Optics Communications 427 (2018) 238–243

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

# Realization of photonic spin Hall effect by breaking the rotation symmetry of optical field in light–matter interaction

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## ARTICLE INFO

*Keywords:*
Photonic spin hall effect
Spin-dependent shift
Rotation symmetry
Pancharatnam–Berry phase

## ABSTRACT

Photonic spin Hall effect (SHE) manifests itself as spin-dependent shift or splitting of a light beam, which is derived from spin–orbit interactions, and can be realized by breaking the rotation symmetry of light–matter interaction systems. Here, we demonstrate the observation of a photonic SHE by breaking the rotation symmetry of the optical field, while keeping the rotation symmetry of the inhomogeneous waveplate. The inhomogeneous waveplate constructed by dielectric nanostructures, introduces a spin-dependent Pancharatnam–Berry phase to the two spin components of the input beam, i.e., the left- and right-circular polarization components acquire exactly opposite vortex phases. During beam propagation, they experience opposite azimuthal rotations, and induce a four-lobe spin-dependent splitting in the azimuthal direction. In addition, the spin-dependent splitting becomes more evident upon beam propagation, and can be enhanced by increasing the topological orders of the nanostructures. For comparison, we also examine that no spin-dependent splitting can be observed when keeping the rotation symmetry of the incident optical field.

## 1. Introduction

Photonic spin Hall effect (SHE) manifests itself as a transverse spin-dependent shift or splitting of light beam, which is derived from spin–orbit interaction [1–5]. spin–orbit interaction describes the mutual interplay between the spin angular momentum and orbital angular momentum [6,7], and can be explained in terms of two types of geometric phases [8,9]: the Rytov–Vladimirskii–Berry (RVB) phase associated with the evolution of the propagation direction of light and Pancharatnam–Berry (PB) phase related to the manipulation with the polarization state of light.

The RVB-phase-dependent SHE can be observed when a light beam illuminates obliquely at a planar optical interface (e.g., an air–glass interface) [1–3,5], or normally impinges onto an inhomogeneous metasurface with a strong dynamical phase gradient in the transverse direction [10]. In a sense, the rotation symmetry of these light–matter interaction systems are broken with respect to the normal direction of the interface in the oblique incidence geometry or in the normal incidence case but deflected by a transverse phase gradient. This rotation symmetry-breaking indicates the generation of photonic SHE. On the other hand, the PB phase optical elements have been employed to generate and manipulate vortex beams and vector beams which are both rotation symmetry [11–13]. The PB-phase-dependent SHE can also be observed when breaking the rotation symmetry in appropriate ways, such as in semi-annular nano-gratings [14], one-dimensional PB phase elements [15,16], and specific-structured microstructures [17–20]. Most of the existing research focused on breaking the rotation symmetry of the light–matter interaction system via seeking for a medium without rotation symmetry.

In this work, we present, both theoretically and experimentally, the photonic SHE by breaking the rotation symmetry of incident optical field, while keeping the rotation symmetry of inhomogeneous waveplate. The asymmetric optical field is generated by a spatial light modulator, and the inhomogeneous waveplate is fabricated via the femtosecond laser writing of spatially varying nanogrooves in a fused silica sample [21]. The inhomogeneous waveplate introduces a spin-dependent PB phase to the input beam, i.e., the left- and right-circular polarization components of the input beam acquire exactly opposite PB

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https://doi.org/10.1016/j.optcom.2018.06.056
Received 13 April 2018; Received in revised form 12 June 2018; Accepted 21 June 2018

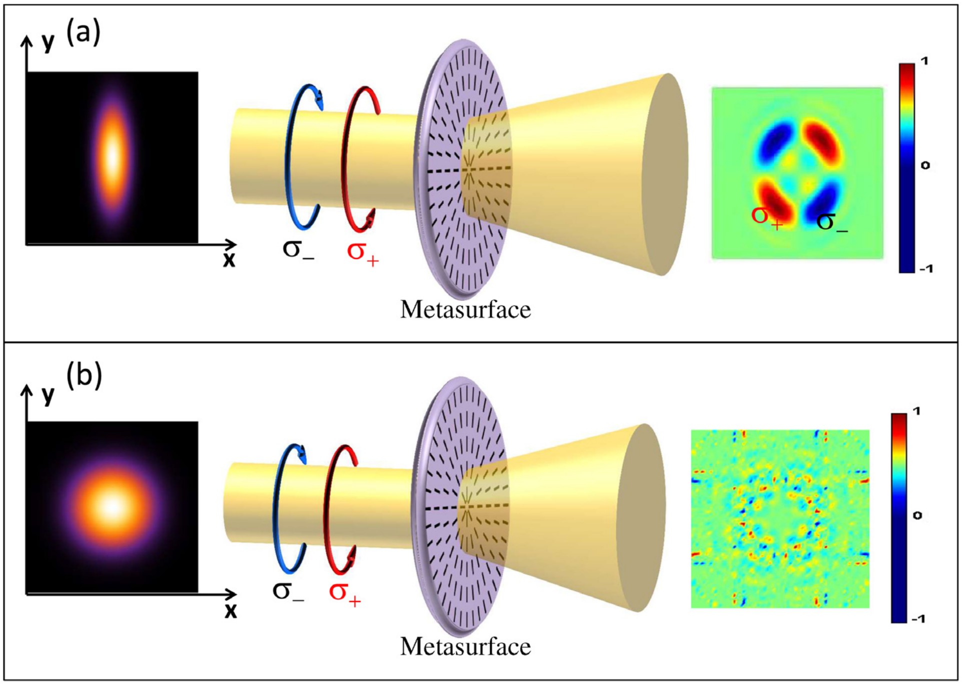

**Fig. 1.** The contrast between linearly polarized (a) ellipse-shaped and (b) circle-shaped Gaussian beams impinging into the half-wave inhomogeneous waveplate with $q = 1$. A linearly polarized ellipse-shaped beam normally passes through the inhomogeneous waveplate, and an azimuthal spin-dependent splitting occurs. The cylindrical symmetry of the light–matter interaction system is broken by the elliptical profile of the incident beam. However, when the inhomogeneous waveplate is illuminated by a linearly polarized fundamental Gaussian beam, no spin-dependent splitting appears.

