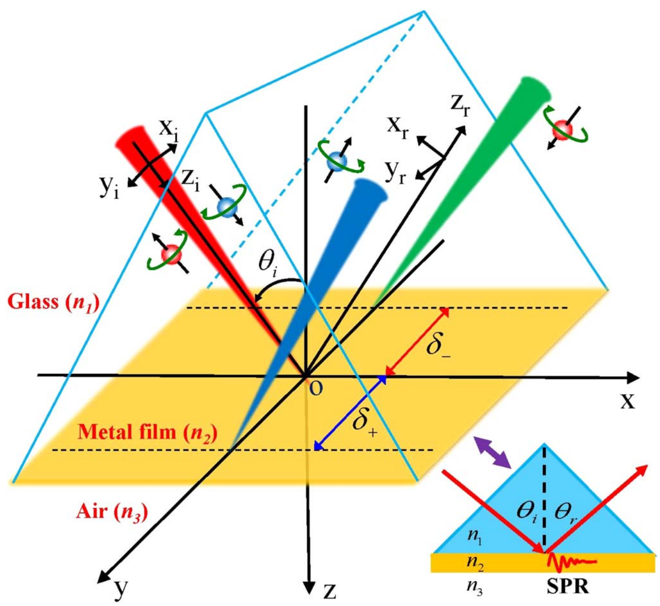
IEEE Photonics Journal
An IEEE Photonics Society Publication

Open Access

Enhanced Photonic Spin Hall Effect Due to Surface Plasmon Resonance

Volume 8, Number 1, February 2016

Xinxing Zhou
Xiaohui Ling



DOI: 10.1109/JPHOT.2016.2523253
1943-0655

Enhanced Photonic Spin Hall Effect Due to Surface Plasmon Resonance

Xinxing Zhou[1] **and Xiaohui Ling**[2]

[1]Synergetic Innovation Center for Quantum Effects and Applications, College of Physics and Information Science, Hunan Normal University, Changsha 410081, China
[2]Laboratory for Optics and Optoelectronics, College of Physics and Electronic Engineering, Hengyang Normal University, Hengyang 421002, China

DOI: 10.1109/JPHOT.2016.2523253

Manuscript received January 8, 2016; revised January 25, 2016; accepted January 27, 2016. Date of publication January 28, 2016; date of current version February 10, 2016. This work was supported in part by the National Natural Science Foundation of China under Grant 11447010 and in part by the Hunan Province Natural Science Foundation of China under Grant 2015JJ3026 and Grant 14JJ6007. Corresponding authors: X. Zhou and X. Ling (e-mail: xinxingzhou@hunnu.edu.cn; xhling@hynu.edu.cn).

Abstract: In this paper, by considering the surface plasmon resonance (SPR) effect, we theoretically study the photonic spin Hall effect (SHE) in a three-layer structure composed of glass, metal, and air. It is revealed that the obtained spin-dependent splitting in photonic SHE is far greater than the previously reported results in refraction when the incident angle is near the resonant angle. The inherent physics behind this interesting phenomenon is attributed to the sharp decrease in Fresnel reflective coefficients around the SPR. We also find that there exists an optimal thickness for minimal resonant reflection, above which the huge beam displacement is also observed. These findings provide us a pathway for modulating the photonic SHE and open the possibility of developing nanophotonic applications such as the SPR-based sensor.

Index Terms: Photonic spin Hall effect (SHE), spin-dependent splitting, surface plasmon resonance (SRP).

1. Introduction

The photonic spin Hall effect (SHE) is an interesting transport phenomenon in which an applied field on the spin photons leads to the spin-dependent splitting of light beam perpendicular to the field [1]–[3]. It is the optical analogy of SHE in electronic system where the spin photons play the role of the spin electrons and the refractive index gradient plays the role of the applied electric field [4]–[7]. The photonic SHE is currently attracting growing attention and has been widely investigated in different physical systems such as optical physics [8], [9], [23]; semiconductor physics [10]; high-energy physics [11], [12]; metamaterial [13]–[15]; and even in free-space [16], [17]. Generally, the photonic SHE is very weak, and the corresponding spin-dependent splitting is restricted to a few tens of nanometers so that the normal experimental equipments can not detect it directly. Thanks to the weak measurement method [18]–[22], the Kwait's group first observed this tiny transverse displacement of refracted light at the air-glass interface [3].

