

Tailored photonic spin-orbit interactions for spin-valley and quantum applications [Invited]

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Abstract: Tailored photonic spin-orbit interactions (SOIs) in structured nanophotonic systems provide a powerful platform for controlling spin-dependent light-matter interactions. By engineering structural symmetry or geometric phases in photonic crystals and metasurfaces, photonic SOIs give rise to spin-dependent dispersion, spin-momentum locking, spin-textured dynamics, and nontrivial topological states. In this review, we first discuss the design principles of emerging spin-engineered nanophotonic structures, particularly geometric-phase photonic crystals, within a general perturbative framework. We then review representative spin-valley functionalities enabled by integrating these structures with transition metal dichalcogenide monolayers, where intrinsic spin-valley locking establishes versatile interfaces for coherent manipulation of both photonic spin and electronic valley pseudospin. Finally, we briefly discuss emerging opportunities for integrated quantum light sources enabled by photonic SOIs. These developments establish photonic SOIs as a versatile route toward coherent, nonlinear, topological, and quantum nanophotonic devices.

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1. Introduction

Light carries both spin and orbital angular momentum, where the former is associated with circular polarization and the latter originates from the spatial phase distribution of optical fields. When light interacts with anisotropic, inhomogeneous, or symmetry-broken structures, coupling between its spin and orbital (or linear) momentum gives rise to ubiquitous photonic SOIs. In such systems, the spin of light becomes intrinsically linked to its spatial degrees of freedom, such as propagation direction, momentum-space dispersion, spin-textured distribution and evolution. Enabled by recent advances in structured nanophotonic platforms, photonic SOIs have evolved into a versatile framework for spin-dependent light manipulation at subwavelength scales. By tailoring structural symmetry and geometric phases, photonic SOIs can induce a variety of emergent phenomena, including spin-momentum locking, Rashba-type spin splitting, and nontrivial topological photonic states, thereby opening new opportunities for efficient spin-dependent light-matter interactions.

Metamaterials are artificially engineered structures composed of subwavelength building blocks, enabling electromagnetic responses and functionalities unattainable in natural materials, with epsilon-near-zero metamaterials representing a prominent example [1,2]. Photonic crystal slabs (PCSs) and metasurfaces, metamaterials of reduced dimensionality, are two important

structured platforms for controlling light at subwavelength scales. Similar to the periodic potential experienced by electrons in solids, periodic dielectric modulation in PCSs shapes the optical modes into photonic bands, giving rise to characteristic dispersions, band gaps, and symmetry-protected degeneracies. Depending on the lattice symmetry and structural perturbations, these bands can further exhibit spin-dependent dispersions and nontrivial topological properties. Moreover, under appropriate symmetry-mismatch or destructive-interference conditions, radiative coupling can vanish even within the radiation continuum, giving rise to bound states in the continuum (BICs) with diverging radiative lifetimes and characteristic momentum-space polarization vortices. Together, these band- and radiation-engineering mechanisms underpin diverse optical phenomena in PCSs, including guided modes [3,4], photonic band gaps [5], slow light [6–8], topological edge states [9,10], and high- Q resonances [11,12], while providing a versatile basis for generating spin-textured optical fields and engineering photonic SOIs. These properties make the Bloch modes of PCSs especially powerful for enhancing coherent light-matter interactions, with applications in low-threshold spin-optical lasers [13–16], narrowband filters [17], nonlinear frequency conversion [18–20], cavity quantum electrodynamics [21,22], and on-chip quantum photonic circuits [3].

Metasurfaces, on the other hand, consist of planar arrays of subwavelength scatterers that control the amplitude, phase, polarization, and propagation direction of external coherent light within an ultrathin optical interface, and they have been widely explored for flat lenses [23,24], beam steering [25,26], vortex-beam generation [27,28], and multifunctional wavefront shaping [29]. In particular, geometric-phase metasurfaces composed of anisotropic nanoantennas with spatially varying orientations provide a versatile approach for spin-dependent light manipulation. The underlying mechanism originates from polarization evolution on the Poincaré sphere, which imparts a spin-dependent Pancharatnam–Berry phase (geometric phase) to the spin-converted components according to $\phi_g(x, y) = 2\sigma_{\pm}\theta(x, y)$, where $\sigma_{\pm} = \pm 1$ denotes the polarization helicity and $\theta(x, y)$ is the local orientation angle of the nanoantenna. The merging of PCSs and metasurfaces has been an intensified research field in recent decades, which leads to a hybrid photonic platform that simultaneously persists the resonant confinement of Bloch modes and the wavefront shaping from tailored local scatterers.

2. Perturbation-engineered geometric-phase photonic crystal slabs

2.1. Geometric-phase PCSs for enhanced light-matter interactions

The design principle of such platforms, namely, geometric-phase PCSs [30], and highly relevant concepts such as nonlocal metasurfaces [31–34] and Brillouin-zone folding (BZF) BIC [35], can be interpreted from a perturbation theory perspective. Within this broad perturbative framework, the outcome of a structural modification is determined not only by its strength but also by its symmetry. In the weak-perturbation regime, the original modal profile is largely preserved while a small radiation channel is opened, producing quasi-BIC resonances with the characteristic quadratic power law scaling $Q \sim 1/\delta^2$ [36,37]. In addition, group theory provides a systematic way to determine which coupling channels are allowed, as studied in recent selection-rule analyses of quasi-BICs in PCSs [38].

