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Spin-orbit interaction of light

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A spin-dependent topological deflection of classical light propagates along a smooth helical trajectory.

Spin-orbit interaction is a weak coupling between intrinsic (spin) and extrinsic (orbital motion) degrees of freedom of spinning particles. It implies mutual conversion between a particle's spin and orbital angular momenta. Classical polarized light also carries spin and reveals spin-orbit coupling when propagating along a curved trajectory.[1] This manifests itself in two mutual phenomena. First, the curved trajectory affects the evolution of the light's polarization state, which is described by the Berry phase and parallel-transport law: see Figure 1(a). Second, the light trajectory also experiences a reaction from the spin, i.e., a polarization-dependent perturbation of the trajectory occurs. This can also be described in terms of the Berry phase and represents a topological spin transport of photons also known as the spin-Hall effect of light or the optical Magnus effect: see Figure 1(b). We recently reported the first direct observation of this effect.[2]

Remarkably, the spin-orbit coupling phenomena have a dual, geometro-dynamical nature. On the one hand, the parallel transport of the polarization and the spin-Hall effect can be attributed to the inertia of the wave field and the Coriolis effect. On the other, the spin-orbit interaction of light has an inherent geometrical origin that is described by the Berry-phase topological monopole in momentum space.

Two decades ago, the Berry phase brought a geometrical beauty to the description of quantum-adiabatic evolution.[3,4] Physicists started to realize that seemingly 'passive' geometrical concepts, such as Berry curvature, also manifest themselves dynamically, producing a real action on physical objects. As a result, geometry-induced forces appear that affect the dynamics of quantum particles with some internal properties.[5] In particular, they describe the Magnus effect of quantum vortices[6] and spin-Hall effect of spinning particles.[7,8] This offers a novel type of quantum transport that is robust against the details of the system and is determined solely by the geometry and intrinsic properties of the particles.

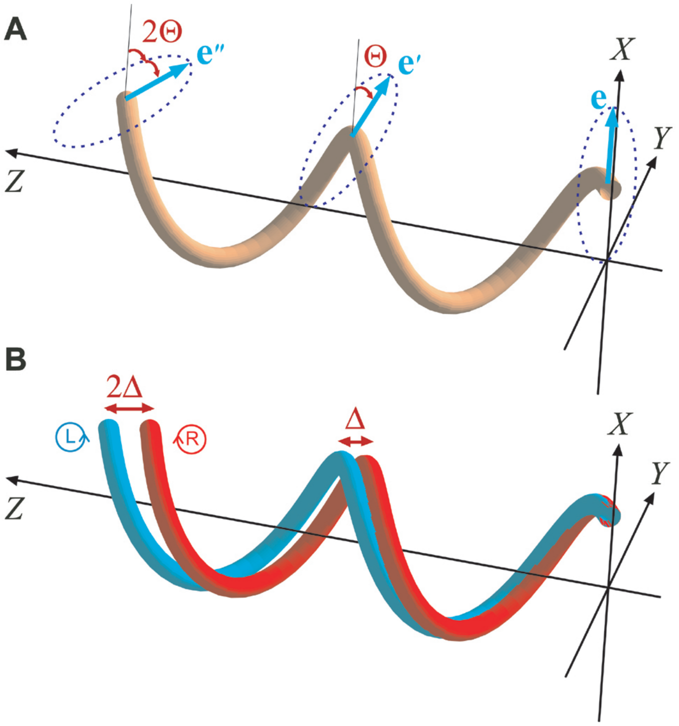

Figure 1. *Spin-orbit interaction of light. (a) Evolution of the polarization vector (e → e′ → e″) along a helical trajectory according to the Berry phase and parallel-transport law. Θ: Polarization rotation angle for each helix. (b) Topological spin transport of photons: Reaction of spin to the trajectory causes splitting of right- and left-hand circularly polarized beams. Δ: Splitting for each helix. (Reproduced with permission from Nature Photonics.[2])*

In our experimental setup,[2] we launched a laser beam at a grazing angle to the internal surface of a glass cylinder so that the light propagated along a smooth, helical trajectory (because of the total internal reflection): see Figure 2. Such a path induces a spin-orbit interaction between the trajectory's geometry and the intrinsic spin angular momentum carried by the polarized light. Theory and our experimental setup provide a fairly complete picture of the geometrodynamical evolution of polarized light. We detected trajectory-dependent variations of