Some methods were proposed to obtain the large spin-dependent splitting in photonic SHE. For example, a layered nanostructure can be used to enhance or suppress the transverse beam displacements [23]. When the light beam is reflected near the Brewster's angle, a huge transverse and in-plane splitting of left- and right-handed circularly polarized components appear

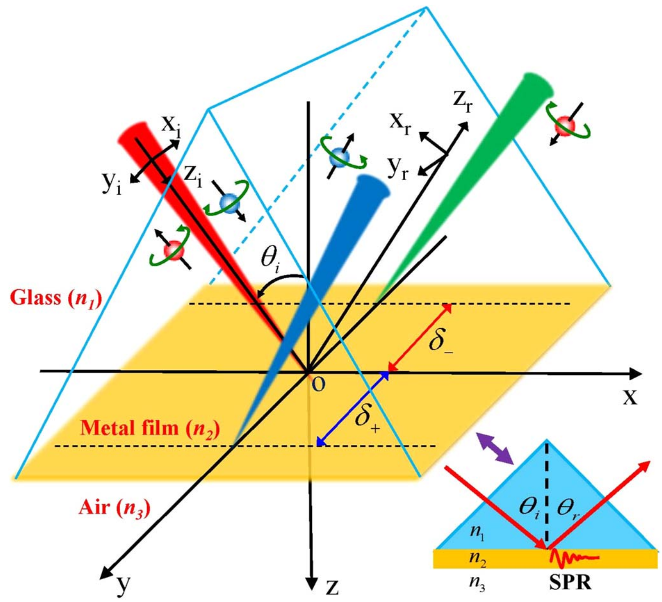


Fig. 1. Schematic of the photonic SHE in a three-layer structure (composed of glass, metal, and air) by considering the SPR effect. Here, θ_i and θ_r are the incident and reflected angles. The refractive index of the corresponding materials are n_1 (glass), n_2 (metal), and n_3 (air). δ_+ and δ_- denote the transverse beam displacements of left- and right-handed circularly polarized components, respectively. (Inset) Overall structure of the SPR model.

[24], [25]. Yin *et al.* reported a strong photonic SHE resulting in the direct observation of large transverse motion of circularly polarized beam, even at normal incidence [14]. Using the dielectric-based metamaterial, a giant photonic SHE in momentum space was observed resulting from the Pancharatnam-Berry geometric phase gradient [26]. Recently, the surface plasmon resonance (SPR) effect was proposed to enhance the other types of optical beam displacements such as Goos-Hänchen and Imbert-Fedorov shifts [27]. There exists a resonant angle where the optical beam shifts are far greater than the previous results.

In this work, we theoretically investigate the photonic SHE in a three-layer structure composed of glass, metal, and air by considering the SPR effect. When the SPR is excited by a horizontal (H) polarization beam, we discover a huge transverse beam displacement which is far greater than the previous reported results observed at the air-glass interface. On the contrary, there is no plasmon field for vertical (V) polarized incident light excitation so that the spin-dependent splitting is relatively small. We also find that there exists an optimal thickness for minimal resonant reflection above which the huge beam shift is also observed. These findings provide us a pathway for enhancing the photonic SHE and open the possibility of developing new nanophotonic applications. In fact, in order to make a direct comparison, we choose the calculated parameters as the same in the previous work [3]. The rest of the paper is organized as follows. At first, we establish the general beam propagation model to study the optical beam reflection coefficients and obtain the expression of beam shifts. Then, we theoretically analyze the abnormal behavior of photonic SHE due to the SPR effect and the corresponding physical mechanism. Finally, a conclusion is given.

2. Theoretical Analysis

A three-layer structure composed of glass, metal, and air is our model (see Fig. 1). If we choose the suitable polarization state, incident angle, and the thickness of metal film, the SPR will be excited when the light beam is reflected at the glass-metal interface. Simultaneously, the photonic SHE appears resulting in the splitting of left- and right-handed circularly polarized components. First, let us analyze the incident and reflected electric fields of this model. In the spin basis set, the angular spectrum can be written as $\tilde{\mathbf{E}}_i^H = (\tilde{\mathbf{E}}_{i+} + \tilde{\mathbf{E}}_{i-})/\sqrt{2}$ and $\tilde{\mathbf{E}}_i^V = i(\tilde{\mathbf{E}}_{i-} - \tilde{\mathbf{E}}_{i+})/\sqrt{2}$. Here, H and V denote the horizontal and vertical polarization states, respectively. The left- and right-handed circularly polarized (spin) components are represented as the positive and negative signs.

