the enhanced SHE of light in theory and detect the large spin-dependent splitting in an experiment via weak measurements. The large spin-dependent splitting is attributed to the large ratio between the Fresnel reflection coefficients near Brewster angle. Finally, we explore the switchable SHE of light. We demonstrate that the transverse displacements can be tuned to either a negative or a positive value, or even zero, by slightly adjusting the incident angle. The underlying secret can be inferred because the horizontal field component changes its phase across the Brewster angle. As an analogy of SHE in an electronic system, the spin accumulations can be switched in the SHE of light.

II. GENERAL PROPAGATION MODEL

We first develop a general propagation model to describe the SHE of light near the Brewster angle on reflection. The z axis of the laboratory Cartesian frame (x,y,z) is normal to the air-prism interface. We use the coordinate frames (x_i,y_i,z_i) and (x_r,y_r,z_r) to denote incident and reflection, respectively [Fig. 1(a)]. In the spin basis set, the incident angular spectrum can be written as

$$\tilde{\mathbf{E}}_i^H = \frac{1}{\sqrt{2}}(\tilde{\mathbf{E}}_{i+} + \tilde{\mathbf{E}}_{i-}), \tag{1}$$

$$\tilde{\mathbf{E}}_i^V = \frac{1}{\sqrt{2}}i(\tilde{\mathbf{E}}_{i-} - \tilde{\mathbf{E}}_{i+}). \tag{2}$$

Here, H and V represent horizontal and vertical polarizations, respectively. $\tilde{\mathbf{E}}_{i+} = (\mathbf{e}_{ix} + i\mathbf{e}_{iy})\tilde{E}_i/\sqrt{2}$ and $\tilde{\mathbf{E}}_{i-} = (\mathbf{e}_{ix} - i\mathbf{e}_{iy})\tilde{E}_i/\sqrt{2}$ denote the left and right circularly polarized (spin) components, respectively. We consider the incident beam with a Gaussian distribution, and its angular spectrum can be written as

$$\tilde{E}_i = \frac{w_0}{\sqrt{2\pi}} \exp\left[-\frac{w_0^2\left(k_{ix}^2 + k_{iy}^2\right)}{4}\right], \tag{3}$$

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where w_0 is the beam waist. The complex amplitude for the reflected beam can be conveniently expressed as

$$\mathbf{E}_r(x_r,y_r,z_r) = \int dk_{rx}dk_{ry}\tilde{\mathbf{E}}_r(k_{rx},k_{ry})\exp[i(k_{rx}x_r + k_{ry}y_r + k_{rz}z_r)], \tag{4}$$

where $k_{rz} = \sqrt{k_r^2 - (k_{rx}^2 + k_{ry}^2)}$ and $\tilde{\mathbf{E}}_r(k_{rx},k_{ry})$ is the reflected angular spectrum.

The reflected angular spectrum is related to the boundary distribution of the electric field by means of the relation [2]

$$\begin{bmatrix} \tilde{E}_r^H \\ \tilde{E}_r^V \end{bmatrix} = \begin{bmatrix} r_p & \frac{k_{ry}(r_p+r_s)\cot\theta_i}{k_0} \\ -\frac{k_{ry}(r_p+r_s)\cot\theta_i}{k_0} & r_s \end{bmatrix} \begin{bmatrix} \tilde{E}_i^H \\ \tilde{E}_i^V \end{bmatrix}, \tag{5}$$

where r_p and r_s denote the Fresnel reflection coefficients for parallel and perpendicular polarizations, respectively. In Eq. (5), we have introduced the boundary condition $k_{rx} = -k_{ix}$ and $k_{ry} = k_{iy}$. By making use of a Taylor series expansion based on the arbitrary angular spectrum component, r_p and r_s can be expanded as a polynomial of k_{ix}:

$$r_{p,s}(k_{ix}) = r_{p,s}(k_{ix}=0) + k_{ix}\left[\frac{\partial r_{p,s}(k_{ix})}{\partial k_{ix}}\right]_{k_{ix}=0} + \sum_{j=2}^{N}\frac{k_{ix}^N}{j!}\left[\frac{\partial^j r_{p,s}(k_{ix})}{\partial k_{ix}^j}\right]_{k_{ix}=0}. \tag{6}$$

The reflection coefficient changes its sign across the Brewster angle, which means the electric field reverses its directions [Figs. 1(b) and 1(c)]. The polarizations associated with the angular spectrum components experience different rotations in order to satisfy the boundary condition after reflection.

