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Controlling photonic spin Hall effect via exceptional points

Xinxing Zhou,^{1,2,*} Xiao Lin^{1,*},[†] Zhicheng Xiao,³ Tony Low,⁴ Andrea Alù,^{5,3} Baile Zhang,^{1,6,‡} and Handong Sun^{1,6,7,§}

¹*Division of Physics and Applied Physics, School of Physical and Mathematical Sciences, Nanyang Technological University, Singapore 637371, Singapore*

²*Synergetic Innovation Center for Quantum Effects and Applications, School of Physics and Electronics, Hunan Normal University, Changsha 410081, China*

³*Department of Electrical and Computer Engineering, The University of Texas at Austin, Austin, Texas 78712, USA*

⁴*Department of Electrical and Computer Engineering, University of Minnesota, Minneapolis, Minnesota 55455, USA*

⁵*Photonics Initiative, Advanced Science Research Center, City University of New York, New York 10031, USA*

⁶*Centre for Disruptive Photonic Technologies (CDPT), School of Physical and Mathematical Sciences, Nanyang Technological University, Singapore 637371, Singapore*

⁷*MajuLab, CNRS-UCA-SU-NUS-NTU International Joint Research Unit, Singapore 637371, Singapore*

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The photonic spin Hall effect (SHE), featured by a spin-dependent transverse shift of an impinging optical beam driven by its polarization handedness, has many applications including precise metrology and spin-based nanophotonic devices. It is highly desirable to control and enhance the photonic SHE. However, such a goal remains elusive, due to the weak spin-orbit interaction of light, especially for systems with optical loss. Here we reveal a flexible way to modulate the photonic SHE via exceptional points, by exploiting the transverse shift in a parity-time (PT) symmetric system with balanced gain and loss. The underlying physics is associated with the near-zero value and abrupt phase jump of the reflection coefficients at exceptional points. We find that the transverse shift is zero at exceptional points, but it is largely enhanced in their vicinity. Moreover, the transverse shift switches its sign across the exceptional point, resulting from spontaneous PT-symmetry breaking. Due to the sensitivity of transverse shift at exceptional points, our work also indicates that the photonic SHE can enable a precise way to probe the location of exceptional point in photonic systems.

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I. INTRODUCTION

The photonic spin Hall effect (SHE), in analogy to SHE in electronic systems [1], is caused by the spin-orbit interaction of light at the interface, which is associated with the geometric Berry phase and originates from the transverse nature of light [2–7]. As illustrated in Fig. 1(a), for an incident Gaussian beam, its different plane-wave components acquire different polarization rotations in the transverse direction upon reflection. The spatial-dependent polarization rotation directly leads to the spin splitting of the reflected beam in the transverse direction, featured by a spin-dependent transverse shift [8–17], where the spin state of photons corresponds to left-handed or right-handed circular polarizations (LCP or RCP). In other words, the photonic SHE introduces additional spin degrees of freedom for the flexible manipulation of light. As such, the photonic SHE shows promising applications in various realms, including optical sensing [18,19], spin-based nanophotonic devices [20], precise metrology [21,22], quantum information processing, and plasmonics [6,23]. To enable and further extend these applications, a giant photonic SHE

is desirable. However, the photonic SHE is generally weak, and its featured transverse shift is in the nanometer scale, due to weak spin-orbit interaction [4,24]. Therefore, controlling (e.g., enhancing) the photonic SHE in a flexible way remains an open challenge, highly desirable for its importance in modern photonics.

Several recent proposals to enhance the photonic SHE have been put forward, based on the Brewster effect [12,25], anisotropic and inhomogeneous metamaterials [20,26,27], and surface plasmon resonance phenomena [28,29]. These methods, however, are limited to transparent systems or systems with minimal material loss. Loss, however, is ubiquitous and oftentimes can be very large in optical systems, becoming detrimental to the enhancement of photonic SHE; a typical example of the effect of loss on the photonic SHE is shown in Figs. 1(b) and S2. Open questions are how to mitigate the influence of material loss on the photonic SHE and how to flexibly control it in systems with loss, especially for light with arbitrary polarization and incident angle.