We consider a monochromatic Gaussian beam reflects at the glass-metal interface. It can be formulated as a localized wave packet whose spectrum is arbitrarily narrow

$$\widetilde{\mathbf{E}}_{i\pm} = (\mathbf{e}_{ix} + i\sigma\,\mathbf{e}_{iy})\frac{w_0}{\sqrt{2\pi}}\exp\left[-\frac{w_0^2\left(k_{ix}^2 + k_{iy}^2\right)}{4}\right]. \tag{1}$$

Here, w_0 is the beam waist, and the polarization operator $\sigma = \pm 1$ corresponds to left- and right-handed circularly polarized light beam, respectively. In order to obtain the reflected field, we need first to establish the relationship between the incident and reflected fields. Through the coordinate rotation, we can calculate the reflected angular spectrum according to the relation $\tilde{\mathbf{E}}_r(k_{rx}, k_{ry}) = \mathbf{M}_R\tilde{\mathbf{E}}_i(k_{ix}, k_{iy})$ [24]. The $\mathbf{M}_R$ stands for

$$\begin{bmatrix} \widetilde{\mathbf{E}}_r^H \\ \widetilde{\mathbf{E}}_r^V \end{bmatrix} = \begin{bmatrix} r_p & \frac{k_{ry}\cot\theta_i(r_p + r_s)}{k_0} \\ -\frac{k_{ry}\cot\theta_i(r_p + r_s)}{k_0} & r_s \end{bmatrix} \begin{bmatrix} \widetilde{\mathbf{E}}_i^H \\ \widetilde{\mathbf{E}}_i^V \end{bmatrix}. \tag{2}$$

Here, r_p and r_s are Fresnel reflection coefficients for H and V polarization states. k_0 is the wave number in free space.

According to (1) and (2), we can first get the expressions of the reflected angular spectrum

$$\widetilde{\mathbf{E}}_r^H = \frac{r_p}{\sqrt{2}}\left[\exp(+ik_{ry}\delta_r^H)\widetilde{\mathbf{E}}_{r+} + \exp(-ik_{ry}\delta_r^H)\widetilde{\mathbf{E}}_{r-}\right] \tag{3}$$

$$\widetilde{\mathbf{E}}_r^V = \frac{ir_s}{\sqrt{2}}\left[-\exp(+ik_{ry}\delta_r^V)\widetilde{\mathbf{E}}_{r+} + \exp(-ik_{ry}\delta_r^V)\widetilde{\mathbf{E}}_{r-}\right]. \tag{4}$$

Here, $\delta_r^H = (1 + r_s/r_p)\cot\theta_i/k_0$ and $\delta_r^V = (1 + r_p/r_s)\cot\theta_i/k_0$. $\widetilde{\mathbf{E}}_{r\pm}$ can be written as the similar style with (1). The calculation of the reflected beam shifts in photonic SHE requires the explicit solution of the boundary conditions at the interfaces. Thus, we need to know the generalized Fresnel reflective coefficient of SPR model (the multilayered structure), which can be written as [5]

$$r_A = \frac{R_A + R_A'\exp\left(2ik_0\sqrt{n_2^2 - n_1^2\sin^2\theta_i}d\right)}{1 + R_A R_A'\exp\left(2ik_0\sqrt{n_2^2 - n_1^2\sin^2\theta_i}d\right)}. \tag{5}$$

Here, $A\epsilon\{p, s\}$, R_A is the Fresnel reflection coefficient at the first interface (glass-metal). R_A' is the corresponding coefficient at the second interface (metal-air). n_2 and d represent the refractive index and thickness of the metal film, respectively. n_1 is the refractive index of glass. Therefore, we have established the general beam-propagation model for describing the light beam reflected from the three-layer SPR model.

The photonic SHE is described for the spin-dependent splitting of left- and right-handed circularly polarized components, and therefore, the reflected field centroid should be calculated. At any given plane z_a, the shifts of light beam centroid compared to the geometrical-optics prediction is given by

$$\delta_\pm = \frac{\int\int \tilde{\mathbf{E}}^* i\partial_{k_{ry}}\tilde{\mathbf{E}}\,dk_{rx}dk_{ry}}{\int\int \tilde{\mathbf{E}}^*\tilde{\mathbf{E}}\,dk_{rx}dk_{ry}}. \tag{6}$$