Perturbation theory is a general framework for understanding how a small structural or material modification $\Delta\epsilon$ reshapes the eigenmodes, eigenfrequencies, symmetry properties, and radiation channels of PCSs and metasurfaces [39]. A perturbation may act within a primitive unit cell (Fig. 1(a)) [36], across a supercell (Fig. 1(c)) [35,40], or through the stretching or compressing of unit cells. The perturbation within a primitive unit cell effectively introduces a local radiation dipole $\mathbf{p}(\mathbf{r}) = \Delta\epsilon(\mathbf{r})\mathbf{E}_{\text{Blo}}(\mathbf{r})$. Here, $\mathbf{E}_{\text{Blo}}(\mathbf{r})$ is the vector field distribution of the eigen Bloch mode under consideration, and $\Delta\epsilon(\mathbf{r})$ describes the difference of dielectric constant before and after perturbation. Within the first-order Born approximation [41], the modified field can be expressed as $\mathbf{E}_{\text{per}}(\mathbf{r}) \approx \mathbf{E}_{\text{Blo}}(\mathbf{r}) + \mathbf{G}(\mathbf{r}, \mathbf{r}') \cdot \mathbf{p}(\mathbf{r}')$, where $\mathbf{G}(\mathbf{r}, \mathbf{r}')$ is the dyadic Green's function.

Physically, the radiative loss of PCSs is determined by the amplitude of the perturbation-induced radiation dipole. Whether a nonzero radiation dipole can be induced is governed by group theory principles [38]: when the perturbation enables coupling between the unperturbed Bloch mode and a symmetry-compatible free-space radiation channel, a finite net dipole moment emerges; otherwise, the corresponding radiative coupling remains forbidden. In the weak-coupling regime, the coupling strength is related to the magnitude of perturbation δ , giving rise to the production of Fano-like sharp spectral features and the power-law dependence of the radiative Q -factor in the transition from BICs to quasi-BICs (Fig. 1(b)) [42]. Moreover, if $\Delta\epsilon(\mathbf{r})$ varies among different unit cells in an arbitrary manner, then any customized wavefront can be generated, namely, $\mathbf{E}_{\text{Radiation}}(\mathbf{r}) = \int \mathbf{G}(\mathbf{r}, \mathbf{r}') \cdot \Delta\epsilon(\mathbf{r}') \mathbf{E}_{\text{Blo}}(\mathbf{r}') d\mathbf{r}'$. For a sufficiently small $\Delta\epsilon(\mathbf{r})$, these perturbations will not change the property of the original Bloch modes in the near field. From this viewpoint, BZF is a specific consequence of periodic supercell perturbations. In a conventional photonic crystal, the primitive unit cell defines the largest reduced Brillouin zone, and many high- Q guided modes remain outside the light cone because of momentum mismatch. When a supercell composed of multiple primitive cells is introduced, the reciprocal lattice is reduced, and modes originally located at high-symmetry points can be folded toward the reduced-zone Γ point. Thus, BZF uses the reciprocal vectors introduced by periodic perturbation to bridge evanescent guided modes and radiative free-space channels [35,40].

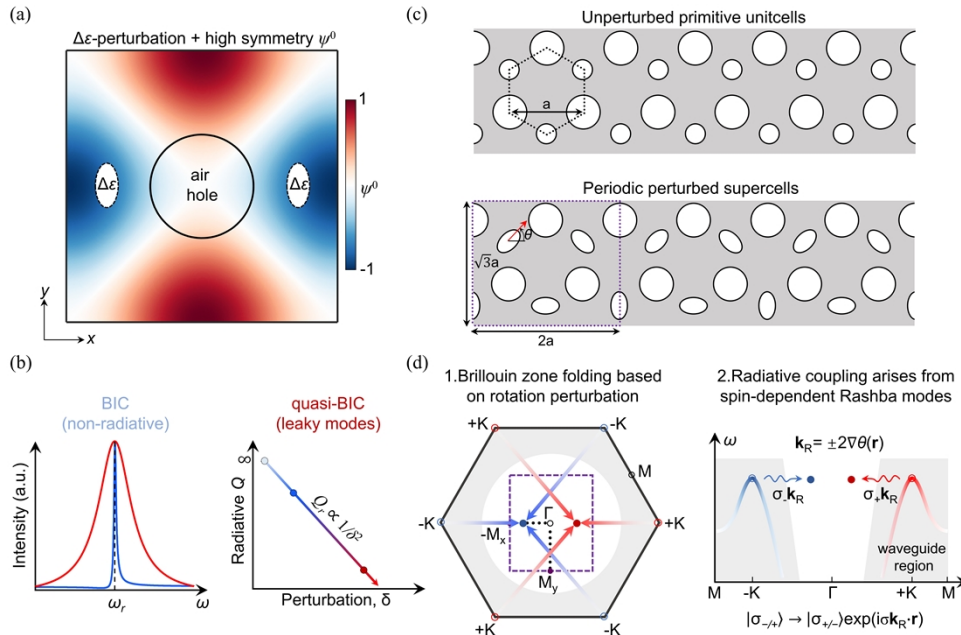


Fig. 1. Physical mechanism of the photonic Rashba radiation within the framework of geometric-phase perturbation. (a) Schematic of in-plane perturbation $\Delta\epsilon$ on the Bloch states ψ^0 at the high-symmetry points. (b) Spectral transition from non-radiative BIC to the leaky modes like quasi-BIC (left panel) and the quadratic power law dependence of the radiative Q -factor on the perturbation strength δ (right panel). (c) Structures of unperturbed unit cells (black dotted line) with C_3 symmetry supporting evanescent valley modes (top panel) and the supercells (purple dotted line) with Berry-phase perturbation on the small circular holes. (d) Two steps of the spin-dependent Rashba radiation: (1) BZF-induced additional momentum translates the $\pm K$ states into the radiative zone inside the light cone (left panel). (2) Periodic rotation of the anisotropic elliptical holes imprints a generic Rashba momentum on spin-dependent Bloch states $|\sigma_{\pm}\rangle$ [30].

