Intrinsic photonic spin Hall effect of vector beam with rotational symmetry breaking

Xiaohui Ling$^{1,3}$, Xunong Yi$^1$, Xinxing Zhou$^2$, Yachao Liu$^2$, Hailu Luo$^{1,2,*}$, and Shuangchun Wen$^{1,2}$

$^1$SZU-NUS Collaborative Innovation Center for Optoelectronic Science and Technology, and Key Laboratory of Optoelectronic Devices and Systems of Ministry of Education and Guangdong Province, Shenzhen University, Shenzhen 518060, China
$^2$Laboratory for spin photonics, College of Physics and Microelectronic Science, Hunan University, Changsha 410082, China
$^3$Department of Physics and Electronic Information Science, Hengyang Normal University, Hengyang 421002, China

*Corresponding author: hailulu@hnu.edu.cn

We report the observation of intrinsic photonic spin Hall effect (SHE) of cylindrical vector beam by breaking its rotational symmetry. Using a fan-shaped aperture to block part of the vector beam, the SHE occurs and the spin photons accumulate at the edge of the broken beam. It is attributed to rotational symmetry breaking of the spin-dependent vortex phases that the two spin components of the vector beam carry. This phase is very similar to the geometric Panchartnam-Berry phase that produced by some inhomogeneous anisotropic media, which is no longer continuous in the azimuthal direction, and results in the spin accumulation. The spin-dependent shift increases with the rise of the topological charge of the vector beam and restricts by the aperture dimension. It is large enough to be directly observed rather than using a weak measurement technology. Because of the inherent nature of the phase and independency of light-matter interaction, the observed photonic SHE is intrinsic.

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Photonic spin Hall effect (SHE) describes the mutual influence of the photon spin (polarization) and the trajectory (orbital momentum) of light beam propagation, i.e., spin-orbit interaction [1–3]. It manifests as spin-dependent splitting of light, which corresponds to two types of geometric phases: the Rytov-Vladimirskii-Berry phase associated with the evolution of the propagation direction of light and the Pancharatnam-Berry phase related to the manipulation with the polarization state of light [3–5]. When a light beam reflecting/refracting at a planar interface or passing through an inhomogeneous anisotropic medium, it may acquire a locally varying geometric phase, i.e., the different part of the beam carrying different geometric phase [5–8]. The interference upon transmission leads to the redistribution of the beam intensity and may show a spin-dependent shift of beam centroids, that is, the photonic SHE. Recent advances in this field provide new opportunities for advantageous measurement of the optical parameters of nanostructures such as metallic film and graphene [9, 10], and enable spin-based photonics applications in the future [11]. Actually, the photonic SHE is not always dependent upon the light-matter interaction, it can be observed in an oblique observation plane respect to the beam propagation direction even in the free space [12, 13]. Projecting the angular spectrum components onto the observation plane, their polarization vectors acquire different effective “rotations”, and leads to the generation of effective, space-variant Rytov-Vladimirskii-Berry phase, and therefore the geometric SHE of light. This effect is intrinsically dependent upon the polarization geometry of the beam projected on the oblique observation plane rather than any kind of light-matter interaction.

On the other hand, cylindrical vector beam (CVB) that exhibits inhomogeneous polarization distribution with rotational symmetry has drawn great attention due to its great potential in many fields including optical manipulation, nonlinear optics, and optical communications (see [14] for a review and the references therein). It can be viewed as superposition of two sub-beams carrying opposite spin angular momentum (circular polarization) and opposite orbital angular momentum (vortex phase), and can be geometrically represented by the so-called higher order Poincaré sphere [15, 16] and algebraically described by the following equation in terms of the azimuthal and polar angles ($\phi, \beta$) in the sphere:

$$|\psi(\phi, \beta)\rangle = \cos\left(\frac{\phi}{2}\right)|R\rangle e^{-i\beta/2} + \sin\left(\frac{\phi}{2}\right)|L\rangle e^{i\beta/2}. \quad (1)$$