Here we address these issues by introducing a viable scheme to flexibly control the photonic SHE in an optical system with loss, through the judicious incorporation and parametric modulation of exceptional points [30–34]. The exceptional point is a singularity in non-Hermitian systems, such as parity-time (PT) symmetric systems, in which at least two resonances coalesce in both eigenvalues and eigenfunctions [35–39]. Although exceptional points have recently ignited tremendous interest [40–46], its connection with the photonic

*These authors contributed equally to this work.

[†]Corresponding author: xiaolinbnwj@ntu.edu.sg

[‡]Corresponding author: blzhang@ntu.edu.sg

[§]Corresponding author: hdsun@ntu.edu.sg

SHE has never been explored. We rely on the emerging physics at the intersection of these two interesting yet distinct physical concepts. We find that the transverse shift stemming from the photonic SHE is zero at the exceptional points, but can be dramatically enhanced in the vicinity of exceptional points. Because of the spontaneous PT-symmetry breaking across the exceptional point, the giant transverse shifts have opposite signs at the two sides of exceptional points. Such a giant photonic SHE near the exceptional point can be flexibly designed to work with incident light of arbitrary polarization and incident angle, while this is hard to achieve in systems without exceptional points. Remarkably, due to the sensitivity of transverse shift at exceptional points, one can also precisely probe the location of exceptional points through the measurement of photonic SHE. Conversely, the photonic SHE can be an indispensable tool to study the exotic physics near/at the exceptional point in various photonic systems.

II. RESULTS AND ANALYSIS

We consider the photonic SHE in a typical PT-symmetric structure, namely a bilayer structure with balanced loss and gain distribution in Fig. 1(c). Each slab has a thickness of $d = \lambda/5$, where λ is the wavelength in free space. The slab

FIG. 2. Representation in parameter space of giant photonic SHE near exceptional points for the reflected beam. Here δ_{LCP} is plotted as a function of $|\text{Im}(n_{loss/gain})|$ and the incident angle θ_i . The structural setup is the same as Fig. 1(c).

with loss (gain) has a refractive index of $n_{loss} = n_R + in_I$ ($n_{gain} = n_R - in_I$), where $n_R = 3$ is chosen. Then $n_{gain} = n_{loss}^*$, which fulfills the PT-symmetry condition [34,38]. The gain materials, whose imaginary part of the refractive index are negative, may consist of dye molecules [47], semiconductors [48], quantum dots [49], and rare earth [50], and they can be realized through optical pumping.

Due to the importance of exceptional points in the manipulation of photonics SHE, we briefly introduce the exceptional points below. For the two-port PT-symmetric structure in Fig. 1(c), the scattering matrix is $\bar{S} = \begin{bmatrix} t & r_{+z} \\ r_{-z} & t \end{bmatrix}$ [51–53], where t is the transmission coefficient and r_{+z} (r_{-z}) is the reflection coefficient if the incident light propagates to the $+z$ ($-z$) direction (see the Supplemental Material [54]). For $\bar{S}$, its two eigenvalues are $\psi_{\pm} = t \pm \sqrt{r_{+z}r_{-z}}$. According to the generalized conservation relations, one has $|T - 1| = \sqrt{r_{+z}r_{+z}^*r_{-z}r_{-z}^*}$ [55], where $T = t/t^*$ is the transmittance. By using the generalized conservation relation in the expression of the two eigenvalues, we have $|\psi_{+}| = |\psi_{-}|$ if $T < 1$; the PT-symmetric structure is in the exact PT symmetric phase. In contrast, if $T > 1$, $|\psi_{+}| \neq |\psi_{-}|$; the PT-symmetric structure exhibits the broken PT symmetric phase. Particularly, if $T = 1$ (which appears when $r_{+z}r_{-z} = 0$), the two eigenvalues, along with the two eigenfunctions for $\bar{S}$, coalesce to the same value; such a case is denoted as the exceptional point for $\bar{S}$.

