# Topological spin–orbit interaction of light in anisotropic inhomogeneous subwavelength structures

**Avi Niv, Yuri Gorodetski, Vladimir Kleiner, and Erez Hasman***

*Micro and Nanooptics Laboratory, Faculty of Mechanical Engineering, and Russell Berrie Nanotechnology Institute,*
*Technion—Israel Institute of Technology, Haifa 32000, Israel*
**Corresponding author: mehasman@tx.technion.ac.il*

Received September 2, 2008; accepted October 23, 2008;
posted November 5, 2008 (Doc. ID 101033); published December 4, 2008

Spin–orbit interaction resulting from spatial polarization state manipulation is demonstrated. Polarization-state manipulation is achieved by utilizing the effective birefringent nature of subwavelength structures acting as an anisotropic inhomogeneous medium. Experimental verification is obtained by measuring the effect of the unavoidable spin-dependent Pancharatnam–Berry phase modulation on the far-field diffraction pattern of the beam. Unlike the usual dynamic spin–orbit interaction that splits spin states in the temporal frequency (energy) domain, this topological spin–orbit interaction results in the splitting of spin states degenerated by their spatial frequencies (momentum). © 2008 Optical Society of America

*OCIS codes:* 050.6624, 260.5430, 050.2770.

Spin–orbit interaction occurs when the intrinsic (spin) and extrinsic (orbital) angular momentums interact, resulting in the splitting of degenerated system states. As a fundamental effect, it can be found in diverse fields of physics and at different scales, ranging from stellar objects to fundamental particles. It is well known that electromagnetic waves can carry both spin and orbital angular momenta [1]. It is thus surprising to find that only recently has the role of spin–orbit interaction in phenomena such as the Imbert–Fedorov shift, the Rytov–Vladimirskii–Berry phase, and the Pancharatnam–Berry phase been appreciated [2–5].

In a recently published paper, Bliokh *et al.* [2] studied topological spin–orbit interaction, where splitting occurs in the spatial frequencies (momentum) of degenerated spin states. This is in contrast to the more common dynamic interaction in which splitting occurs for the temporal frequencies (energy) of the states. As a result, a spin-dependent geometrical phase appears—the Pancharatnam–Berry phase—rather than the usual dynamic phase. This Letter reports an experimental confirmation of this fundamental effect in a basic system using a well-collimated monochromatic light beam. The interaction is mediated by space-variant dielectric subwavelength structures that effectively serve as the required anisotropic inhomogeneous medium. Experimental verification is obtained by measuring the effect of the geometrical Pancharatnam–Berry phase on the far-field diffraction pattern of the beam.

Propagation of light in linear anisotropic media brings about an interaction between the polarization (spin up/down for right- and left-handed circularly polarized light) and the material. If, in addition, inhomogeneity is introduced, spin–orbit interaction may occur. In our case, nonabsorbing media were used; therefore, inhomogeneity was manifested only by the orientation of the anisotropy axis. Let us consider a $\pi$-retardation waveplate. As this device elastically scatters light, the spin of the emerging beam has a sign opposite to that of the incident beam. If, in addition, the $\pi$-retardation waveplate is rotating, spin–orbit interaction results in a rotational Doppler effect [6],

$$\Delta\omega = 2\sigma\Omega. \tag{1}$$

Here, $\sigma = \pm 1$ is the spin value of the incident wave, $\Omega$ is the rotation rate of the waveplate, and $\Delta\omega$ is the frequency shift. Figure 1 illustrates this case. In Eq. (1) temporal rotation is usually assumed (i.e., $\Omega$ is measured in radians per unit of time). However, as pointed out by Bilokh *et al.* [2], for spatial rotation in a plane transverse to the propagation direction of the beam (i.e., $\Omega$ is measured in radians per unit of length), Eq. (1) is valid albeit with a spatial frequency shift $\Delta\mathbf{k}_{\perp}$ replacing the temporal frequency shift $\Delta\omega$. Bliokh *et al.* also showed that the geometric Pancharatnam–Berry phase ($\phi_{PB}$) results from this spatial version of the rotational Doppler effect according to

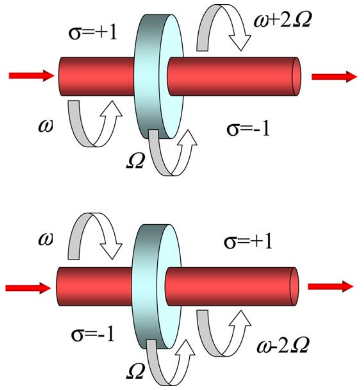

Fig. 1. (Color online) Illustration of the rotational Doppler effect on a circularly polarized laser beam at frequency $\omega$ incident upon a $\pi$-retardation waveplate rotating at frequency $\Omega$.

0146-9592/08/242910-3/$15.00

$$\phi_{PB} = 2\sigma \int \Omega \mathrm{d}\xi, \qquad (2)$$

where $\xi$ is a spatial coordinate. As the geometric phase can be viewed as having arisen from a topological monopole charge at the center of a suitable parameter space [7], we consider this spin–orbit interaction to be a topological effect (rather than a dynamic one).

