A spin-optical monolayer laser based on a photonic spin lattice

Inspired by valley pseudospins in two-dimensional materials, high-quality-factor (high-*Q*) spin–valley states were created through the photonic Rashba-type spin splitting of a bound state in the continuum. This approach enabled the construction of a coherent and controllable spin-optical laser using monolayer-integrated spin–valley microcavities without requiring magnetic fields or cryogenic temperatures.

This is a summary of:
Rong, K. et al. Spin-valley Rashba monolayer laser. *Nat. Mater*. https://doi.org/10.1038/s41563-023-01603-3 (2023).

The question

Spin-optical light sources combine photonic modes and electronic transitions and therefore provide a way to study the exchange of spin information between electrons and photons and to develop advanced optoelectronic devices. To construct these spin-optical sources, the spin degeneracy between the two opposite spin states must be lifted either in the photonic modes or the electronic transitions, which is often accomplished by using magnetic fields to induce a Faraday or Zeeman effect. However, these approaches generally require strong magnetic fields and cannot produce miniaturized sources. Another promising approach takes advantage of artificial magnetic fields to generate photonic spin-split states in momentum space, underpinned by a geometric phase mechanism[1]. Unfortunately, previous observations of spin-split states have relied heavily on propagation modes with low quality factors, which impose undesired limitations on the spatial and temporal coherence of the sources. This approach is also hindered by the spin-controllable properties of a bulk laser gain material being unavailable or non-trivial to access for active control of the sources, especially in the absence of magnetic fields at room temperature.

The solution

To achieve high-*Q* spin-split states we constructed photonic spin lattices with different symmetry properties, which comprise an inversion-asymmetry (IaS) core and inversion-symmetry (IS) cladding integrated with a WS_2 monolayer to create laterally confined spin–valley states (Fig. 1a). These structures are analogues of electronic spin lattices in which the spins of the electrons form ordered configurations with distinct spatial symmetries in antiferromagnets. The IaS lattice has a controllable spin-dependent reciprocal lattice vector owing to the space-variant geometric phases originating from its inhomogeneous, anisotropic nanoholes. This vector splits a spin-degenerate band into two spin-polarized branches in momentum space, known as the photonic Rashba effect. Additionally, the IaS lattice has a pair of high-*Q* symmetry-enabled (quasi-) bound states in the continuum[2], that is, ±K (corners of the Brillouin zone) photonic spin–valley states, at the band edges of the spin-split branches. These two states form a coherent superposition state with equal amplitudes.

We used a WS_2 monolayer as the gain material because this direct-bandgap transition metal dichalcogenide possesses unique valley pseudospins[3]. Specifically, the ±K′ valley excitons, which are radiated as in-plane spin-polarized dipole emitters, can be selectively excited using spin-polarized light according to valley-contrasted selection rules, enabling the active control of spin-optical light sources without the need for magnetic fields.

In the monolayer-integrated spin–valley microcavities, ±K′ valley excitons couple to ±K spin–valley states owing to polarization matching, and spin-optical excitonic lasing is achieved at room temperature through strong optical feedback (Fig. 1b). Meanwhile, ±K′ valley excitons (initially without a phase correlation) are driven by the lasing mechanism to find the minimum-loss state of the system, which leads them to re-establish a phase-locked correlation according to the opposite geometric phases of ±K spin–valley states (Fig. 1c). This valley coherence removes the need for cryogenic temperatures to suppress the intervalley scattering. Moreover, the minimum-loss state of the Rashba monolayer laser can be regulated by changing the polarization of the pump. We found that changing from linear to circular polarization substantially decreased the spatial coherence and intensity of the lasing (Fig. 1d).

Future directions

The photonic spin–valley Rashba effect provides a general mechanism for constructing surface-emitting spin-optical light sources. Although we only demonstrate lasing from a two-dimensional material, similar lasing is expected from other gain materials such as quantum wells[4]. Additionally, more sophisticated functionalities (such as vortex beams) could be achieved by exploring the use of various IaS photonic spin lattices to shape intracavity modes.

The superposition intracavity mode design used in this study enables spin-dependent light–matter interactions that are phase-correlated; however, it can also prevent an independent manipulation of individual spin-polarized modes.

Achieving entanglement between ±K′ valley excitons is desirable to enable quantum applications of two-dimensional materials such as qubits. The valley coherence in the monolayer-integrated spin–valley microcavity demonstrated here is a step towards achieving this goal. One of our future directions is to study this structure platform for new effects and applications in the quantum regime.