The exceptional points of $\bar{S}$ are found to be dependent on the polarization and propagation direction of the incident beam. In short, there can be four different types of exceptional points, which appear at $r_{+z}^p = 0$, $r_{-z}^p = 0$, $r_{+z}^s = 0$, and $r_{-z}^s = 0$, respectively. To facilitate the discussion, we denote these exceptional points as EP_{+z}^p , EP_{-z}^p , EP_{+z}^s , and EP_{-z}^s . Here and below, the superscripts p/s and the subscripts $+z/-z$ indicate the polarization and propagation direction of incident light, respectively. These four types of exceptional points in the parameter space, and their dispersion as a function of the incident angle θ_i and the imaginary part of refractive index $|\text{Im}(n_{loss/gain})|$, are shown in Fig. 2.

We now proceed to calculate the photonic SHE near/at the exceptional points. We consider an incident Gaussian beam with linear polarization (p or s polarized); its angular spectrum is proportional to $e^{-w^2(k_y^2+k_x^2)/4}$, where $w = 30\lambda$ is the beam waist and k_{iy} (k_{ix}) is the y (x) component of wave vector. For the reflected (transmitted) waves, the spin-dependent transverse shift is dependent on the reflection (transmission) coefficients [12,21]. Due to reciprocity and structural asymmetry of the PT-symmetric system, if the incident angle is fixed, the transverse shift for reflected waves (transmitted waves) is sensitive to (independent of) the propagation direction of the incident beam. Therefore, we focus our discussion of photonic SHE on the reflected wave, since it provides an additional degree of freedom to control the photonic SHE compared with the transmitted wave. In addition, it is emphasized that the intensity of the reflected Gaussian beam will not tend to zero when the PT-symmetric structure works near the exceptional point, since the reflected Gaussian beam is related to the reflection coefficient of both p - and s -polarized waves at a finite range of incident angles.

For the analysis of spin-dependent transverse shifts, the reflected fields for LCP or RCP waves needs to be computed, so that their barycenter or centroid can be obtained. To be specific, a three-dimensional propagation model is needed for the derivation of the Gaussian beam reflection (see Supplemental Material [54]). A Taylor series expansion for reflection coefficients, i.e., $r = r(\theta_i) + \frac{\partial r}{\partial \theta_i} \frac{k_{ix}}{k}$, should be introduced if $r(\theta_i) \rightarrow 0$, which arises at the exceptional point. Moreover, for the PT-symmetric structure in Fig. 1(c), it is noted that $\delta_{\text{LCP}} = -\delta_{\text{RCP}}$, where δ_{LCP} and δ_{RCP} are the transverse shifts of reflected waves with LCP and RCP, respectively.

Figure 2 shows exotic photonic SHE near/at exceptional points. When the incident beam propagates towards the $+z$ direction in Figs. 2(a) and 2(b), the transverse shift $\delta_{+z, \text{LCP}}^{p/s}$ is suppressed down to zero at the exceptional point $\text{EP}_{+z}^{p/s}$. When the system slightly deviates away from $\text{EP}_{+z}^{p/s}$, the absolute value of $|\delta_{+z, \text{LCP}}^{p/s}|$ becomes largely enhanced. To be specific, one has $|\delta_{+z, \text{LCP}}^p| > 10\lambda$ in Fig. 2(a), which is over two orders of magnitude larger than that found in the typical air-glass interface (the related transverse shift is about $\lambda/10$) [4]. Moreover, $\delta_{+z, \text{LCP}}^{p/s}$ switches its sign if the system moves across $\text{EP}_{+z}^{p/s}$. This finding represents direct evidence of photonic SHE related to spontaneous PT-symmetry breaking. Similarly, when the incident beam propagates to the $-z$ direction in Figs. 2(c) and 2(d), exotic transverse shift $\delta_{-z, \text{LCP}}^{p/s}$ also arises near/at the exceptional point $\text{EP}_{-z}^{p/s}$.

