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Large in-plane asymmetry spin angular shifts of light beam near critical angle

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Photonic spin Hall effect (SHE) manifests itself as the transverse and in-plane spin-dependent shifts of light beam. Normally, the spin shifts are tiny due to the weak spin-orbit coupling. Therefore, it is very important and interesting to explore some effective methods for enhancing this phenomenon. In this letter, we theoretically propose and experimentally verify a simple method for obtaining the large and asymmetric in-plane spin angular shifts when an arbitrary linearly polarized beam reflects near the critical angle (for total internal reflection). The universal expressions of spatial and angular shifts are deduced. Remarkably, by modulating the incident and polarization angles, the left- and right-handed circularly polarized components can be distinguished directly. © 2018 Optical Society of America

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The plane wave reflects and refracts at a planar interface following the traditional Snell's Law and the Fresnel formulas. However, the situation is different for the spatial confined light beam. When a linearly polarized light beam passes from one material to another with different refractive index, the left- and right-handed circularly polarized components will split in both the transverse and in-plane directions [1, 2]. This interesting phenomenon called photonic spin Hall effect (SHE) has attracted much attention [3–13]. The photonic SHE can be regarded as an optical analogy of SHE in the electronic system and its physical mechanism is attributed to the spin-orbit coupling which lies in the transverse properties of the light polarization [4, 13]. As for the spatially confined beam, the polarization states corresponding to the plane wave components undergo different rotations

for satisfying the transversality ($\mathbf{k} \cdot \mathbf{E} = 0$) after reflection and refraction [3].

Interestingly, the photonic SHE holds great potential applications in precision metrology owing to the reason that the spin-dependent shifts in photonic SHE are very sensitive to the physical parameter variations of different systems [14–16]. However, the spin-dependent displacements of photonic SHE in these systems are too small to be detected directly. Although using the weak measurement technique [17–19] can resolve this problem, it is still very important to explore some effective methods for amplifying this effect. Recently, some works have been proposed to get large spin shifts. By considering the light beam reflection at air-glass interface near the Brewster angle, the large transverse and in-plane spatial spin splitting were explored [20–22]. The surface plasmon resonance effect can also be used to amplify the spatial and angular spin shifts [23, 24]. It was also possible to directly measure the photonic SHE by eliminating the influence of the in-plane wavevector [25].

In this work, we theoretically and experimentally study the in-plane SHE of light beam on reflection near the critical angle [for total internal reflection (TIR)]. We derive the general expressions of the spatial and angular spin shifts. It should be noted that some equations have been obtained when the light beam reflects at the air-glass interface without TIR [26]. However, these expressions are not valid for the TIR condition because the Fresnel coefficients are complex. In addition, the spin-dependent angular shifts and asymmetric spatial shifts were not explored. As for our theory, it works well in both TIR and non-TIR situations. It is found that the angular shifts are spin independent or spin-dependent when the incident angles are smaller or larger than the critical angle. Remarkably, the large and asymmetric in-plane spin angular shifts are explored by choosing the optimal incident and polarization angles.

To reveal the in-plane asymmetric photonic SHE in TIR, we should establish the general propagation model to describe the light beam reflection at the glass-air interface. As shown in Fig. 1,

Fig. 1. Schematic of the in-plane asymmetric photonic SHE in the glass-air model. An arbitrary linearly polarized beam (with polarization angle β) reflects near the critical angle leading to the spatial ($\delta_{\pm}^x$) and angular ($\Delta_{\pm}^x$) shifts of left- and right-handed circularly polarized components. Here, θ is the incident angle and the transverse spin displacements are not considered. The inset shows the overall reflection model.

we first consider the incident beam with a Gaussian distribution, and its angular spectrum can be written as

$$\tilde{E}_i = \frac{w}{\sqrt{2\pi}} \exp \left[-\frac{w^2(k_{ix}^2 + k_{iy}^2)}{4} \right], \quad (1)$$

where w is the beam waist. For arbitrary linearly polarized incident beam, its polarization states can be expressed by the Jones vector $(\cos \beta, \sin \beta)^T$ in which the β represents for the polarization angle (the angle between the incident central wave vector and x_i axis). It is noted that the in-plane spin splitting will be zero when the polarization angle is chosen as 0 or $\pi/2$ [26].