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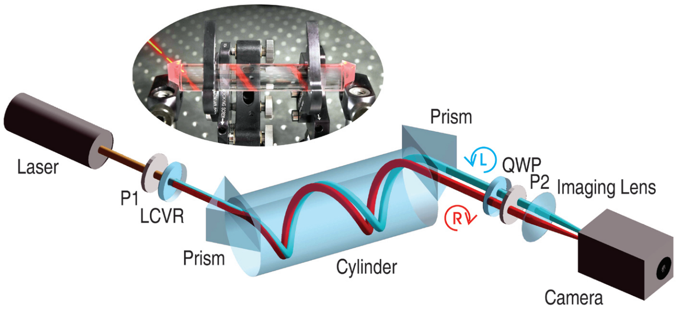

Figure 2. *Experimental setup. Trajectories of left- and right-handed circularly polarized light beams propagating along the reflecting surface of a glass cylinder are shown. The spin-orbit coupling between the intrinsic angular momentum of light and a curved trajectory of propagation produces opposite deflections for the two beams. P1, P2: Polarizers. QWP: Quarter-wave plate. LCVR: Liquid-crystal variable retarder. (Reproduced with permission from Nature Photonics.*[2]*)*

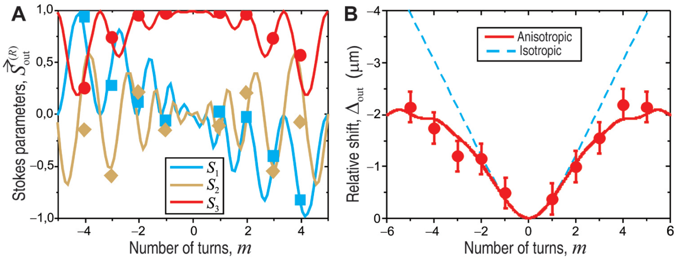

Figure 3. *Experimental (symbols) versus theoretical (curves) characteristics of the output laser beams, depending on the number of coils, m, in the helical trajectory (see Figure 2). (a) Output Stokes parameters (S_1, S_2, S_3) characterizing variations of the light's polarization state. (b) Relative transverse shift between initially right- and left-hand circularly polarized laser beams. (Reproduced with permission from Nature Photonics.*[2]*)*

the output polarization of light by measuring the Stokes parameters. We also detected a polarization-dependent shift of the output beam position, tangent to the cylinder surface. All measurements showed excellent agreement with our theoretical calculations based on the Berry-phase picture of the spin-orbit coupling of light (see Figure 3).

In addition to a fundamental scientific interest, the spin-Hall effect may have practical applications. It was originally invented in the context of semiconductor spintronics,[7] but also appears naturally within the fundamental equations of high-energy physics.[8] Nonetheless, it seems that optics provides an ideal field for its exploration. Light propagation can be directly observed in relatively clean and simple systems, and the accuracy of modern optics allows subwavelength resolution at nanoscales. Classical light captures all of the basic features of relativistic spinning particles, which enables us to extrapolate results to a range of physical systems where such observations are impossible. Using this effect in optical devices may lead to the development of a promising new area of research, spinoptics. We hope that we will be able to control light in all-optical nanometer-scale devices in ways that were impossible in the past.[9,10] While tiny wavelength-scale effects were negligible a decade ago, now they can be crucial for numerous nano-optical applications. In the future, we plan to explore spin-orbit coupling in near-field plasmonic systems.

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Konstantin Bliokh is a researcher. He obtained his PhD from Kharkov National University in 2001. His areas of research include wave propagation, interaction, and scattering in inhomogeneous media, evolution of quantum particles in external fields, geometric phases, spin-transport effects, and wave localization.

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Avi Niv is currently working on metamaterials and nanoemitters under the guidance of Xiang Zhang. He earned his PhD at Technion in Haifa, Israel, under the supervision of Erez Hasman. His interests focus on geometry-related wave phenomena, light-matter interactions, and advanced concepts in optical engineering with emphasis on nanotechnology.

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Vladimir Kleiner has wide experience in solid-state physics and physical optics. His areas of research include geometric-phase phenomena, spin-orbit interaction in light scattering, and radiation by nanoscale anisotropic structures maintaining surface-plasmon polaritons.

Erez Hasman has wide experience in physical optics and specifically in nanoscale optics. His group has made significant contributions in the field of nanophotonics, and specifically for developing a new branch in optics, spinoptics. Symmetry breaking in nanostructures due to spin-orbit interactions potentially opens a new avenue for controlling light in nanometer-scale optical devices. His nano-optics laboratory is involved in research on nanoscale structures, surface-plasmon polaritons, near-field manipulation, and thermal radiation from nanoscale structures.

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