phases which are indeed vortex phase. The two spin components carrying opposite vortex phases exhibit exactly opposite azimuthal energy flows. Hence, during beam propagation, the two components experience just opposite rotations in the azimuthal direction, and results in a four-lobe spin-dependent splitting pattern in the azimuthal direction. We also find that the spin-dependent splitting becomes more significant when either the value of the topological order of the inhomogeneous waveplate or the transmission distance is increased. Note that blocking a sector of the incident beam with an aperture is also an effective way to breaking the rotation symmetry, and can also be employed to manipulate the spin–orbit interaction and photonic SHE [22–24], but this method has nothing to do with the PB phase.

## 2. Pancharatnam–Berry geometric phase

We consider that the optical field possesses an asymmetric structure of intensity which can be expressed as [25]

$$E_0(x,y,z) = \frac{A_0\sqrt{w_{0x}w_{0y}}}{\sqrt{w_x(z)w_y(z)}}\exp\left[-\left(\frac{x^2}{w_x^2(z)}+\frac{y^2}{w_y^2(z)}\right) - ik\left(\frac{x^2}{2R_x(z)}+\frac{y^2}{2R_y(z)}\right)+i\eta(z)-ikz\right], \tag{1}$$

$$w_{x(y)}(z) = w_{0x(y)}\sqrt{1+\frac{z^2}{z_{Rx(y)}^2}}, \quad R_{x(y)}(z) = z+\frac{z_{Rx(y)}^2}{z}, \quad z_{Rx(y)} = \frac{1}{2}kw_{0x(y)}^2, \tag{2}$$

where $k = 2\pi/\lambda$ is the wavenumber of the incident beam. $z_{Rx(y)}$, $R_{x(y)}(z)$, and $w_{x(y)}(z)$ is the Rayleigh range, the radius of wavefront curvature, and the radius of the beam in the $x(y)$ direction, respectively. $w_{0x(y)}$ is the beam waist width. $\eta(z) = [\arctan(z/z_{Rx}) + \arctan(z/z_{Ry})]/2$ is the Gouy phase. The remarkable characteristic of an ellipse-shaped beam is that the beam waist in $x$ direction is unequal to that in $y$ direction [Fig. 1(a)].

We introduce a dielectric-based metsurface which can be regarded as an inhomogeneous waveplate with rotation symmetry in the light–matter interaction. The dielectric nanostructures are fabricated by a femtosecond laser writing in silica glass [21]. As the writing pattern varies in subwavelength scale, it creates an inhomogeneous anisotropic medium due to the form birefringence with phase retardation $\delta = \pi$. The local optical axes at each point are parallel and perpendicular to the subwavelength grooves, respectively. This builds an artificial uniaxial crystal with locally variant optical axes [Fig. 2(c)–(e)]. In particular, the direction of optical axis (fast axis) can be specified by the following expression:

$$\alpha(x,y) = q\phi + \alpha_0, \tag{3}$$

where $q$ is a constant specifying the rotation rate of the inhomogeneous waveplate, $\phi = \arctan(y/x)$ indicates the azimuthal angle, and $\alpha_0$ is a constant angle denoting the initial orientation for $\phi = 0$.

We then consider that the metasurface is illuminated by a circularly polarized, ellipse-shaped beam with spin angular momentum $\sigma_\pm\hbar$ per photon [26], where $\sigma_+ = +1$ denotes the left-handed circular polarization and $\sigma_- = -1$ the right-handed one, respectively. Its Jones vector is then given by $\mathbf{E}_{in}(x,y,z) = E_0(x,y,z)\times[1,\sigma_\pm i]^T$. The asymmetric optical field passing through the metasurface $\mathbf{E}_{out}(x,y,z) = \mathrm{T}(x,y)\mathbf{E}_{in}(x,y,z)$ can be described as

$$\mathbf{E}_{out}(x,y,z) = E_0(x,y,z)\exp\left(i2\sigma_\pm q\phi\right)\begin{pmatrix}1\\ \sigma_\mp i\end{pmatrix}, \tag{4}$$

where the Jones matrix of metasurface $\mathbf{T}(x,y)$ has the form [12]

$$\mathbf{T}(x,y) = \begin{pmatrix}\cos 2\alpha & \sin 2\alpha\\ \sin 2\alpha & -\cos 2\alpha\end{pmatrix}. \tag{5}$$

Here we assume $\alpha_0 = 0$. We find that the circularly polarized ellipse-shaped beam passing through the metasurface presents a reversed spin angular momentum and an additional orbital angular momentum given by $2\sigma_\pm q\hbar$. The additional phase $2\sigma_\pm q\phi$ is spin-dependent and geometric in nature [8,9].