Here, $|R\rangle e^{i\beta/2}$ and $|L\rangle e^{-i\beta/2}$ are circularly polarized vortex light corresponding to the south ($\phi = 0$) and north poles ($\phi = \pi$) on the higher order Poincaré sphere, respectively, with $|R\rangle$ and $|L\rangle$ standing for the right- and left-circular polarizations. For $\phi = \pi/2$, Eq. (1) indicates a linear polarized CVB on the equator of the sphere with $\beta$ determining the longitude. In this case, the Jones vector of the CVB can be simply written as (cos $\beta$, sin $\beta R$) where $\beta = m \varphi + \beta_0$ with $m$ the topological charge, $\varphi$ the azimuthal angle, and $\beta_0$ a constant. Other values of $\phi$ represent elliptical polarized CVB. Equation (1) unambiguously illustrates that the two circular polarizations carry just opposite azimuthal vortex phase $e^{i\beta/2}$, i.e., this phase is spin-dependent and similar to the geometric Pancharatnam-Berry phase which can be obtained in some inhomogeneous anisotropic media [7, 8, 17–19]. Although the two components have opposite vortex phases and local energy flows, their superposition does not show a helical wave front. They always superpose exactly at the same position and no spin-dependent splitting can be observed, due to the rotational symmetry.

In this work, we put forward to break the rotational symmetry of the CVB for observing the spin-dependent splitting, i.e., the photonic SHE. By blocking part of the CVB with a fan-shaped aperture (FSA), the two spin components (circular polarizations) no longer superpose exactly and separate from each other (see the schematic picture in Fig. 1). The under-
lying mechanism is attributed to the inherent, spin-dependent vortex phase that it carries, so the observed photonic SHE is intrinsic. The splitting shift increases with the increase of the topological charge of the CVB and limited by the dimension of the aperture because the spin photons accumulate at the edge of the broken beam.

To measure the photonic SHE, we set up a Sagnac interferometer to generate the linear polarized CVB, as shown in Fig. 2(a), which can also be conveniently generated by many other methods [20–24]. This apparatus relies on the superposition of two equal-intensity beams with opposite circular polarizations and opposite vortex phases, according to Eq. (1). The polarizer (P1) can ensure the light output from the He-Ne laser to be 45° polarization respect to the horizontal direction. Then the beam passes through the polarization beam splitter (PBS) and is split into two equal-intensity beams with the transmission beam being horizontal polarization and the reflection beam vertical polarization. The two sub-beams propagate exactly in a common path. A phase-only spatial light modulator (SLM) is used at small incidence angle, and can apply a vortex phase with any desired topological charge to a horizontal polarization beam which is a good approximation of phase vortex-bearing Laguerre-Gauss beam. A half-wave plate (HWP1) with its optical axis 45° inclined to the horizontal direction is employed to change the vertical polarization to a horizontal one and vice versa for its counter-propagating counterpart. A Dove prism (DP) involves one reflection to change the sign of the topological charge alone one beam path, and ensures that the output beam contains two opposite phase vortexes. Then we use a quarter-wave plate (QWP1) with 45° optical axis orientation changes the two sub-beams into opposite circular polarizations. So the CVB is generated after the QWP1 [see Fig. 2(b)] and its intensity shows a donut-shaped profile similar to a vortex beam. The HWP2 can help to modulate the polarization distribution of the CVB, e.g., changing a radial polarization into an azimuthal polarization or any intermediate states [25].

![Fig. 2(a)](image1)

Fig. 2. Experimental setup for generating the CVB and measuring the photonic SHE when it passing through a fan-shaped aperture (FSA). (a) The laser source is a single mode linearly polarized He-Ne laser, wavelength $\lambda = 632.8$ nm. The polarizer (P1) ensures a 45° polarization light to impinge into the polarization beam splitter (PBS) and being equally split into two sub-beams. The Sagnac interferometer comprised of a PBS, a phase-only spatial light modulator (SLM, Holoeye Pluto-Vis, Germany), a Dove prism (DP), a half-wave plate (HWP1) and a mirror (M). A quarter-wave plate (QWP1) changes the two sub-beams from linear polarization to opposite circular polarizations. Then a CVB is produced after the QWP1. Another half-wave plate (HWP2) is used to modulate the polarization distribution of the CVB. BS represents a non-polarizing beam splitter. (b) An example of the generated CVB with radial polarization distribution. (c) Schematic picture of the FSA. (d) CCD recorded intensity of the generated CVB passing through the FSA without the Stokes parameter measurement setup (QWP2 and P2). It shows a direct intensity splitting of the $\sigma_+$ and $\sigma_-$ components.