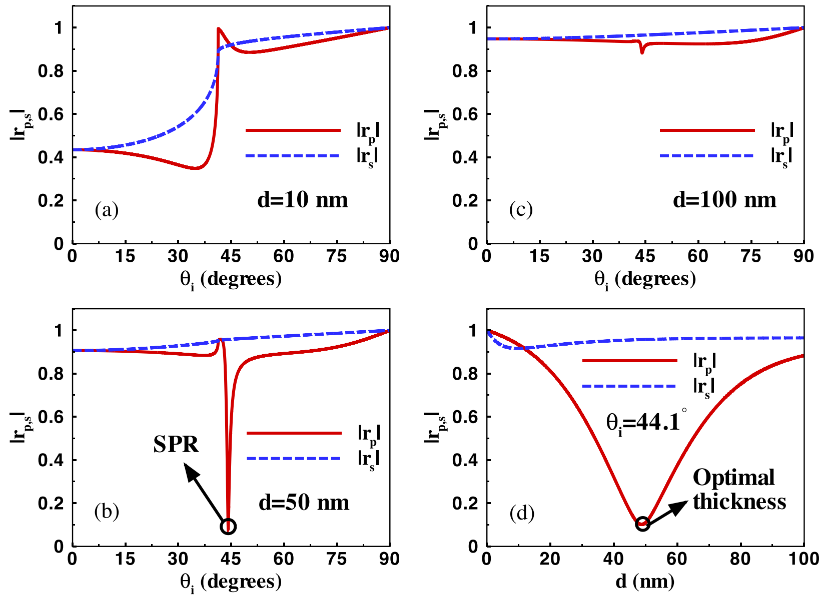


Fig. 2. Role of the thickness of a metal film and the incident angle in the Fresnel reflection coefficients $|r_s|$ and $|r_p|$ under the condition of SPR. (a)–(c) show the Fresnel reflection coefficients changing with the incident angles, and the thickness are fixed to the three values 10 nm, 50 nm, and 100 nm. (d) describes the Fresnel reflection coefficients varying with thickness of the metal film, and the incident angle is fixed to the resonant angle.

Substituting (3) and (4) into (6), we can obtain the transverse spin-dependent displacements of the two spin components

$$\delta_{\pm}^{H} = \mp \frac{\lambda}{2\pi}\left[1 + \frac{|r_s|}{|r_p|}\cos(\varphi_s - \varphi_p)\right]\cot\theta_i \tag{7}$$

$$\delta_{\pm}^{V} = \mp \frac{\lambda}{2\pi}\left[1 + \frac{|r_p|}{|r_s|}\cos(\varphi_p - \varphi_s)\right]\cot\theta_i \tag{8}$$

where $r_{p,s} = |r_{p,s}|\exp(i\varphi_{p,s})$, and λ is wavelength of the incident beam. In order to make a direct comparison, we choose the calculated parameters as the same in the previous work in [3]. The wavelength of the incident beam is selected as 632.8 nm. The metal is chosen as the Au and the corresponding refractive index is $n_2 = \sqrt{-10.4 + 1.4i}$ at 632.8 nm [28]. The refractive index of the glass is $n_1 = 1.515$. In fact, the SPR effect is wavelength dependent and this dependence can be considered starting from dielectric function [29]. Therefore, the further study of photonic SHE in SPR by considering the wavelength dependence will be an interesting work in the future. In the next part, we will theoretically analyze the abnormal behavior of photonic SHE due to the SPR effect and explain the corresponding inherent physical mechanism.

3. Results and Discussion

To obtain a clear physical picture, we draw Fig. 2 to reveal what roles the incident angle and thickness of the metal film play in the enhanced photonic SHE under the condition of SPR. In fact, the SPR effect can be significantly affected by both of the incident angle and thickness of the metal film [30]. Fig. 2(a)–(c) show the Fresnel coefficients r_p and r_s changing with the incident angles for three different thickness (10 nm, 50 nm, and 100 nm) of the metal film. When the thickness of the metal film is small [see Fig. 2(a)], the behavior of the Fresnel reflective coefficients are similar to the condition that a light beam reflects at the pure glass-air interface, and there is no SPR. With the increasing of the thickness, the SPR will be excited gradually.