Geometric-phase perturbations arise from in-plane rotations of anisotropic meta-atoms (C_2 symmetry), imprinting a Pancharatnam-Berry phase on the radiation channel and enabling polarization conversion and wavefront shaping while retaining photonic-crystal resonance enhancement. A representative manifestation is the photonic Rashba effect, characterized by spin-split dispersions in momentum space, analogous to the electronic Rashba effect in which spin-degenerate bands split into dispersive branches with opposite spin polarizations. This mechanism works in Bloch modes that can be decomposed into in-plane circular polarization bases, E_+ and E_- , such that $\mathbf{E}_{\text{Blo}}(\mathbf{r}) = E_+(\mathbf{r})\hat{\sigma}_+ + E_-(\mathbf{r})\hat{\sigma}_-$. The in-plane orientation of anisotropic meta-atoms is described by $\theta(\mathbf{r})$. For periodic rotations, we have $\theta(\mathbf{r}) = \theta_0 + \mathbf{k}_{\text{Ras}} \cdot \mathbf{r}/2$, with $\mathbf{k}_{\text{Ras}}$ being the Rashba momentum, as $2\nabla\theta(\mathbf{r}) = \mathbf{k}_{\text{Ras}}$. Taking one polarization for instance, $E_+(\mathbf{r}) \sim |E_+|e^{i\mathbf{K}\cdot\mathbf{r}}\hat{\sigma}_+$, and $\mathbf{K}$ is the BZF-induced additional Bloch momentum (left panel of Fig. 1(d)). The geometric phase leads to $\hat{\sigma}_+e^{i\mathbf{K}\cdot\mathbf{r}} \rightarrow \hat{\sigma}_-e^{i\mathbf{K}\cdot\mathbf{r}+i\mathbf{k}_{\text{Ras}}\cdot\mathbf{r}}$ and, similarly, $\hat{\sigma}_-e^{i\mathbf{K}\cdot\mathbf{r}} \rightarrow \hat{\sigma}_+e^{i\mathbf{K}\cdot\mathbf{r}-i\mathbf{k}_{\text{Ras}}\cdot\mathbf{r}}$ as shown in the right panel of Fig. 1(d). Therefore, a pair of spin-dependent Rashba modes at $\mathbf{K} \pm \mathbf{k}_{\text{Ras}}$ is formed [13,30,43,44]: BZF first brings the $\pm \mathbf{K}$ Bloch states into the radiative region, while the geometric phase subsequently introduces spin-dependent Rashba momentum. In hexagonal lattices, the C_3 rotational symmetry of $E_{\pm}(\mathbf{r})$ around the C_2 meta-atoms is the perfect ingredient for the spin-dependent Rashba splitting. As has been demonstrated, the rotation of elliptical meta-atoms barely affects the eigenfrequency of the original Bloch modes, and the radiation loss relates to the shape of elliptical meta-atoms following strictly the perturbation theory. Because of this, those geometric-phase PCSs serve as a suitable platform to enhance the spin-dependent light-matter interactions, for instance, generating any radiation laser modes [30,45,46].

2.2. Near-field vortex dynamics induced by rotational perturbations in triangular meta-atoms

Although in-plane rotation of anisotropic meta-atoms is commonly associated with geometric-phase control, a qualitatively different physical mechanism can emerge when the rotated inclusions are triangular. In hexagonal PCSs, Dirac points often appear at the $+\mathbf{K}$ and $-\mathbf{K}$ valleys due to lattice symmetry and modal degeneracy [20,47]. Rotating a triangular air hole within the unit cell (Fig. 2(a)) breaks mirror symmetry while largely preserving the threefold rotational symmetry of the structure. This perturbation lifts the degeneracy of the two valley modes at the $\pm \mathbf{K}$ points (Fig. 2(d)) and can be interpreted as the formation of an effective valley mass. Physically, the rotation changes the overlap between the two opposite vortex-like valley modes and the triangular boundary, causing the modes to acquire different frequency shifts, which manifest as a δ -dependent cosine dispersion relation (Fig. 2(f)). Consequently, the initially gapless Dirac cone opens into a finite band gap, providing a simple geometric route for controlling valley splitting, topological band gaps, and valley-dependent photonic transport.

Recent work has further extended this idea by introducing a C_3 -symmetric supercell PCS with unusual near-field vortex dynamics [20]. The supercell consists of three triangular meta-atoms arranged in a hexagonal lattice (Fig. 2(b)), where opposite rotations of the two lower triangles tune the in-plane rotational symmetry and the coupling between valley modes (Fig. 2(e,f)). As these triangles rotate, three free vortices in the supercell migrate toward the upper triangle, leading to a sequence of distinct Bloch-mode configurations characterized by different vortex distributions (Fig. 2(h)). This evolution reveals four representative regimes: valley modes, quasi-BICs, frustrated modes, and quasi-valleys. Before rotation, the valley modes are located at the $+\mathbf{K}$ and $-\mathbf{K}$ points. Under rotational perturbation, these valley modes can be folded to the Γ point, giving rise to quasi-BICs in a regime where the Q -factor follows perturbative scaling (Fig. 2(i)). At a critical rotation angle, four vortices merge and form degenerate frustration-like states, described by “two-down-one-up” and “two-up-one-down” vortex configurations, where “up” and “down” denote the handedness of the phase vortex (Fig. 2(h)). This pseudospin texture provides an optical

