NANOPHOTONICS

Photonic Rashba effect

The intercalation of an antennae array with a geometric Pancharatnam–Berry phase into a defective two-dimensional photonic crystal slab enables a spin-dependent splitting of directional emission in momentum space, that is, a Rashba effect for photons.

Alex Krasnok

Provoked by the recent discovery and investigation of atomically thin transition metal dichalcogenides (TMDs), valleytronics offers novel technology information processing, where the valley polarization rather than electric charge is used as an alternative information carrier. Unlike graphene, another extensively studied two-dimensional (2D) material, TMDs are semiconductors with a wide bandgap and strong exciton resonances due to reduced dielectric screening. Remarkably, their time-reversal symmetry, strong spin–orbit coupling, and the breaking of the crystal inversion symmetry lead to opposite spins at the +K and −K points of the momentum space, effectively locking the spin and valley degrees of freedom[1–3]. Here K denotes the corners of the Brillouin zone for the electronic band structure, in which the energy-momentum extrema are referred to as valleys. As a result, being excited by circularly polarized light, a TMD acquires different exciton populations at +K and −K, that is, a valley polarization, and keeps it for a while. This polarization can, in principle, be used to encode information, which makes monolayer TMDs of interest for next-generation nanometric photonic and optoelectronic devices. However, fast valley depolarization at room temperature impedes the use of pristine TMDs in valleytronics[4,5], and requires the development of resonant structures that could split valley-polarized photons in real or momentum space. Writing in *Nature Nanotechnology*, Kexiu Rong, Bo Wang and colleagues now present a solution based on the combination of an all-dielectric metasurface with a monolayer TMD, which could, in principle, be compatible with complementary metal–oxide–semiconductor (CMOS) technology[10].

Prior to this study, various approaches have been proposed to get around the problem of depolarization, among which the most fruitful is the one based on metasurfaces, 2D arrays of customized nanoantennae[6]. These arrays enable control over the amplitude, phase and polarization states of light at the subwavelength scale. In particular, metasurfaces can couple between spin and orbital angular momentums of photons, which results in numerous fundamental effects, including a spin Hall effect of light and a photonic Rashba effect[7]. In other words, because of the spin–orbit coupling in metasurfaces, the light of different polarization states picks up a different geometric phase that causes a spin–split dispersion in momentum space, just like the Rashba effect in solids[8]. Thus, excitons belonging to different valleys and therefore having different polarizations can be separated in ordinary and reciprocal space[6]. By now, solid-state devices enable a full sequence of generating, manipulating and detecting valley information at room temperature[9].

Nevertheless, all the metasurface-based solutions proposed so far rely on metallic nanostructures with plasmon resonances, which usually dissipate more than dielectric structures due to Joule heating. Also, they are incompatible with semiconductor CMOS technology. For this reason, exploring all-dielectric structures supporting spin–orbit coupling of light and a photonic Rashba effect for valleytronic applications is highly demanded.

Kexiu Rong, Bo Wang and colleagues report on a wisely designed all-dielectric structure that provides a photonic Rashba effect, that is, spin-dependent splitting of directional emission from incoherent quantum emitters, namely excitons in TMD and quantum dots in this work[10]. The structure consists of an array of anisotropic Si nanoantennae (NA) arranged in a way to provide a Pancharatnam–Berry geometrical phase, that is, the orientation of the NA gradually varies along the structure. The researchers embedded this Berry phase