We find that the sign switch of transverse shifts across the exceptional point is dependent on the propagation direction of the incident beam. As a typical example, when $|\text{Im}(n_{\text{loss/gain}})|$ increases, the large-value $\delta_{-z, \text{LCP}}^p$ changes from positive to negative across EP_{-z}^p in Fig. 2(c), which is opposite to the sign change of $\delta_{+z, \text{LCP}}^p$ across EP_{+z}^p in Fig. 2(a). Besides, it is noted that the PT-symmetric structure is in the broken (exact) PT-symmetric phase if the value of $|\text{Im}(n_{\text{loss/gain}})|$ is between (beyond) the two trajectories of $\text{EP}_{-z}^{p/s}$ and $\text{EP}_{+z}^{p/s}$ in Fig. 2. Therefore, it is reasonable to argue that the dependence of sign change of the giant transverse shift is related to the phase transition in PT-symmetric systems. On the other hand, the sign of

FIG. 3. Explaining the exotic photonic SHE near/at the exceptional points from the perspective of reflection coefficients. The magnitude and phase of reflection coefficients are shown in (a)–(d) and (e)–(h), respectively.

the giant transverse shift across the exceptional point is also polarization dependent. For example, when $|\text{Im}(n_{\text{loss/gain}})|$ increases, the large $\delta_{+z, \text{LCP}}^p$ changes from negative to positive across EP_{+z}^p for the p -polarized incident beam in Fig. 2(a); in contrast, the large $\delta_{+z, \text{LCP}}^s$ changes from positive to negative across EP_{+z}^s for the s -polarized incident beam in Fig. 2(b).

For the incident beam with arbitrary polarization and incident angle, the giant transverse shift can show up through judicious structural design; see Figs. 2 and S4. This capability can be an advantage over other systems without exceptional points, which is generally dependent on the polarization or incident angle. Our findings in Figs. 2 and S4 thus indicate that the exceptional points allow for flexible parametric control of photonic SHE, including enhancing or suppressing the magnitude of the transverse shift and switching its sign.

From the quantitative analysis of photonic SHE, the transverse shift is closely associated with the reflection coefficients [7,12]. Figure 3 shows the magnitude and phase of the reflection coefficients. We find these exotic phenomena of photonic SHE in Fig. 2 are caused by the near-zero magnitude of reflection coefficients near the exceptional point in Figs. 3(a)–3(d) and their abrupt phase change at the exceptional point in Figs. 3(e)–3(h). A detailed explanation is given below.

Let us start with a p -polarized incident beam. The transverse shift is found to be proportional to $|r^p|^2[1 + \text{Re}(\frac{r^s}{r^p})]$ (see Supplemental Material [54]). Since $|r^p| = 0$ at the exceptional point EP^p in Figs. 3(a) and 3(b), the transverse shift is exactly zero at the exceptional point in Figs. 2(a) and 2(c). If $|r^p| \neq 0$, the magnitude of giant transverse shift becomes closely related to $|r^s|/|r^p|$, while the sign of the giant transverse shift is related to the term $\cos(\phi_s - \phi_p)$, where $\phi_{p/s}$ stands for the phase of $r^{p/s}$. Figures 3(a)–3(d) shows that there is a finite value of $|r^s|$ but a near-zero value of $|r^p|$ near EP^p . Thus, one would have a very significant value of $|r^s|/|r^p|$ near EP^p . This directly leads to the appearance of the giant photonic SHE near EP^p for the p -polarized incident beam. Moreover, r^p has an abrupt phase jump of π at EP^p in Figs. 3(e) and 3(f), while r^s smoothly changes its phase at EP^p in Figs. 3(g) and 3(h). Then if the system transits across the exceptional point EP^p , the term $\cos(\phi_s - \phi_p)$ will change its sign. This further gives rise to a sign switch in the giant transverse shift for the p -polarized incident beam. For the s -polarized incident beam, the transverse shift is proportional to $|r^s|^2[1 + \text{Re}(\frac{r^p}{r^s})]$ (see Supplemental Material [54]). Due to the near-zero value and the abrupt phase jump of r^s across the exceptional point EP^s in Figs. 3(c), 3(d), 3(g), and 3(h), an analysis similar to the one above can also explain the exotic photonic SHE for the s -polarized incident beam in Fig. 2. Besides, the transverse shift near the exceptional points in Fig. 2 is not always large for arbitrary incident angles. The reason is that the transverse shift is also dependent on other terms, such as $\frac{\partial r^{s/p}}{\partial \theta_i}$, which may weaken the photonic SHE and play a dominant role over the enhancement term of r^s/r^p or r^p/r^s .