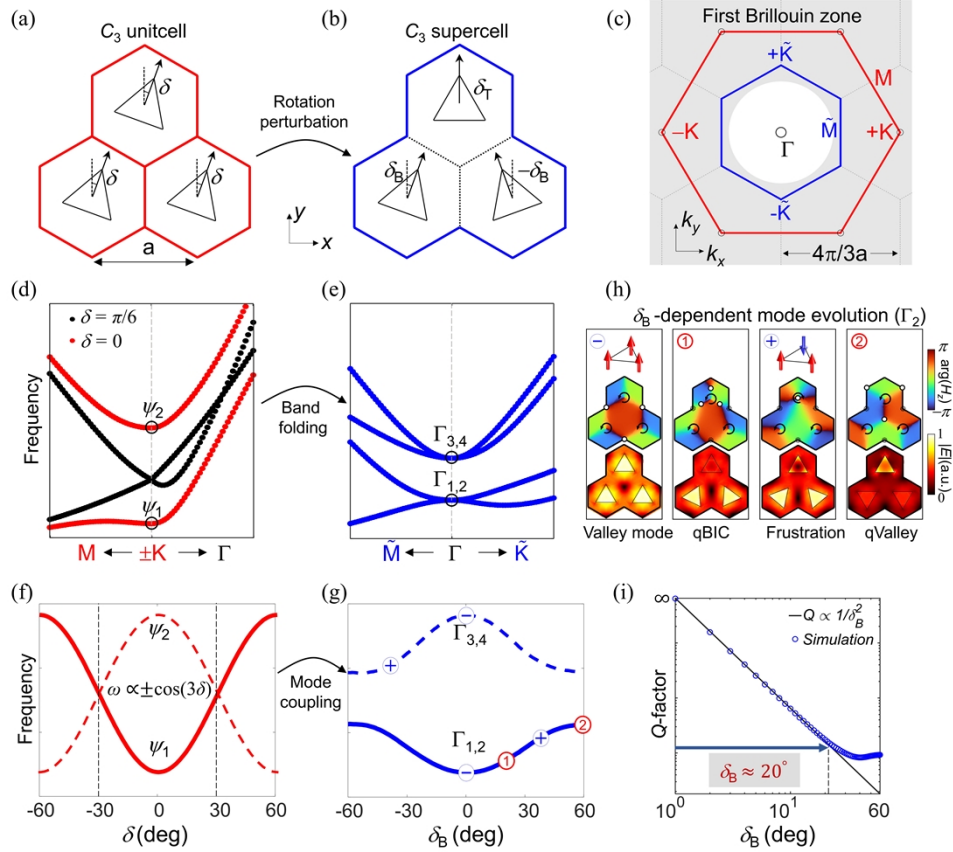


Fig. 2. Perturbation-induced mode coupling and energy splitting in C_3 supercell PCS.

(a) Schematic of the Valley PCS with triangular holes uniformly rotated by angle δ . (b) Structure of the supercell PCS characterized by a pair of non-zero opposite angles of bottom triangular meta-atoms $\pm\delta_B$. (c) First Brillouin zones for the unperturbed PCS (red hexagon) and the perturbed PCS (blue hexagon). Typical band structures of (d) the valley PCS around $\pm K$ points and (e) supercell PCS around Γ points. (f) Continuous evolution of the K-states band-edge frequencies versus the rotation angle δ , exhibiting a valley-pseudospin-dependent cosine dispersion [47]. (g) Corresponding eigenfrequency evolution of two pairs of degenerate Γ -point modes versus δ_B . (h) Selected pseudospin textures $\mathbf{S}$ (top panel), nearfield phase vortex (middle panel) and electric field distributions (bottom panel) of Γ_2 modes marked in (g). (i) Dependence of the radiative Q -factor on δ_B (log-log scale). Reprinted with permission from [20], Copyright 2025 by the American Physical Society.

analogue of geometric frustration, reminiscent of asymmetric spin configurations in magnetic systems.

More broadly, rotational perturbations of triangular inclusions offer a versatile strategy for engineering supercell PCs. Beyond the specific C_3 supercell, the same design principle can be generalized to larger supercells or extended from in-plane rotation to out-of-plane tilting. Such control over near-field vortex topology, valley coupling, and quasi-BICs formation provides new opportunities for nonlinear optics, optical force engineering, and photonic crystal lasers.

3. Photonic SOIs at spin-valley interfaces

The realization of next-generation optoelectronic devices increasingly relies on the ability to encode, transfer, and process information using internal degrees of freedom of carriers beyond charge. Among these, the binary spin has emerged as a promising information carrier owing to its compatibility with high-speed operation and potential for low-power consumption. In the pursuit of new spin-empowered systems, a long-sought goal is to establish an interface between spin-optics and spintronics, enabling efficient exchange of spin information between photons and electrons and thereby facilitating rich and controllable spin-dependent functionalities. Achieving such an interface requires not only strong spin selectivity but also compatibility with nanoscale integration, which remains challenging for conventional material platforms, particularly under room-temperature operation and in the absence of external magnetic fields.