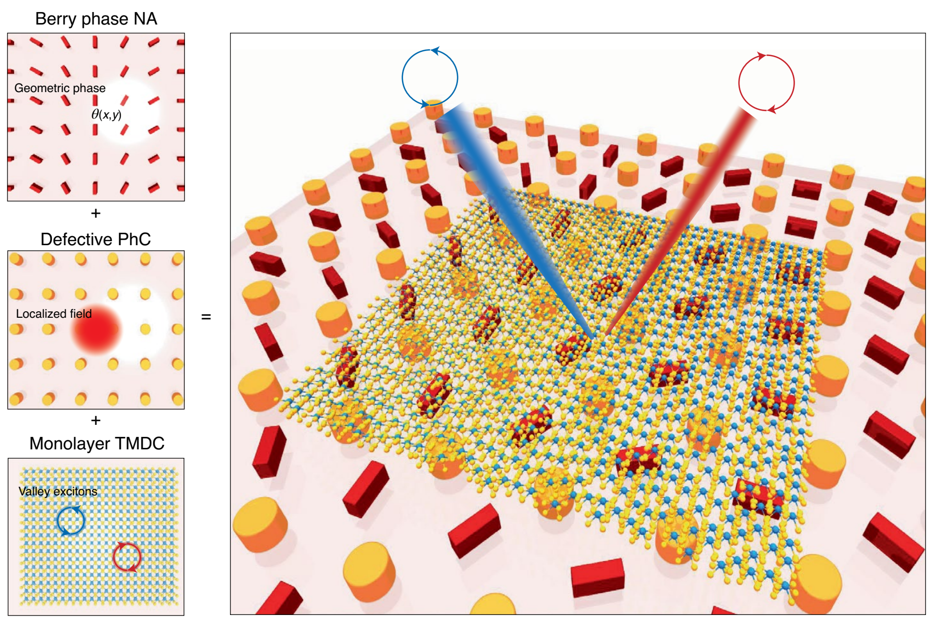

Fig. 1 | All-dielectric metastructure for the photonic Rashba effect. The metastructure is formed by a Berry phase nanoantennae array (NA) embedded into a defective 2D photonic crystal (PhC) slab. The radiation from the ±K valley excitons with opposite helicities couples to the near-field Berry phase defect mode enabling the spin-dependent splitting of emission in momentum space.

NA array into a defective photonic crystal (PhC) (Fig. 1). The purpose of the former is to introduce the light spin–orbit coupling, whereas the latter significantly increases the light–matter interactions with the superimposed WSe_2 monolayer (Fig. 1). The insertion of the nanoantennae array into the PhC slab gives rise to a defect mode residing in the PhC bandgap at the frequency corresponding to the emission wavelengths of the emitters (~800 nm). The local field distribution of the defect mode undergoes a space-variant rotation following the orientations of the Berry phase NAs. This rotation enables a space-variant polarization manipulation of the emitted light from the structure, resulting in a spin-dependent geometric phase pickup. To implement this structure on a polycrystalline silicon film, the researchers employed a standard e-beam lithography technique and controlled the quality of the highly-crystalline WSe_2 monolayer grown by chemical vapour deposition before and after transferring it onto the structure by Raman spectroscopy.

The resulting heterostructure comprising a WSe_2 monolayer and a Berry phase defective PhC demonstrates a spin-dependent splitting of photoluminescence (PL) in momentum space, though it is excited by a laser with linear polarization, and hence both valleys are populated equally at room temperature. Although the PL emission from the pristine WSe_2 monolayer is spatially incoherent, the all-dielectric metastructure increases the PL intensities by the Purcell effect and shapes the emission spectra by wavelength selection. All this results in a spin–split dispersion from valley excitons in momentum space, manifesting as the photonic Rashba effect. The researchers also measured a similar structure but without geometrical phase and observed no valley polarization effect. In this case, the PL light was polarized along the NAs, which reveals the strong interaction of the nanoantennas with the WSe_2 monolayer. In order to show the generality of their approach based on a Berry phase defective PhC, the authors also demonstrated the spin–split emission from quantum dots in the same scenario.

Although this work reports on the long-sought valley separation in a TMD monolayer with a metal-free structure at room temperature and, hence, lays the foundation for all-dielectric valleytronics devices, it currently has some fundamental and technical limitations. First, although the proposed metal-free structure could be more advantageous in terms of power consumption, this has not been demonstrated in this work. Second, separation of valley polarized excitons in real space rather than in the momentum space is more desired for planar valleytronic devices[6]. And finally, in this approach, the spin-polarized light comes from many quantum emitters coupled to the structure. The question of whether this approach can work in the case of a few or even one emitter remains open. The demonstration of the Rashba effect in the single quantum source limit would provide valley polarized non-classical light states and hence have great importance for modern quantum optics. ❐

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Competing interests

The authors declare no competing interests.