The generated CVB then passes through a fan-shaped aperture [FSA, Fig. 2(c)] at normal incidence. For the sake of simplicity and without loss of generality, the FSA can be described by the following expression:

$$T(\theta) = \begin{cases} 1 & \text{for } \theta \text{ radian} \\ 0 & \text{otherwise} \end{cases}$$

(2)

It is known that the Stokes parameter $S_3$ can be used to describe the circular polarization degree [26], so the spin-dependent splitting of light can be obtained by measuring the $S_3$ parameter pixel by pixel in the output using a typical setup: a quarter-wave plate (QWP2), a polarizer (P2), and a CCD camera. In the experiments, the $S_3$ parameter can be given by

$$S_3 = \frac{I_{\sigma_+} - I_{\sigma_-}}{I_{\sigma_+} + I_{\sigma_-}}.$$  

(3)

Here, $I_{\sigma_+}$ and $I_{\sigma_-}$ represent the intensities measured in the circular polarization basis, respectively.

We first consider the influence of the topological charge $m$ on the intrinsic photonic SHE. The vortex phase creates a
Fig. 3. Intrinsic photonic SHE of the CVB with different topological charges for different FSAs with three typical aperture angles $\theta$. The dashed circles indicate the rough profile of the incident CVB. The measured light spot of the $S_3$ parameters have a little deviation from the dashed circles because of the unavoidable experimental errors in the process of the $S_3$ measurement.

phase gradient in the azimuthal direction, which results in a spin-dependent shift in $k$ space: $\Delta k = \sigma \nabla \beta = \sigma \hat{m} \hat{e}_\phi$ with $\sigma = \pm 1$ representing the left and right circular polarization and $\hat{e}_\phi$ the unit vector in the azimuthal direction, respectively \[11,25\]. Hence, this shift is proportional to the value of $m$. However, for a CVB, the spin-dependent splitting cannot be observed in free-space propagation, due to its rotational symmetry. Breaking the rotational symmetry, it is expected to observe the spin accumulation at the edge of the broken beam.

Figure 3 shows the measured $S_3$ parameters of the photonic SHE for different CVBs and different aperture angles $\theta$. The spin-dependent shift increases with the rise of the value of $m$. On the other hand, the shift distance is limited by the dimension of the aperture angle because the spin photons accumulate at the broken beam edge. Also because of this, the spin-dependent splitting increases with the increase of $\theta$. If we reverse the sign of $m$ by modulating the phase picture displayed on the SLM, the spin accumulation is also inverted ($\Delta k$), as shown in Fig. 4. Because the sign of $m$ directly determines the handedness of the vortex phase that the two spin components of the CVB carry. The measured $S_3$ parameters have a little deviation from the expected position (dashed circles in Figs. 3 and 4) due to the unavoidable experiment errors in the $S_3$ measurement.

The splitting distance of the photonic SHE of the CVB can be large enough for direct measurement rather than using the weak measurement technology \[5\]. With the increase of the value $m$ of the CVB, we can directly observe the intensity separation of the $\sigma_+$ and $\sigma_-$ components, as shown in Fig. 5 for $\theta = 30^\circ$. In (a) and (b) for $m = 1$ and 2, the two components do not separate enough from each other and show a single-spot profile, however, it still can be discriminated by measuring the $S_3$ parameter just like in Figs. 3 and 4. If the phase gradient is large enough, the $\sigma_+$ and $\sigma_-$ components are almost completely separated, as shown in Fig. 5(c) and 5(d). The induced spin-dependent shift is within millimeters (the beam waist of the He-Ne laser is 0.7 mm and expanded to 2.1 mm by a beam expander), which is many times larger than the optical wavelength (632.8 nm). It is also much larger than that had observed previously in beam reflection and refraction with the shift of the order of a fraction of wavelength \[5,6\]. This enables us to observe a giant photonic SHE.

Fig. 4. Intrinsic photonic SHE of the CVB with negative topological charges $m = -1, -2, -3,$ and $-4$ for the aperture angle of the FSA $\theta = 45^\circ$.

Fig. 5. Direct intensity illustration of the giant photonic SHE with the aperture angle of the FSA $\theta = 30^\circ$. The four screen-shots shows the results of CVBs with different topological charges $m$.
the broken CVB at a propagation distance much less than the Rayleigh distance, so the spin photons accumulate at the edge of the broken beam.

In summary, we have experimentally demonstrated the intrinsic SHE of the CVB by breaking its rotational symmetry using a FSA to block part of the CVB. The spin accumulation occurs at the edge of the broken beam, and the spin-dependent shift increases with the topological charge of the CVB and restricts by the aperture angle of the FSA. The underlying mechanism is attributed to the discontinuous local energy flow that results from the broken, spin-dependent vortex phase. This enables us to observe a direct and giant photonic SHE which is intrinsic to the CVB. Our findings reveal that the photonic SHE may be manipulated (enhanced or inverted) by directly tailoring the polarization geometry of light.

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