Atomically thin transition metal dichalcogenide (TMD) monolayers provide a compelling solution to this challenge. Due to broken inversion symmetry and strong intrinsic spin-orbit coupling, these materials host spin-split electronic states at inequivalent $\pm K$ valleys in momentum space. Consequently, optical excitation with opposite circular polarizations selectively addresses excitons at specific valleys, that is, $\pm K$ valley excitons, establishing a direct correspondence between photonic spin and electronic valley pseudospin. Integrating spin-engineered photonic structures with those TMD monolayers thus forms a spin-valley interface for photonic SOIs, opening a pathway toward compact spin-optical devices at the nanoscale. Moreover, the interplay between photonic spin and valley pseudospin enables a diverse range of functionalities across different light-matter interaction regimes, ranging from passive emission control to active and collective phenomena. This capability creates new opportunities for coherent, nonlinear, and topological nanophotonic devices based on TMD monolayers. In the following, we discuss three representative manifestations of this spin-valley interface: spin-valley information routing, spin-valley Rashba lasing, and spin-valley exciton-polaritons.

3.1. Spin-valley information routing

A key limitation in 2D valleytronics is the short valley depolarization time of excitons at room temperature, which severely restricts the direct transport of valley information. This has prompted the development of an efficient valley-photon interface, where valley information can be reliably converted into photonic degrees of freedom for long-range propagation and high-fidelity manipulation. In this context, valley-selective directional routing remains an essential task, as it enables the spatial separation and readout of the valley degree of freedom through optical channels. Photonic SOIs provide a natural mechanism for this conversion by linking optical spin to spatial propagation with a desired momentum, allowing the valley pseudospin to be mapped onto controllable photonic outputs, referred to here as spin-valley information routing.

In plasmonic systems, this interface is commonly associated with the transverse spin of evanescent fields and, more generally, spin-momentum locking in confined optical modes. When interfaced with TMD monolayers, where $\pm K$ valley excitons behave as spin-polarized dipole emitters, this mechanism directly enables valley-dependent directional information routing (Fig. 3(a,b)) [48,49]. This concept has also been extended to on-chip nanocircuits, where chirality-dependent unidirectional routing of valley photons is achieved in metal-dielectric hybrid

structures through a spin-dependent beating (Fig. 3(c)) [50]. The strong field confinement in these plasmonic structures enhances light-matter interaction, enabling efficient routing as well as extensions to coherent and nonlinear valley-dependent processes (Fig. 3(d)) [51].

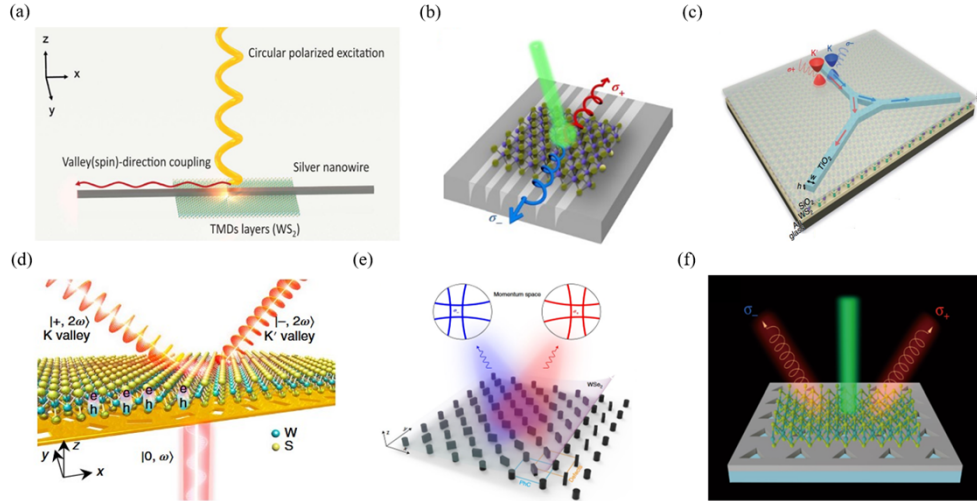


Fig. 3. Spin-valley directional information routing. (a) Plasmonic valley-photon interface via transverse optical spin [48]. Reprinted with permission from AAAS. (b) Separation of valley excitons via metallic asymmetric nanogroove array [49]. Reprinted with permission from Springer Nature. (c) Chirality-dependent valley routing in an on-chip nanocircuit [50]. Reprinted with permission from Springer Nature. (d) Coherent steering of nonlinear valley photons via plasmonic metasurface [51]. Reprinted with permission from Springer Nature. (e) Momentum-space valley separation via photonic Rashba effect in inversion-asymmetric Berry-phase defective photonic crystal [43]. Reprinted with permission from Springer Nature. (f) Valley emission routing through delocalized Bloch modes upon inversion-symmetry breaking [52]. Reprinted with permission from Springer Nature.

In dielectric platforms, spin-valley information routing can be achieved through the perturbation-engineered band and radiation control introduced in Section 2.1. By incorporating geometric-phase metasurfaces as defects in PCSs, such a Rashba-type spin-splitting offers a flexible route to realize spin-valley routing in momentum space (Fig. 3(e)) [43]. In addition, controlled symmetry breaking in meta-atom geometries (Fig. 3(f)) can induce spin-polarized radiation channels governed by topological charge conservation, enabling valley-selective emission in momentum space with enhanced coherence owing to high Q -factor of these resonances [52].

Overall, these schemes share the common principle of mapping valley pseudospin onto distinct photonic channels through photonic SOIs. Plasmonic platforms mainly exploit transverse spin-momentum locking with strong field confinement, whereas dielectric platforms rely on engineered spin-dependent radiation channels with high- Q resonances and enhanced coherence.