We note that the exceptional point or the PT symmetry breaking can also appear in entirely passive optical systems. The reason is that the bilayer optical system in Fig. 1(c) with an arbitrary loss and gain profile can be mathematically transformed into a PT-symmetric one [40,56]. However, for passive optical systems, the reflection coefficients cannot be exactly zero at the exceptional points. Then it is reasonable to argue that the value of r^s/r^p or r^p/r^s at the exceptional points of passive optical systems will be much smaller than that at the exceptional points of PT-symmetric systems with balanced gain and loss distribution studied here. This way, according to the analysis of Fig. 3, a PT-symmetric system with balanced gain and loss distribution is needed to achieve a giant photonic SHE.

To further the understanding of the exotic photonic SHE near/at exceptional points, Fig. 4 shows the field distribution of reflected beam with LCP, where a p -polarized Gaussian beam (i.e., a Hermitian-Gaussian beam with TEM_{00} mode profile) with incident angle $\theta_i = 30^\circ$ is chosen for illustration. On one hand, if $|\text{Im}(n_{\text{loss/gain}})|$ increases, the transverse position of the beam centroid will transit from a positive (negative) value of y to a negative (positive) value in Figs. 4(a) and 4(e) [Figs. 4(b) and 4(f)] when crossing the exceptional point. On the other hand, although the transverse spin splitting does not occur in Figs. 4(c) and 4(d), the reflected fields show a symmetric double-peak profile either along the x direction at the exceptional point EP_{-z}^p in Fig. 4(c) or along the y direction at EP_{+z}^p in Fig. 4(d); see more analysis in Figs. S4 and S5. Such a counterintuitive phenomenon emerges because the

FIG. 4. Real-space demonstration of photonic SHE near/at exceptional points for the reflected beam. (a)–(f) Field distribution of the reflected beam with LCP at the interface. The p -polarized Gaussian beam with an incident angle of 30° is chosen. (g), (h) Magnitudes of $|\frac{\partial r^p}{\partial \theta_i}|$ and $|r^s|$ near the exceptional points.