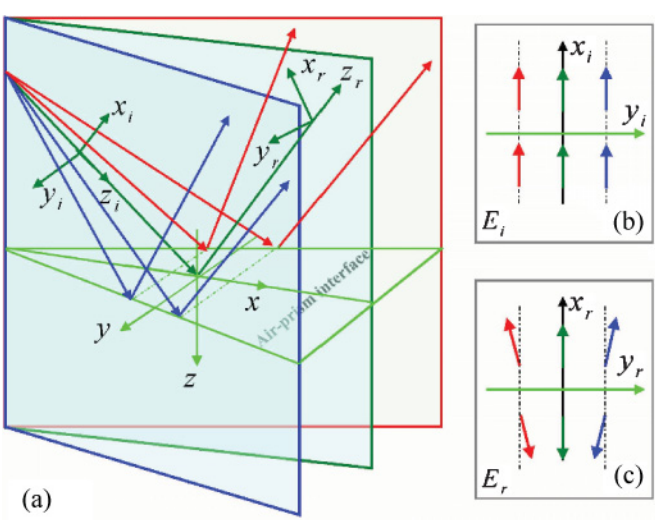

FIG. 1. (Color online) (a) Schematic illustrating the reflection of central and local wave vectors at an air-prism interface in a Cartesian coordinate system. (b) The incidence beam has a uniform polarization in the cross section. (c) The polarization components experience different rotations in reflection to satisfy transversality.

In the spin basis set, the reflected angular spectrum can be written as

$$\tilde{\mathbf{E}}_r^H = \frac{1}{\sqrt{2}}(\tilde{\mathbf{E}}_{r+} + \tilde{\mathbf{E}}_{r-}), \tag{7}$$

$$\tilde{\mathbf{E}}_r^V = \frac{1}{\sqrt{2}}i(\tilde{\mathbf{E}}_{r-} - \tilde{\mathbf{E}}_{r+}). \tag{8}$$

We consider the incident Gaussian beam with H polarization. In fact, after the incident angular spectrum is known, Eq. (4), together with Eqs. (3)–(8), provides the general expression of the reflected field:

$$\mathbf{E}_{r\pm}^H = \frac{r_p(\mathbf{e}_{rx} \pm i\mathbf{e}_{ry})}{\sqrt{\pi}w_0}\frac{z_R}{z_R + iz_r}\exp\left[-\frac{k_0}{2}\frac{x_r^2+y_r^2}{z_R+iz_r}\right] \times\left[r_p - \frac{ix}{z_R+iz_r}\frac{\partial r_p}{\partial\theta_i} \pm \frac{y}{z_R+iz_r}(r_p+r_s) \pm\frac{ixy}{(z_R+iz_r)^2}\left(\frac{\partial r_p}{\partial\theta_i}+\frac{\partial r_s}{\partial\theta_i}\right)\right]\exp(ik_r z_r), \tag{9}$$

where $z_R = k_0 w_0^2/2$ is the Rayleigh length. Our analysis is confined to the first order in Taylor series expansion of Fresnel reflection coefficients.

III. SPIN HALL EFFECT OF LIGHT

We now determine the spin-dependent splitting of field centroid. At any given plane $z_a = \text{const}$, the transverse displacement of field centroid compared to the geometrical optics prediction is given by

$$\delta_\pm^H = \frac{\int\int y_r I_\pm^H(x_r,y_r,z_r)\mathrm{d}x_r\mathrm{d}y_r}{\int\int I_\pm^H(x_r,y_r,z_r)\mathrm{d}x_r\mathrm{d}y_r}. \tag{10}$$

The intensity distribution of beam is closely linked to the longitudinal momentum currents $I(x_r,y_r,z_r) \propto \mathbf{p}_r\cdot\mathbf{e}_{rz}$. The time-averaged linear momentum density associated with the electromagnetic field can be shown to be $\mathbf{p}_r \propto \mathrm{Re}[\mathbf{E}_r \times \mathbf{H}_r^*]$, where the magnetic field can be obtained by $\mathbf{H}_r = -ik_r^{-1}\nabla\times\mathbf{E}_r$.