The reflected angular spectrum can be calculated using the three-dimensional boundary matrix [20]

$$\begin{bmatrix} \tilde{E}_r^H \\ \tilde{E}_r^V \end{bmatrix} = \begin{bmatrix} r_p & \frac{k_{ry} \cot \theta (r_p + r_s)}{k} \\ -\frac{k_{ry} \cot \theta (r_p + r_s)}{k} & r_s \end{bmatrix} \begin{bmatrix} \tilde{E}_i^H \\ \tilde{E}_i^V \end{bmatrix}. \quad (2)$$

Here, r_p and r_s denote the Fresnel reflection coefficients for horizontal (H) and vertical (V) polarizations in glass-air model (not shown here), and k is the wave number. Using the relationship $\tilde{E}_r^H = (\tilde{E}_{r+} + \tilde{E}_{r-})/\sqrt{2}$ and $\tilde{E}_r^V = i(\tilde{E}_{r-} - \tilde{E}_{r+})/\sqrt{2}$, we can get the reflected angular spectrum of left- (positive sign in subscript) and right-handed (negative sign in subscript) circularly polarized components. Next, we need to determine the reflected field centroid of these two parts. In the present work, we only consider the spin shifts in the x direction. At any given plane $z = \text{const.}$, the in-plane spin displacements of field centroid compared to the geometrical-optics prediction are given by

$$\langle \mathbf{x}_{r\pm} \rangle = \frac{\langle \tilde{E}_{r\pm} | i \partial_{\mathbf{k}_{rx}} | \tilde{E}_{r\pm} \rangle}{\langle \tilde{E}_{r\pm} | \tilde{E}_{r\pm} \rangle} + \frac{z}{nk} \frac{\langle \tilde{E}_{r\pm} | \mathbf{k}_{rx} | \tilde{E}_{r\pm} \rangle}{\langle \tilde{E}_{r\pm} | \tilde{E}_{r\pm} \rangle}. \quad (3)$$

In the above equation, $\partial_{\mathbf{k}_{rx}} = \frac{\partial}{\partial k_{rx}} \mathbf{e}_{rx}$ and $\mathbf{k}_{rx} = k_{rx} \mathbf{e}_{rx}$. n is the refractive index of glass. The first and second terms in Eq. (3) denote the spatial and angular spin shifts, respectively. To get the correct results, we should expand the Fresnel reflection coefficients around the central wave vector (Taylor series expansion)

Fig. 2. The in-plane spatial [(a)-(d)] and angular [(e)-(h)] spin shifts with different incident and polarization angles. The refractive index of glass is chosen as $n = 1.515$ and the corresponding critical angle is 41.305° . Here, the propagation distance of light beam is selected as $z = 250 \text{ mm}$.

for introducing the in-plane wave vector part [20, 26]:

$$r_{p,s} = r_{p,s}(\theta) + \frac{\partial r_{p,s}}{\partial \theta} \frac{k_{ix}}{k}. \quad (4)$$

If the incident angle is larger than the critical angle, the Fresnel reflection coefficients become the complex numbers (including the real and imaginary parts). For a general consideration, we rewrite the above parameters as: $r_p(\theta) = p + ip$, $r_s(\theta) = s + i\zeta$, $\partial r_p / \partial \theta = \chi + i\gamma$, and $\partial r_s / \partial \theta = \eta + i\epsilon$. Put everything together, we can obtain the expressions of the in-plane spatial and angular shifts

$$\delta_\sigma^x = \frac{kw^2(A + \sigma B + C)}{D + E + \sigma F}, \quad (5)$$

$$\Delta_\sigma^x = \frac{2z(G + \sigma H + J)}{n(D + E + \sigma K)}. \quad (6)$$