reflected fields in the momentum space have $E_{\text{LCP}}^p(k_{rx}, k_{ry}) \propto (\frac{\partial r^p}{\partial \theta_i} k_{rx} + i k_{ry} r^s \cot \theta_i) e^{-w^2(k_{ry}^2 + k_{rx}^2)/4}$ at exceptional points. To be specific, since $|\frac{\partial r^p}{\partial \theta_i}| \gg |r^s|$ at EP_{-z}^p with $|\text{Im}(n_{\text{loss/gain}})| = 0.6043$ in Fig. 4(g), the term related to $\frac{\partial r^p}{\partial \theta_i} k_{rx}$ in the momentum space plays a dominant role in determining the field distribution of the reflected beam in the real space. This way, the reflected beam has a symmetric double-peak profile along the x direction in Fig. 4(c), and it is essentially a Hermitian-Gaussian beam with TEM_{10} mode profile. In contrast, since $|\frac{\partial r^p}{\partial \theta_i}| \ll |r^s|$ at EP_{+z}^p with $|\text{Im}(n_{\text{loss/gain}})| = 0.9425$ in Fig. 4(h), the term related to $i k_{ry} r^s \cot \theta_i$ becomes dominant. Then the reflected beam has a symmetric double-peak profile along the y direction in Fig. 4(d) and becomes a Hermitian-Gaussian beam with TEM_{01} mode profile. The reflected Hermitian-Gaussian beam with TEM_{10} or TEM_{01} mode profile revealed here has also been reported in systems without exceptional points [57]. Reference [57] shows it by tuning the waist of the incident Gaussian beam, where its incident angle is near the Brewster angle. As a different scheme, such a goal here is achieved by merely letting the

PT symmetric structure work at different exceptional points in Figs. 4(c) and 4(d).

Last but not least, there is an alternative definition of the scattering matrix for the two-port PT-symmetric structure in Fig. 1(c), namely $\bar{S}' = \begin{bmatrix} r_{+z} & t \\ t & r_{-z} \end{bmatrix}$ [41,55], which corresponds to the permutation of $\bar{S} = \begin{bmatrix} t & r_{+z} \\ r_{-z} & t \end{bmatrix}$ [51–53]. Although both definitions of the scattering matrix are widely used, “because the permutation operation does not preserve the eigenvalues, these two different definitions of S (i.e., scattering) matrix lead to different criteria for the symmetric and broken-symmetry phases, as well as for the phase boundary (exceptional points)”, as highlighted in Ref. [55]. Our results show that exotic photonic SHE mainly happens near/at the exceptional points of $\bar{S}$, instead of $\bar{S}'$. In addition, there are some recent studies of the Goos-Hänchen effect, which is characterized by a longitudinal shift in the incident plane, in PT-symmetric structures [58–61]. It is worthy to note that the Goos-Hänchen effect and the photonic SHE are two different physical phenomena, since the Goos-Hänchen effect has nothing to do with the spin-orbit interaction.

III. CONCLUSIONS

In summary, we have theoretically studied the photonic SHE in a PT-symmetric structure, especially the spin-dependent transverse shift near and at the exceptional points. We find that the design of exceptional points in PT-symmetric structures can be a viable scheme to enhance and manipulate the photonic SHE, including tuning the magnitude of transverse shifts and changing the sign of transverse shifts. Such a flexible control of the photonic SHE in PT-symmetric structures originates from two facts, namely the near-zero value and the abrupt phase jump of the reflection coefficients

at exceptional points. The revealed scheme may mitigate the detrimental influence of material loss on the photonic SHE and may enable other promising applications, such as the design of optical sensors based on exceptional points and photonic SHE. In addition to the flexible control of photonic SHE studied here, we note that there are other promising applications and intriguing phenomena near/at exceptional points, such as the unidirectional invisibility [52], enhanced spontaneous emission rate [35] and sensing [45,46], and anomalous lasing [42,43]. Remarkably, these intriguing phenomena may have distinct features for different types of exceptional points. In addition to the second-order exceptional point studied here, other types of exceptional points have also been reported, including paired exceptional points [36], ring or line of exceptional points [62], exceptional surfaces [63], and high-order exceptional points [35,64,65]. Hence, our work may trigger other intriguing questions for photonic SHE, including the possibility to further enhance the photonic SHE via high-order exceptional points, and some features of photonic SHE from the PT-symmetric inhomogeneous and anisotropic metasurface where the geometric Pancharatnam-Berry phase [7] is involved (in our work, only the geometric Rytov-Vladimirskii-Berry phase is involved). This way, it is still highly desirable to continue the exploration of photonic SHE in other exotic systems with exceptional points or PT symmetry.

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