Experimental verification was obtained by exploiting the effective birefringence of quasiperiodic subwavelength structures; when the periodicity of a grating is sufficiently smaller than the illumination beam's wavelength, it effectively behaves as a uniaxial crystal with optical axes that are parallel and perpendicular to the grating strips. By correctly controlling the etched depth of the grating, an effective $\pi$-retardation waveplate can be achieved. In addition, unlike natural crystals, subwavelength gratings allow for variations in the grating orientation, thereby introducing inhomogeneity to the already existing anisotropy of the device [8]. Let us consider an effective $\pi$-retardation subwavelength grating with a local groove orientation $\theta$ (effective fast axis orientation) given by

$$\theta = m\vartheta/2, \qquad (3)$$

where $(r,\vartheta)$ are polar coordinates and $m$ is an integer number. In this case, the spatial rotation rate is $\Omega = m/2$, and according to Eq. (2), the Pancharatnam–Berry phase has a spiral structure given by

$$\phi_{PB} = \sigma m \vartheta. \qquad (4)$$

Thus spin–orbit interaction results in the appearance of vortex with topological charge $\sigma m$ at the phase of the beam.

Figure 2 shows a schematic illustration of the experiment. A collimated beam of 10.6 $\mu$m wavelength light from a $CO_2$ laser, with a spin set to either $\sigma = \pm 1$, traversed a space-variant $\pi$-retardation subwavelength grating with a clear aperture of 10 mm. The grating consisted of a 2 $\mu$m subwavelength period that was etched 5 $\mu$m deep into a GaAs wafer. A detailed description of the fabrication process can be found in [8]. The inset shows a scanning electron microscope image of the grating. Note the local grating orientation according to Eq. (3), with $m=1$. According to Eq. (4), this device is expected to induce a helical phase of unit charge whose sign depends on the spin of the incident wave. However, the measured quantity is the intensity of the wave, which is identical with respect to the sign of the helical phase. Typically, this problem is resolved by producing an interference with a reference wave [5]. We took a different, yet simpler, approach. The beam that emerged from the space-variant subwavelength structure impinged on a *refractive* helical phase plate (ZnSe), depicted as a spiral in Fig. 2. This device adds a unit-charged helical phase regardless of the spin of the incident wave. Therefore, the cumulative phase will have a zero charge for $\sigma=-1$ and a charge of two for $\sigma=+1$. Consequently, we expected the far-field diffraction pattern to consist of a confined intensity lobe for $\sigma=-1$, and a charge-two doughnut-shaped distribution for $\sigma=+1$. Far-field intensity distributions were captured at the focus of a 1 m focal length lens using a pyroelectric camera (Spiricon, Pyrocam III). Figure 3 shows the measured spin-dependent diffraction patterns. For a left-handed circularly polarized beam ($\sigma=-1$), a confined intensity lobe appeared, while for a right-handed circularly polarized beam ($\sigma=+1$), a doughnut-shaped intensity lobe was seen. Typical cross sections of the diffraction patterns are also shown in Fig. 3; a good agreement between calculated and measured values confirms the zero and double charge of the intensity distributions, respectively. In addition, the spins of the emerging beams were verified to be of opposite signs with respect to the incident beam, as expected. Our experiment demonstrates the spin-dependent phase modulation of a transmitted wave, confirming the topological spin–orbit interaction for light impinging upon an anisotropic inhomogeneous structure.

In conclusion, we have verified that the origin of the Pancharatnam–Berry phase results from a topological spin–orbit interaction within anisotropic inhomogeneous media. This connection is important both for an understanding of the fundamental principle involved as well as its role in the future development of spin-based optical applications, such as mode switching.

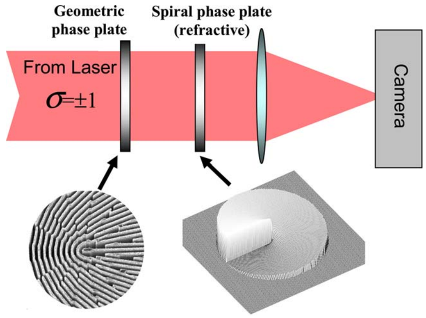

Fig. 2. (Color online) Schematic illustration of the experiment.

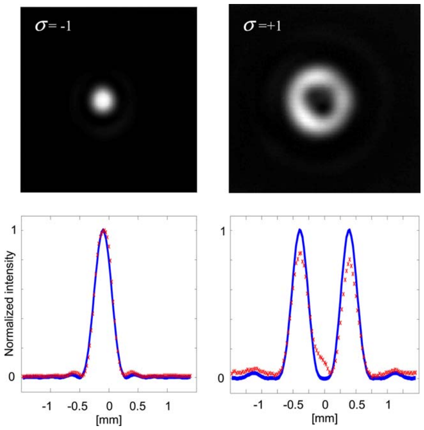

Fig. 3. (Color online) Upper row shows the captured intensity distributions for different illumination helicities (circular polarized light: left-handed, $\sigma=-1$; right-handed, $\sigma=+1$). The lower row shows experimental (crosses) and predicted (solid curve) typical cross sections.

## References

1. L. Allen, M. W. Beijersbergen, R. J. C. Spreeuw, and J. P. Woerdman, Phys. Rev. E **45**, 8185 (1992).
2. K. Y. Bliokh, Y. Gorodetski, V. Kleiner, and E. Hasman, Phys. Rev. Lett. **101**, 030404 (2008).
3. M. Onoda, S. Murakami, and N. Nagaosa, Phys. Rev. Lett. **93**, 083901 (2004).
4. Y. Gorodetski, A. Niv, V. Kleiner, and E. Hasman, Phys. Rev. Lett. **101**, 043903 (2008).
5. L. Marrucci, C. Manzo, and D. Paparo, Phys. Rev. Lett. **96**, 163905 (2006).
6. B. A. Garetz and S. Arnold, Opt. Commun. **31**, 1 (1979).
7. M. V. Berry, Proc. R. Soc. London, Ser. A **392**, 45 (1984).
8. A. Niv, G. Biener, V. Kleiner, and E. Hasman, Opt. Commun. **251**, 306 (2005).