3.2. Spin-valley Rashba lasing

Beyond passive valley routing, the development of spin-valley coupled light sources provides a pathway toward active control of spin and valley information. Spin-optical light sources, which couple spin-dependent photonic modes with electronic transitions, offer a platform to explore the exchange of spin information between light and matter while enabling advanced optoelectronic functionalities. A key requirement for realizing such sources is to lift the degeneracy between opposite spin states either in the photonic modes or in the electronic transitions. Conventional

approaches typically rely on magnetic-field-induced effects, such as the Faraday or Zeeman effect, which require strong external fields and are therefore not compatible with compact and integrated device architectures.

An alternative strategy is to engineer artificial magnetic fields to generate photonic spin-split states in momentum space, underpinned by a geometric phase mechanism. For example, in inversion-asymmetric systems endowed with photonic SOIs, this approach can give rise to a Rashba-type spin splitting in momentum space, resulting in spin-resolved photonic modes without the need for external magnetic fields. By integrating with TMD monolayers, spin-valley Rashba lasers can be realized when valley-selective gain materials couple directly to spin-resolved photonic modes. This configuration enables active and all-optical control of the lasing states through the polarization of the excitation light, providing a compact and efficient route toward spin-valley light sources.

Based on this concept, the Rashba-type spin splitting is employed to generate two independent spin-polarized modes from high- Q guided resonances, which selectively couple to the $\pm K$ valley excitons for optical feedback [30]. This enables valley-addressable (or spin-symmetry breaking) lasing by actively manipulating spin-valley coupling (Fig. 4(b,c)), providing a versatile platform for coherent spin-polarized emission at room temperature without the need for magnetic fields (Fig. 4(a)). Furthermore, the photonic Rashba effect is used to spin-split a single BIC (Fig. 4(d)), leading to the formation of an intracavity mode arising from the coherent superposition of two opposite spin-valley states with equal amplitudes and opposite geometric phases [13]. Driven by stimulated emission arising from the interaction between the intracavity mode and $\pm K$ valley excitons, initially incoherent $\pm K$ valley excitons re-establish phase-locked correlations at room temperature (Fig. 4(e,f)), thereby generating valley coherence in the TMD monolayer. This geometric-phase-locked valley coherence relaxes the conventional requirement for linearly polarized excitation—a coherent superposition of opposite pump helicities—and can therefore be established under arbitrary pump polarizations capable of achieving population inversion.

3.3. Spin-valley exciton polaritons

The spin-valley routing and Rashba lasing as discussed above mostly rely on weak light-matter interactions, where the photonic nanostructure controls the radiation channel, mode selection, or gain pathway of $\pm K$ valley excitons. A more profound regime can be reached when the coherent energy exchange rate between cavity photons and excitons exceeds their respective loss rates, which is usually achieved by tailoring the light-matter interaction strength through high cavity Q -factor, strong field confinement, and large excitonic oscillator strength. Quantitatively, within a coupled-oscillator model, the vacuum Rabi splitting $2\hbar\Omega_R$ at zero detuning is

$$2\hbar\Omega_R = 2\sqrt{g^2 - (\gamma_{\text{cav}} - \gamma_{\text{exc}})^2/4},$$

where g is the exciton-photon coupling strength, and γ_{exc} and γ_{cav} are the half-widths of the uncoupled exciton and cavity resonances, respectively. The onset of strong coupling requires $g > |\gamma_{\text{exc}} - \gamma_{\text{cav}}|/2$, while a spectrally resolvable anti-crossing typically requires the measured Rabi splitting to satisfy $2\hbar\Omega_R > |\gamma_{\text{exc}} + \gamma_{\text{cav}}|$.

In this strong-coupling regime, excitons and photons no longer remain separate entities, but hybridize into exciton-polaritons with mixed light-matter character as described by the system Hamiltonian. The excitonic component introduces stronger interparticle interactions and enhanced sensitivity to external perturbations, which are essential for nonlinear and actively tunable devices. Meanwhile, the photonic component improves spatiotemporal coherence, extends propagation distance, and modifies exciton dynamics.

Importantly, exciton-polaritons can preserve the valley pseudospins of TMD excitons by forming spin-valley exciton polaritons, and even further enhance valley polarization or coherence