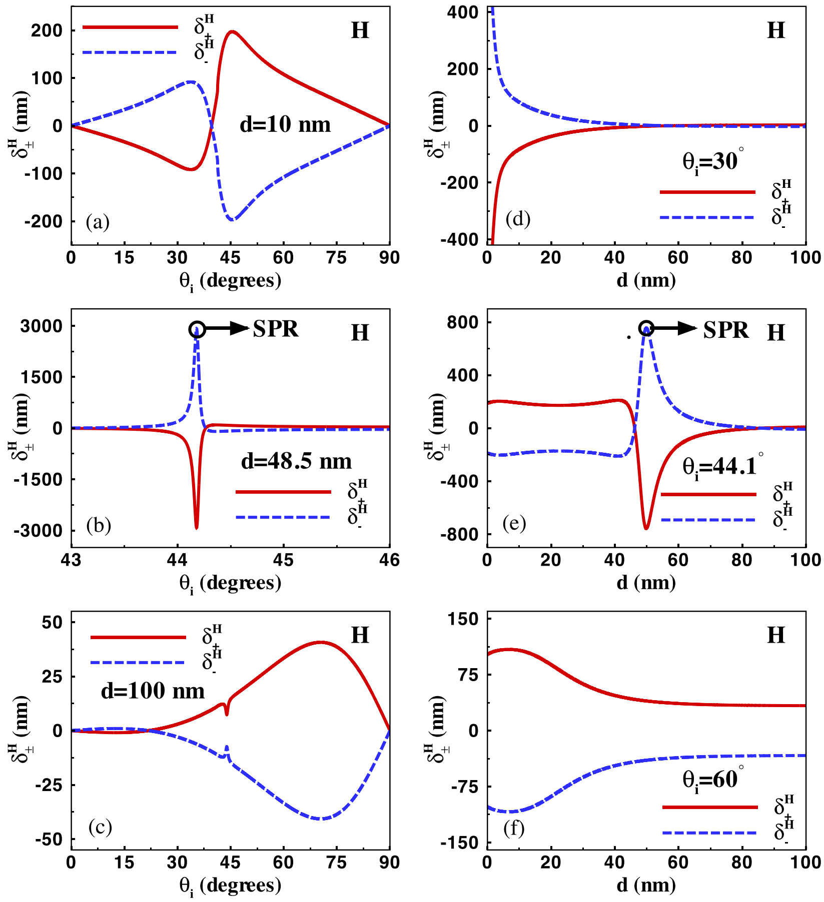


Fig. 3. Photonic SHE in SPR model under the condition of H polarization state. (a)–(c) show the spin-dependent splitting varying with the incident angles. Here, we choose three different thickness 10 nm, the optimal thickness 48.5 nm, and 100 nm. (e)–(f) plot the spin-dependent splitting in photonic SHE changing with the thickness of metal film. The incident angles are selected as three values 30°, the resonant angle 44.1°, and 60°.

Remarkablly, there exists a fixed incident angel called resonant angle (about 44.1°) where the Fresnel coefficient r_p undergoes a sharp decreasing [see Fig. 2(b)]. However, the r_s keeps almost stable. So, under this condition, the value of $|r_s|/|r_p|$ can reach very large. From the expression of beam shifts (7), the value of the spin-dependent splitting mainly depends on the part $|r_s|/|r_p|$. Therefore, the photonic SHE will be greatly enhanced due to the SPR. In fact, the inherent physical mechanism of photonic SHE is spin-orbit coupling which describes the mutual influence of the spin (polarization) and the trajectory of the light beam. From (3), the term $\exp(\pm ik_{ry}\delta_r^H)$ denotes the spin-orbit coupling. From the above analysis, under the condition of SPR, the Fresnel reflective coefficient r_p will greatly decrease, and the ratio $|r_s|/|r_p|$ which plays a great role in spin-orbit coupling term, can be significantly enhanced. Therefore, the spin-orbit coupling in photonic SHE can also be amplified, which leads to the enhancement of spin-dependent splitting. With the thickness continually increasing [see Fig. 2(c)], the SPR effect will become weak and the resonance nearly disappears. The results show that the local resonance decreasing clearly appears only for a suitable range of thickness. Fig. 2(d) describes the $r_{p,s}$ changing with thickness and the incident angle is fixed to the resonant angle. We find that there exists an optimal thickness for minimal resonant reflection (about 48.5 nm).

Fig. 3 shows the spin-dependent splitting in photonic SHE under the condition of H polarization state in which the SPR can be excited. Fig. 3(a)–(c) describe the transverse beam shifts varying with the incident angles. Here, we choose three different thickness 10 nm, the optimal thickness 48.5 nm, and 100 nm. When the thickness reaches small value (10 nm), there is no SPR effect and the corresponding beam displacements is tiny. It is noted that a switchable spin accumulation in photonic SHE is observed, which is similar to the previous work [24]. Under the condition of optimal thickness 48.5 nm, the SPR effect is significantly excited. Importantly, we find that the spin-dependent splitting reaches 3000 nm, which is about 40 times larger than the previously reported values in refraction [3]. It is an effective way to enhance the photonic SHE. With the thickness running away from the optimal value, the SPR effect gradually disappears and the corresponding beam shifts become weak. Here, we select the thickness 100 nm as an example and find that the maximum splitting is just about 40 nm.