Here, $A = (\rho\chi - p\gamma) \cos \beta^2$, $B = (-\gamma\zeta + p\eta + \epsilon\rho - s\chi) \cos \beta \sin \beta$, $C = (\zeta\eta - s\epsilon) \sin \beta^2$, $D = (\gamma^2 + k^2 w^2 p^2 + k^2 w^2 \rho^2 + \chi^2) \cos \beta^2$, $E = (\epsilon^2 + k^2 w^2 s^2 + k^2 w^2 \zeta^2 + \eta^2) \sin \beta^2$, $F = (-\gamma\eta + k^2 w^2 p\zeta - k^2 w^2 s\rho + \epsilon\chi) \sin 2\beta$, $G = -(\gamma\rho + p\chi) \cos \beta^2$, $H = (s\gamma - p\epsilon + \eta\rho - \zeta\chi) \cos \beta \sin \beta$, $J = -(\epsilon\zeta + s\eta) \sin \beta^2$, and $K = (p\zeta - s\rho)k^2 w^2 \sin 2\beta$. And the polarization operator $\sigma = \pm 1$ corresponds to left- and right-handed circularly polarized beam, respectively.

The above two equations are the main results of this work. If the incident angle is smaller than the critical angle, the Fresnel reflection coefficients are pure real numbers. Therefore, as for the spatial shifts δ^x , the components A , C , and F are zero. It is found that this spatial shift is spin-dependent (corresponding to σB). As for the angular displacements Δ^x , the components σH and σK are zero. It is shown that this angular shifts is spin independent. These results are similar to the previous work [26]. However, if the incident angle is larger than the critical angle, the Fresnel reflection coefficients are imaginary numbers and the theory should be extended to the general cases [Eqs. (5) and (6)]. Under this condition, we can clearly see that both the spatial and angular shifts have the spin-dependent components (σ dependent) and represent the asymmetric properties. We should also note that the spatial spin displacements are non-zero when the polarization angle is chosen as $\beta = 0$, which is significantly different from the air-glass interface case. This is another interesting result in the present work.

Now, we have established the general theory of spatial and angular spin shifts of light beam near the critical angle. Next, we will explore the corresponding features of beam shifts by considering the different incident and polarization angles. Here, the wavelength of the light is chosen as $632.8nm$. Thus, the refractive index of glass is 1.515 and the matched critical angle is 41.305° . And we choose the initial waist as $w = 27\mu m$. Figure 2 shows the spatial and angular shifts of light beam with incident angle slightly smaller or larger than the critical angle. Here, the incident angles are fixed to four values $\theta = 40^\circ$, 41.3° , 41.31° , and 43° . And the propagation distance of light is fixed to $z = 250mm$. In the case of incident angles $\theta = 40^\circ$ and 41.3° , we can find that the spatial shifts of left- and right-handed circularly polarized components show opposite signs but equal values [Figs. 2 (a) and 2 (b)]. As the increasing of the incident angles, the spin-dependent spatial displacements can be amplified. For a fixed incident angle, the spin shifts first increase with the polarization angle. Then, after reaching its maximum values, the displacements decrease gradually to zero. In this incident angle range, the angular shifts show very different properties. It is spin independent allowing for the overlap of the left- and right-handed circularly polarized parts, as shown in Figs. 2 (e) and 2 (f). When the polarization angle is zero, the angular shifts reach its maximum values. As the polarization angle increasing, the angular displacements also gradually decrease. In this case, the large spin independent angular shifts can be seen as the angular Goos-Hänchen shifts [27–29].

Under the condition of incident angles $\theta = 41.31^\circ$ and 43° , the TIR situation matches. Figures 2 (c) and 2 (d) describe the spatial shifts changing with the polarization angles. We can also clearly see that it shows spin-dependent features. However, the asymmetric spin-dependent displacements appear, which is different from the non-TIR case. When the incident angle is close to the critical angle, the spatial shifts show the relative large values. The in-plane angular displacements are shown in Figs. 2 (g) and 2 (h). Remarkably, it is revealed that the angular shifts represent the spin-dependent properties. Here, the left- and right-handed circularly polarized components show asymmetric splitting. As the increasing of the polarization angles, the asymmetric characteristics are more clear. It should be noted that there exists a large spin angular shifts (about $220\mu m$) when the incident angle is selected as $\theta = 41.31^\circ$ slightly larger than the critical angle. In this case, it is possible to directly observe the splitting of the left- and right-handed circularly polarized components. Thus, we can develop a tunable photonic SHE

Fig. 3. The light intensity distribution and angular shifts of left- and right-handed circularly polarized components. (a)-(f) show the total in-plane spin shifts in photonic SHE when the incident angles are selected as $\theta = 41^\circ$, 41.3° , and 41.31° . (g) and (h) describe the spin-dependent angular shifts changing with the propagation distance.

with any desired spin-dependent shifts for manipulation of spin-polarized photons.