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EXPERT OPINION

"The authors of the paper have made a significant contribution to the field of spin–valley optics, demonstrating the generation of photonic spin–valley states through the photonic Rashba effect. The results represent a significant advancement in the field and have the potential to open up new avenues for the development of photonic devices." **Alex Krasnok, Florida International University, Miami, FL, USA.**

FIGURE

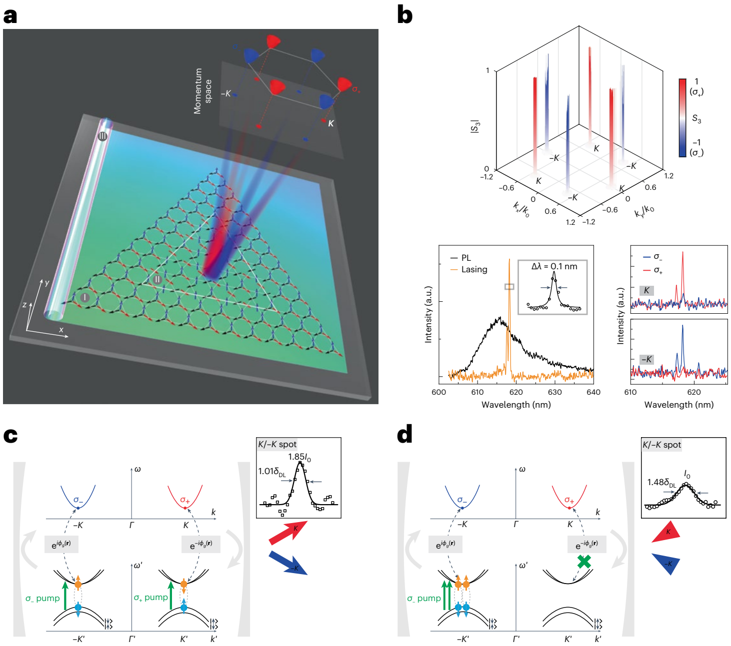

Fig. 1 | Spin–valley Rashba monolayer laser. a, Illustration of the laser architecture. Spin-optical lasing is obtained from a monolayer (III)-integrated spin–valley microcavity composed of an IaS (core, II) and an IS (cladding, I) photonic spin lattice. **b**, Highly spin-polarized directional emission is measured at ±K points in momentum space (top) and in the spectral domain (bottom), demonstrating spin-optical lasing. **c**,**d**, Fulfilled and broken minimum-loss state of the Rashba monolayer laser under linear (**c**) and circular (**d**) pump polarization. The insets show the measured cross-section distributions in each case, which confirm that linear polarization boosts lasing whereas circular polarization breaks the minimum-loss state, degrading lasing. S_3, the third component of the Stokes vector; k_x and k_y, in-plane components of the wavevector; k_0, free-space wavenumber; PL, photoluminescence; ω, angular frequency; Γ, centre of the Brillouin zone; $\sigma_{\pm}$, right- and left-handed circular polarization; $\pm\phi_g$, geometric phase; **r**, position vector; δ_{DL}, diffraction-limited width; I_0, peak intensity. © 2023, Rong, K. et al.

BEHIND THE PAPER

For a long time, our group has been working on developing spin optics to harness photonic spin as an effective tool to control the behaviour of electromagnetic waves. In 2018, we were attracted by valley pseudospins in two-dimensional materials, and therefore began a long-term project to study the active control of atomic-scale spin-optical light sources in the absence of magnetic fields. We initially tackled the challenge of coherent geometric phase pickup from individual valley excitons by using a non-local Berry-phase defect mode[5]. However, the underlying coherent addition of multiple valley excitons of the realized Rashba monolayer light sources remained unsolved, owing to the lack of a strong synchronizing mechanism between the excitons. This issue inspired us to think about high-Q photonic Rashba modes. Following innovations in new physical approaches, we achieved the Rashba monolayer laser described here.

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FROM THE EDITOR

"This work introduces a spin-optical laser where a monolayer transition metal dichalcogenide is coupled to a heterostructure microcavity supporting high-*Q* spin–valley resonances originating from photonic Rashba-type spin splitting of a bound state in the continuum. The device enables room-temperature lasing operation combining intrinsic spin polarizations and high spatial and temporal coherence. Such spin–valley devices offer opportunities to realize integrated spin-optical light sources for classical and quantum applications." **Editorial Team, *Nature Materials*.**