We also plot the spin-dependent splitting changing with the thickness of metal film [see Fig. 3(d)–(f)]. For simplify, the incident angles are chosen as three values 30°, the resonant angle 44.1°, and 60°. When the incident angle is selected as the resonant angle and the thickness of metal film reaches at the optimal thickness, there appears an amplified transverse beam displacement as shown in Fig. 3(e). It is noted that when the incident angle is close to the resonant angle, the spin-dependent splitting is very sensitive to the variations of the incident angles. The tiny changes of the incident angles will strongly affect the values of the displacement. As the incident angle leaving away from the resonant angle, even at the optimal thickness, there is no enhanced beam shifts [see Fig. 3(d) and (f)]. Under this condition, the spin-dependent splitting first get the relatively large value at the small thickness and then become stable with the thickness increasing gradually. We note that the SPR effect only appears in the case of the incident angle and the thickness are chosen as the suitable values. Therefore, the photonic SHE can be greatly enhanced due to SPR.

Fig. 4 describes the spin-dependent splitting in photonic SHE under the condition of V polarization state. It is noted that, under this condition, the SPR can not be excited so that there are no enhanced beam shifts. Fig. 4(a)–(c) denote the transverse beam displacements changing with the incident angles, and we also choose three different thickness 10 nm, the above mentioned optimal thickness 48.5 nm, and 100 nm. We find that there is no resonance enhancement effect, and the maximum value of spin-dependent splitting is about 200 nm [see Fig. 4(a)]. The spin-dependent splitting in photonic SHE varying with the thickness of metal film are shown in Fig. 4(d)–(f). The incident angles are selected as the same as those in the H polarization case. Similar to the H polarization case, the transverse beam shifts also first reach the relatively large value at the small thickness and then tend to be stable with the thickness increasing.

The photonic SHE can be an effective tool for precision metrology. Owing to the fact that the spin-dependent splitting in photonic SHE is just a few tens of nanometers and cannot be distinguished directly, a precise signal enhancement technique called quantum weak measurements can be used to detect this tiny effect [3], [9], [24]. There are some examples for precision metrology such as measuring the thickness of nanometal film [31], identifying the graphene layers [32], and detecting the strength of axion coupling in topological insulators [33]. However, in the field of precision metrology, there is a demand for observing the photonic SHE directly, which will significantly reduce the complexity of experiment and improve the efficiency. Therefore, we need to find some methods for greatly enhancing the spin-dependent splitting in photonic SHE. The SPR effect could be a potential way to amplify the photonic SHE. We can modulate the incident angle and thickness of the metal film, and even the model structure, to greatly strengthen the SPR and then enhance the photonic SHE. Conversely, the photonic SHE can also be an indirect method for observing the SPR effect, which has application potential in nanophotonics such as the SPR-based sensor.

4. Conclusion

In summary, we have investigated the surface plasmon resonance (SPR) induced photonic spin Hall effect (SHE) in a three-layer model made of glass, metal, and air. We have found that the maximum value of spin-dependent splitting reaches about 3000 nm at the resonant angle, which