To detect the displacements, we use the signal enhancement technique [3] known from weak measurements [24,25]. In principle, this enhancement mechanism of this setup can be presented in a classical description [21]. Figure 2 illustrates the experimental setup. A Gaussian beam generated by a He-Ne laser passes through a short focal length lens (lens 1) and a polarizer (GLP1) to produce an initially polarized focused beam. When the beam impinges onto the prism interface, the electrical fields of the two spin components experience different rotations in order to satisfy the boundary condition [see Eq. (5)]. As a result of the polarization-dependent Fresnel reflections at the interface, the opposite displacements of the two spin components actually depend on the input polarization state. The prism was mounted to a rotation stage, which allows for precise control of the incident angle θ_i. The incident beam is preselected in the H polarization state ($\alpha = 0$) by GLP1 and then postselected ($\beta = \pi/2 + \Delta$) by GLP2 in the polarization state with

$$\mathbf{V} = \sin\Delta\mathbf{e}_{rx} + \cos\Delta\mathbf{e}_{ry}. \tag{11}$$

In our measurement, we chose $\Delta = 2 \pm 0.04^\circ$. Note that the interesting cross-polarization effect can be observed as

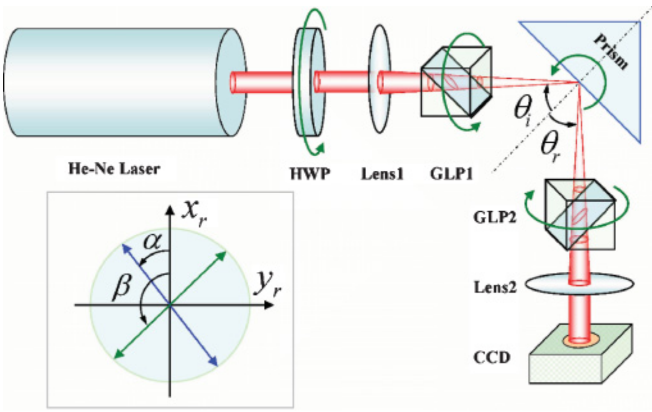

FIG. 2. (Color online) (a) Experimental setup for characterizing the SHE of light in reflection near the Brewster angle. Prism with refractive index $n = 1.515$ (BK7 at 632.8 nm); Lens 1 and Lens 2, lenses with effective focal lengths of 50 mm and 250 mm, respectively; HWP, half-wave plate (for adjusting the intensity); GLP1 and GLP2, Glan laser polarizers; and CCD, charge-coupled device (Coherent LaserCam HR). The light source is a 17-mW linearly polarized He-Ne laser at 632.8 nm (Thorlabs HRP170). The inset clarifies the Glan laser polarizer whose axis is at angles α and β with x_r.

$\Delta = 0$ [26]. As the reflected beam of light splits into several wavelengths, the intensity distribution on the prism interface is nearly unchanged. After the second polarizer GLP2, the two splitting components interfere and produce a field redistribution whose centroid is significantly amplified. We use a CCD to measure the amplified displacement after a long-focal-length lens (lens 2).

The weak measurement of SHE of light is schematically shown in Fig. 3(a). The theoretical transverse displacements given in Eq. (10) show that the two opposite-spin components would have opposite tendencies versus θ_i [Fig. 3(b)]. It indicates that the SHE of light can be greatly enhanced near the Brewster angle. The spin-dependent splitting is 3200 nm at $\theta_i = 56^\circ$, which is 50 times larger than the previous reported values of refraction [3]. The relevant amplitude of the reflected field at the plane of z_r can be obtained as $\mathbf{V} \cdot \mathbf{E}_r^H$. The amplified displacement of field centroid δ_w at the CCD is much larger than the original displacement $|\delta_\pm^H|$. Calculation of the centroid of the distribution of $\mathbf{V} \cdot \mathbf{E}_r^H$ yields the amplifying factor $A_w = \delta_w/\delta_+^H$. Our experimental results for the amplified displacement δ_w versus the incident angle θ_i are reported in Fig. 3(c). We measure the displacements every 0.5° from 52° to 60°. The measured values allow for calculating the original displacement caused by SHE of light. The solid lines represent the theoretical predictions. It should be noted that the amplifying factor in weak measurements is always the same in refraction [3]. However, it presents a valley near the Brewster angle on reflection [Fig. 3(d)]. The experimental results are in good agreement with the theory without using parameter fit.

It is known that the transverse displacements are related to the ratio between the Fresnel coefficients [27]. The reflection coefficient of horizontal polarization r_p vanishes at exactly the Brewster angle and changes its sign across the angle. Hence, the large spin-dependent splitting in SHE of light is attributed to the large ratio of r_s/r_p near the Brewster angle. In contrast,