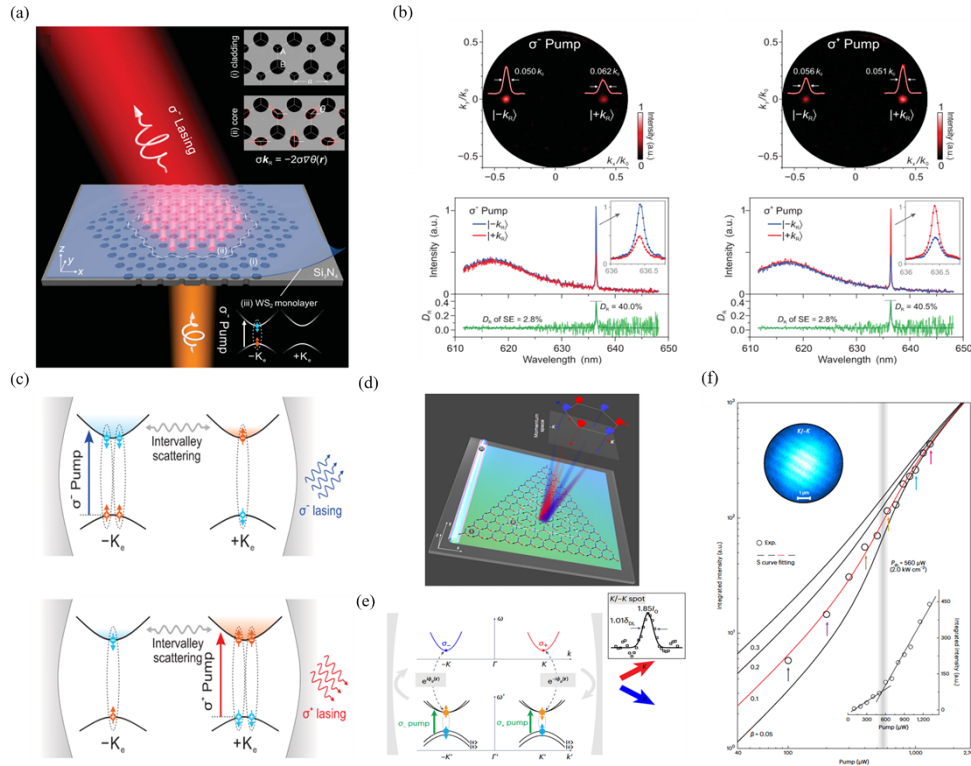


Fig. 4. Spin-valley Rashba monolayer lasing. (a) Spin-symmetry breaking Rashba lasing without magnetic field. (b) Spatiotemporal coherence characteristics of the spin-resolved lasing. (c) Valley-addressable lasing via selective spin-valley coupling under σ^-/σ^+ excitation. (a-c) are from [30]. Reprinted with permission from AAAS. (d) Spin-valley Rashba lasing with inherent valley coherence. (e) Minimum-loss lasing state driven by coherent superposition of intracavity modes. (f) Lasing threshold and valley coherence signature [13]. Reprinted with permission from Springer Nature.

under suitable cavity conditions, as demonstrated in valley-polarized (Fig. 5(a,b)) [53] and valley-coherent (Fig. 5(c)) [54] exciton-polariton systems. In addition, spin-momentum-locked chiralitonic states with emerging valley contrast and coherence have been realized by coupling TMD monolayer to plasmonic SOI modes, indicating that structured photonic environments can help stabilize valley-dependent properties (Fig. 5(d,e)) [55]. Recent works have further explored the interplay between exciton polaritons and topology [56,57]. In these systems (Fig. 5(f,g)), spin-dependent nontrivial edge states hybridize with $\pm K$ valley excitons to form helical spin-valley polariton states with nontrivial topology. In this regime, the valley pseudospin becomes an active degree of freedom in the formation of hybrid topological band structures (Fig. 5(h)). Such developments point toward a new paradigm in which photonic SOIs, topology, and valley excitons are combined to realize spin-textured polariton states, valley-dependent transport, and potentially nonlinear topological photonic devices.

Beyond TMD monolayers, photonic SOIs may also interface with a broader family of van der Waals (vdW) materials and heterostructures. Given the focus of this section on spin-valley interfaces, we only briefly highlight several representative examples. Graphene-based vdW heterostructures can acquire strong proximity-induced SOI and spin-valley coupling [58], while layered materials such as hBN host optically active defect states for spin-dependent quantum

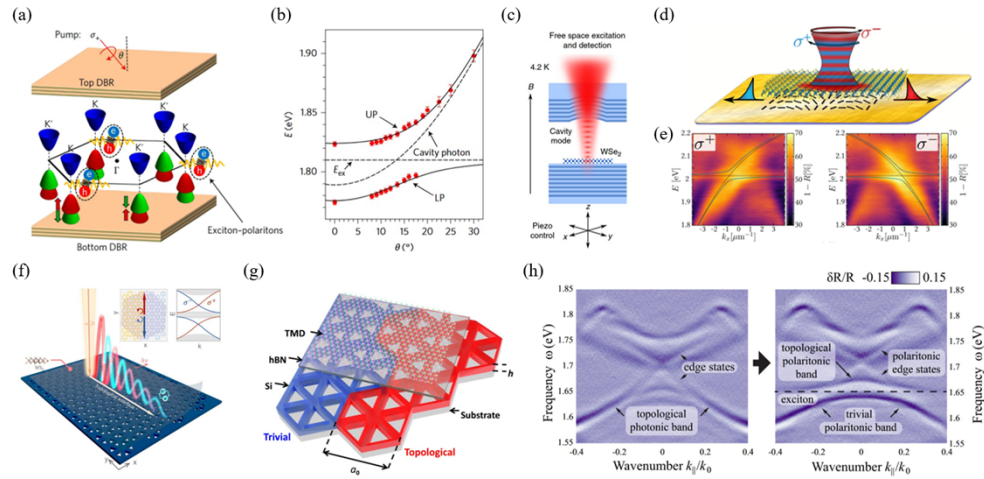


Fig. 5. Spin-valley exciton-polaritons. (a) Valley-polarized exciton-polaritons. (b) Exciton polariton anti-crossing dispersion under strong coupling [53]. Reprinted with permission from Springer Nature. (c) Valley-coherent exciton-polaritons [54]. Reprinted with permission from Springer Nature. (d) Chiral coupling of valley excitons with spin-momentum locked plasmonic modes. (e) Directional polariton flow under opposite circularly polarized excitations. Reprinted with permission from [55]. Copyright [2018] American Chemical Society. (f) Helical topological exciton-polaritons at nontrivial topological interface [56]. Reprinted with permission from AAAS. (g) Topological Z_2 phase exciton-polaritons. (h) Topological polaritonic bands and edge states [57]. Reprinted with permission from Springer Nature.

light–matter interactions [59]. More recently, nanophotonic structures have been directly patterned in bulk vdW materials, leveraging their strong excitonic [60,61] or magnetic [62,63] responses, together with enhanced optical confinement, to realize strong light–matter interactions. These developments further broaden the vdW material landscape for interfacing electronic spin degrees of freedom with structured photonic fields.