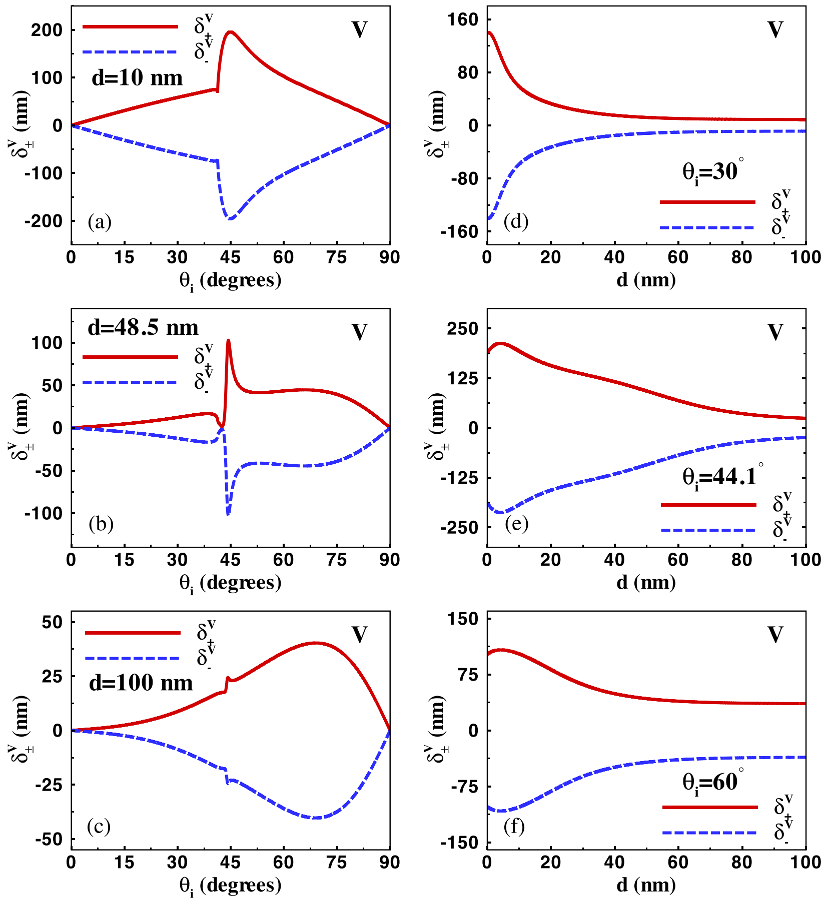


Fig. 4. Photonic SHE in SPR model under the condition of V polarization state. (a)–(c) describe the transverse beam shifts varying with the incident angles. The thickness of the metal film is also chosen as the same in the above case 10 nm, 48.5 nm, and 100 nm. The spin-dependent splitting in photonic SHE changing with the thickness of metal film are shown in (e) and (f). The incident angles are also selected as three values 30°, 44.1°, and 60°.

is 40 times larger than the previously reported values in refraction. The enhanced beam shifts depend on the large ratio between the Fresnel reflection coefficients at the resonant angle. We have also found that there exists an optimal thickness of the metal film for minimal resonant reflection, above which the huge beam displacement is observed. These findings provide an effective pathway for enhancing the photonic SHE and offer an indirect method for measuring the SPR leading to the development of new SPR-based sensor.

References

[1] M. Onoda, S. Murakami, and N. Nagaosa, "Hall effect of light," *Phys. Rev. Lett.*, vol. 93, no. 8, Aug. 2004, Art. ID 083901.

[2] K. Y. Bliokh and Y. P. Bliokh, "Conservation of angular momentum, transverse shift, and spin Hall effect in reflection and refraction of an electromagnetic wave packet," *Phys. Rev. Lett.*, vol. 96, no. 7, Feb. 2006, Art. ID 073903.

[3] O. Hosten and P. Kwiat, "Observation of the spin Hall effect of light via weak measurements," *Science*, vol. 319, no. 5864, pp. 787–790, Feb. 2008.

[4] K. Y. Bliokh, A. Niv, V. Kleiner, and E. Hasman, "Geometrodynamics of spinning light," *Nat. Photon.*, vol. 2, no. 12, pp. 748–753, Dec. 2008.

[5] H. Luo *et al.*, "Spin Hall effect of a light beam in left-handed materials," *Phys. Rev. A*, vol. 80, no. 4, Oct. 2009, Art. ID 043810.

[6] N. Hermosa, A. M. Nugrowati, A. Aiello, and J. P. Woerdman, "Spin Hall effect of light in metallic reflection," *Opt. Lett.*, vol. 36, no. 16, pp. 3200–3202, Aug. 2011.