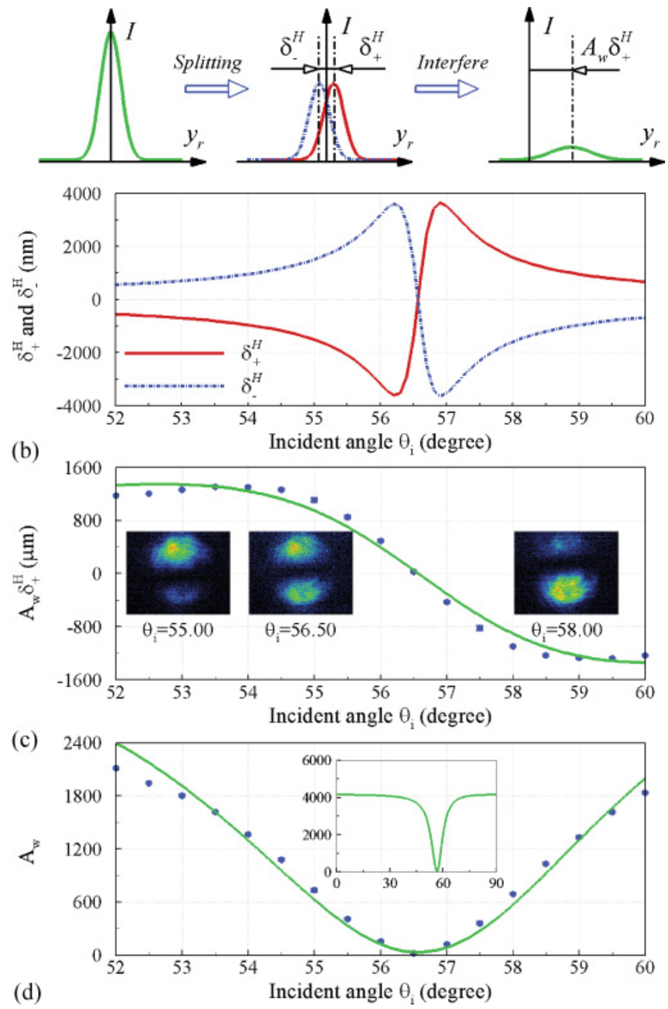

FIG. 3. (Color online) (a) Preselection and postselection polarization give rise to an interference in the CCD, shifting it to its final centroid position proportional to $A_w = \delta_w/\delta_+^H$. (b) Theoretical spin-dependent transverse splitting of spin components at the prism interface. (c) Theoretical and experimental results for amplifying displacements δ_w. Insets show the measured field distribution. (d) Theoretical and experimental results for amplifying factor A_w in the weak measurement. Inset presents a full view.

a small ratio of r_s/r_p would greatly suppress the SHE of light. It should be mentioned that a large value of $\partial r_p/\partial\theta_i$ near Brewster angle will lead to large Goos-Hanchen shifts [28] and angular shifts [29]. It should be noted that the horizontal component of the electric field alters its phase, but the vertical component does not. As a result, the phase difference $\arg[r_s] - \arg[r_p]$ varies π, and the spin accumulation would reverse its directions accordingly. Due to the reversed spin-dependent splitting, the directions of spin accumulation can be switched by slightly adjusting the incident angle.

The SHE of light may open new opportunities for manipulating photon spin and developing a new generation of all-optical devices as counterparts of recently developed spintronics devices [3,15]. It should be mentioned that the spatial separation of the spin components is very small in the refraction, which is a disadvantage for potential application to nanophotonic devices. In refraction [3] and photon tunneling

[30], the reversed spin accumulation requires the reversed refractive index gradient. As shown, the transverse displacements can be tuned to either a negative or a positive value, or even zero, by just adjusting the incident angle. Hence, our scheme provides more flexibility for switching the direction of the spin accumulations. These interesting phenomena show promise for potential applications in spin-based nanophotonic devices. Because of the close similarity of the Brewster angle in optical physics, condensed matter [31], and plasmonics [32], by properly facilitating the reflection near the Brewster angle, the SHE may be effectively modulated in these physical systems.

IV. CONCLUSIONS

In conclusion, we have revealed an enhanced and switchable spin-dependent splitting near the Brewster angle on reflection. The detected spin-dependent splitting reaches 3200 nm near the Brewster angle and is 50 times larger than the previously reported values in refraction. We have found that the amplifying factor is not a constant, which is significantly different from the refraction case. The enhanced spin-dependent splitting is attributed to the large ratio between the Fresnel reflection coefficients near the Brewster angle. As an analogy of SHE in electronic system, the switchable SHE of light has been detected, which can be interpreted from the inversion of horizontal electric field vector across the Brewster angle. We were able to switch the directions of the spin accumulation by slightly adjusting the incident angle near the Brewster angle. These findings provide a pathway for modulating the SHE of light and thereby open the possibility of developing new nanophotonic devices.

ACKNOWLEDGMENTS

We are sincerely grateful to the anonymous referee, whose comments have led to a significant improvement of our paper. This research was partially supported by the National Natural Science Foundation of China (Grant Nos. 61025024, 11074068, and 10904036).

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