To obtain a clear physical picture, Fig. 3 is introduced to reveal what role the left- and right handed circularly polarized components play in the reflected fields. And the propagation distance of light is also fixed to $z = 250mm$. For the incident angle $\theta = 41^\circ$, the left- and right-handed circularly polarized components shift obviously in the same x-direction [Figs. 3 (a) and 3 (b)]. These are corresponding to the spin independent displacements. However, under this condition, the transverse spin-dependent shifts are very tiny so that we can not observe it directly. In order to obtain a relative large angular shift, the polarization angle is chosen as $\beta = 20^\circ$. With the increasing of the incident angles, the shifts of the angular deviation enhance significantly and also show the spin independent properties [Figs. 3 (c) and 3 (d)]. When the incident angle is slightly larger than the critical angle [Figs. 3 (e) and 3 (f)], we can clearly see that the left- and right-handed circularly polarized parts separate into the opposite directions and the corresponding spin-dependent displacements are very large. The in-plane asymmetric spin angular splitting depending on the propagation distances is revealed in

Fig. 4. The experimental observation of large in-plane spin shifts. (a) The setup consisting of linearly polarized He-Ne laser (632.8nm), HWP (half-wave plate), L (lens with effective focal length: 50mm), P1 and P2 (polarizers), QWP (quarter-wave plate), and CCD (charge-coupled device). The sample is a BK7 prism. To make the process more clear, the size of the prism is amplified. (b)-(d) Experimental results. The red and blue stand for the left- and right-handed circularly polarized components. Here, the incident angles are chosen as below ($\theta = 41.25^\circ$) and slightly larger ($\theta = 41.64^\circ$ and 41.91°) than the critical angle.

Figs. 3 (g) and 3 (h). Here, the incident angles are chosen as $\theta = 41.64^\circ$ and 41.91° , and the polarization angle is fixed to $\beta = 55^\circ$. We can clearly find that, with the increasing of the propagation distances, the in-plane spin angular displacements incrementally increase and show asymmetry features.

It is necessary to analyze the polarization distribution of the reflected light beam for verifying the existence of large in-plane spin shifts. Our experimental setup [Fig. 4 (a)] is similar to that in [8]. A quarter-wave plate (QWP) followed by a polarizer (P2) are added at the end of the reflected light beam to analyze the Stokes parameter S_3 . Then, the CCD (charge-coupled device) is used to capture the output signals. The experimental results are shown in Figs. 4 (b)-4 (d). Here, the red and blue denote the left- and right-handed circularly polarized components. The incident angles are chosen as $\theta = 41.25^\circ$, 41.64° , and 41.91° . We can clearly see that there is no spin-dependent splitting when the incident angle is below the critical angle [Fig. 4 (b)]. Interestingly, the obvious in-plane spin-dependent splitting can be explored when the incident angle is slightly larger than the critical angle [Figs. 4 (c) and 4 (d)]. The experimental results agree well with the above theoretical model. It should be noted that there also exists a few micrometers spatial spin-dependent splitting when the incident angle is below the critical angle. However, the Stokes parameter S_3 is not observed under this condition, which means that some other methods such as weak measurements should be involved to detect it indirectly.

In conclusion, we have investigated the in-plane SHE of arbitrary linearly polarized light reflection near critical angle and demonstrated it experimentally. The general expressions of the angular and spatial shifts have been explored. It is shown that the angular displacements are spin independent when the incident angle is smaller than the critical angle. However, under the

condition of incident angle being slightly larger than the critical angle, the angular shifts exhibit spin-dependent and asymmetric properties. We have found that the spatial spin displacements are non-zero when the polarization angle is chosen as $\beta = 0$, which is significantly different from the air-glass interface case. Remarkably, we have revealed the large spin angular splitting where the left- and right-handed circularly polarized components can even be directly observed by modulating the incident and polarization angles. These findings provide us a pathway for controlling the spin-polarized photons and open the possibility of developing novel spin-based nanophotonic applications.

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