[7] Y. Gorodetski *et al.,* “Weak measurements of light chirality with a plasmonic slit,” *Phys. Rev. Lett.*, vol. 109, no. 1, Jul. 2012, Art. ID 013901.
[8] A. Aiello and J. P. Woerdman, “Role of beam propagation in Goos-Hänchen and Imbert-Fedorov shifts,” *Opt. Lett.*, vol. 33, no. 13, pp. 1437–1439, Jul. 2008.
[9] Y. Qin, Y. Li, H. He, and Q. Gong, “Measurement of spin Hall effect of reflected light,” *Opt. Lett.*, vol. 34, no. 17, pp. 2551–2553, Sep. 2009.
[10] J.-M. Ménard, A. E. Mattacchione, M. Betz, and H. M. van Driel, “Imaging the spin Hall effect of light inside semiconductors via absorption,” *Opt. Lett.*, vol. 34, no. 15, pp. 2312–2314, Aug. 2009.
[11] P. Gosselin, A. Bérard, and H. Mohrbach, “Spin Hall effect of photons in a static gravitational field,” *Phys. Rev. D, Cov. Part. Fields Gravitation Cosmol.*, vol. 75, no. 8, Apr. 2007, Art. ID 084035.
[12] C. A. Dartora *et al.,* “Lagrangian-Hamiltonian formulation of paraxial optics and applications: Study of gauge symmetries and the optical spin Hall effect,” *Phys. Rev. A, Cov. At. Mol. Opt. Phys. Quantum Inf.*, vol. 83, no. 1, Jan. 2011, Art. ID 012110.
[13] N. Shitrit *et al.,* “Spin-optical metamaterial route to spin-Controlled photonics,” *Science*, vol. 340, no. 6133, pp. 724–726, May. 2013.
[14] X. Yin, Z. Ye, J. Rho, Y. Wang, and X. Zhang, “Photonic spin Hall effect at metasurfaces,” *Science*, vol. 339, no. 6126, pp. 1405–1407, Mar. 2013.
[15] P. V. Kapitanova *et al.,* “Photonic spin Hall effect in hyperbolic metamaterials for polarization-controlled routing of subwavelength modes,” *Nat. Commun.*, vol. 2, Feb. 2014, Art. ID 3226.
[16] A. Aiello, N. Lindlein, C. Marquardt, and G. Leuchs, “Transverse angular momentum and geometric spin hall effect of light,” *Phys. Rev. Lett.*, vol. 103, no. 10, Sep. 2009, Art. ID 100401.
[17] K. Y. Bliokh, D. Smirnova, and F. Nori, “Quantum spin Hall effect of light,” *Science*, vol. 348, no. 6242, pp. 1448–1451, Jun. 2015.
[18] M. R. Dennis and J. B. Götte, “The analogy between optical beam shifts and quantum weak measurements,” *New J. Phys.*, vol. 14, no. 7, Jul. 2012, Art. ID 073013.
[19] J. Dressel, M. Malik, F. M. Miatto, A. N. Jordan, and R. W. Boyd, “Colloquium: Understanding quantum weak values: Basics and applications,” *Rev. Mod. Phys.*, vol. 86, no. 1, pp. 307–316, Mar. 2014.
[20] A. N. Jordan, J. Martínez-Rincón, and J. C. Howell, “Technical advantages for weak-value amplification: When less is more,” *Phys. Rev. X*, vol. 4, no. 1, Mar. 2014, Art. ID 011031.
[21] G. C. Knee and E. M. Gauger, “When amplification with weak values fails to suppress technical noise,” *Phys. Rev. X*, vol. 4, no. 1, Mar. 2014, Art. ID 011032.
[22] A. Di Lorenzo, “Weak values and weak coupling maximizing the output of weak measurements,” *Ann. Phys.*, vol. 345, pp. 178–189, Jun. 2014.
[23] H. Luo *et al.,* “Enhancing or suppressing the spin Hall effect of light in layered nanostructures,” *Phys. Rev. A, Cov. At. Mol. Opt. Phys. Quantum Inf.*, vol. 84, no. 3, Sep. 2011, Art. ID 033801.
[24] H. Luo, X. Zhou, W. Shu, S. Wen, and D. Fan, “Enhanced and switchable spin Hall effect of light near the Brewster angle on reflection,” *Phys. Rev. A, Cov. At. Mol. Opt. Phys. Quantum Inf.*, vol. 84, no. 4, Oct. 2011, Art. ID 043806.
[25] X. Qiu *et al.,* “Incident-polarization-sensitive and large in-planephotonic-spin-splitting at the Brewster angle,” *Opt. Lett.*, vol. 40, no. 6, pp. 1018–1021, Mar. 2015.
[26] X. Ling *et al.,* “Giant photonic spin Hall effect in momentum space in a structured metamaterial with spatially varying birefringence,” *Light Sci. Appl.*, vol. 4, May. 2015, Art. ID e290.
[27] L. Salasnich, “Enhancement of four reflection shifts by a three-layer surface-plasmon resonance,” *Phys. Rev. A, Cov. At. Mol. Opt. Phys. Quantum Inf.*, vol. 86, no. 5, Nov. 2012, Art. ID 055801.
[28] E. D. Palik, *Handbook of Optical Constants of Solids*. New York, NY, USA: Academic, 1998.
[29] P. G. Etchegoin, E. C. Le Ru, and M. Meyer, “An analytic model for the optical properties of gold,” *J. Chem. Phys.*, vol. 125, no. 16, Oct. 2006, Art. ID 164705.
[30] X. Yin, L. Hesselink, Z. Liu, N. Fang, and X. Zhang, “Large positive and negative lateral optical beam displacements due to surface plasmon resonance,” *Appl. Phys. Lett.*, vol. 85, no. 3, pp. 372–374, Jul. 2004.
[31] X. Zhou, Z. Xiao, H. Luo, and S. Wen, “Experimental observation of the spin Hall effect of light on a nanometal film via weak measurements,” *Phys. Rev. A, Cov. At. Mol. Opt. Phys. Quantum Inf.*, vol. 85, no. 4, Apr. 2012, Art. ID 043809.
[32] X. Zhou, X. Ling, H. Luo, and S. Wen, “Identifying graphene layers via spin Hall effect of light,” *Appl. Phys. Lett.*, vol. 101, no. 25, Dec. 2012, Art. ID 251602.
[33] X. Zhou *et al.,* “Photonic spin Hall effect in topological insulators,” *Phys. Rev. A, Cov. At. Mol. Opt. Phys. Quantum Inf.*, vol. 88, no. 5, Nov. 2013, Art. ID 053840.