4. Perspective of quantum light applications

Quantum light sources are essential for many emerging technologies including quantum communication, quantum simulation, and quantum sensing. A central goal in this field is to realize deterministic single photon sources with well-defined photonic degrees of freedom, such as polarization, propagation direction, orbital angular momentum, and spatial wavefront. However, the spontaneous emission from an isolated quantum emitter is generally weakly directional and often poorly controlled in polarization, since it originates from dipole radiation into a broad continuum of optical modes. Therefore, practical quantum light sources require carefully designed emitter-photonic structure hybrid systems, in which the quantum emitter is precisely coupled to a cavity or resonant nanostructure. Through resonant coupling and Purcell enhancement, the emission rate can be increased and single photons can be extracted more efficiently into selected far-field channels with controlled properties. The same perturbative control of optical modes and radiation channels introduced in Section 2.1 can also be extended to quantum emitters. In this context, tailored photonic SOIs provide a fundamental mechanism to bridge the quantum transition of emitters with specific optical modes, enabling the mapping of quantum states onto various photonic degrees of freedom.

A key challenge is that Purcell enhancement and wavefront shaping usually impose different design requirements. Strong Purcell enhancement requires a cavity with a high Q -factor and a wavelength-scale mode volume, whereas complex wavefront engineering typically requires optical structures extending over many wavelength scales. As a result, customized photon shaping is often realized using an additional optical component, such as a metasurface placed near or after the quantum emitter. By further tailoring the photonic SOIs within these structures, versatile quantum light control has been achieved, enabling on-demand spin-state manipulation of single-photon emission (Fig. 6(a)) [64], spin-orbit entanglement (Fig. 6(b)) [65], high-order orbital angular momentum states (Fig. 6(c)) [66], multidimensionally engineered directional single-photon emission (Fig. 6(d)) [67], and versatile on-chip polarization control (Fig. 6(e)) [68].

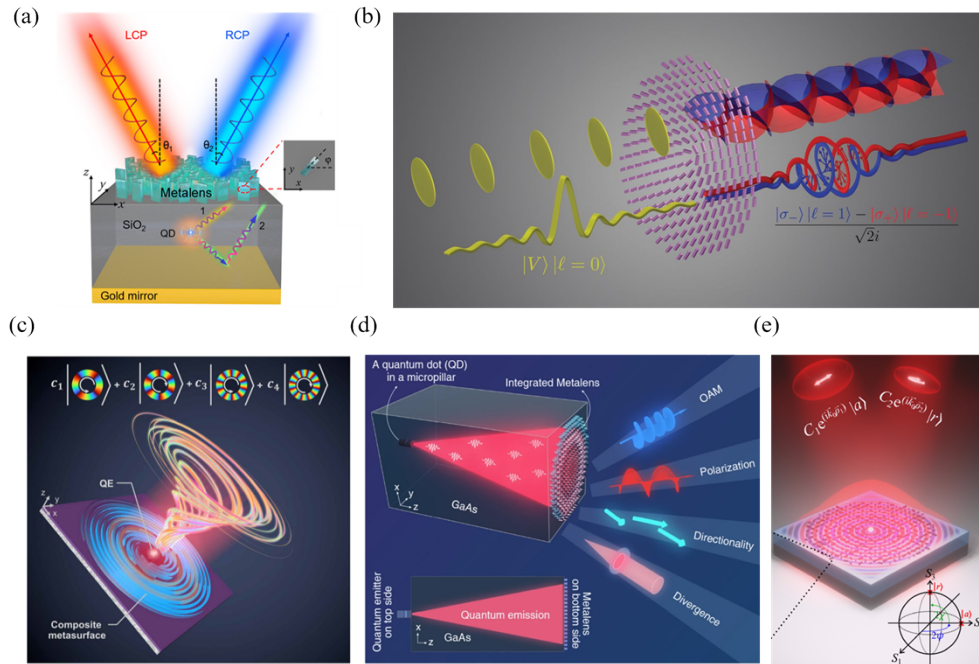


Fig. 6. Quantum light control via metasurfaces. (a) On-demand spin-state manipulation of single-photon emission [64]. Reprinted with permission from AAAS. (b) Generation of quantum spin-orbit entanglement [65]. Reprinted with permission from AAAS. (c) High-dimensional control of orbital angular momentum states [66]. Reprinted with permission from AAAS. (d) Multidimensionally engineered directional single-photon emission [67]. Reprinted with permission from Springer Nature. (e) Versatile on-chip polarization control of quantum emitters. Reprinted with permission from [68], Copyright 2025 by the American Physical Society.

In the future, nonlocal metasurfaces and PCSs may emerge as a promising solution to achieve Purcell enhanced quantum emission with tailored photon modes. These devices may combine the functions of metasurfaces and photonic crystals, and the emitter can couple to an extended resonant mode that provides Purcell enhancement, while the spatially designed metasurface pattern determines the far-field polarization, phase, and emission direction. In particular, nonlocal metasurfaces incorporating geometric-phase mechanisms have been shown to enhance and tailor the emission from on-chip dipole emitters, including quantum dots and TMD

monolayers [13,30,43]. More recently, metacavities have extended this concept to the single-emitter regime by combining Purcell enhancement and customizable single-photon wavefronts within a monolithic platform [69]. This integrated strategy points toward compact quantum light sources that combine efficient photon generation, resonant enhancement, and programmable single-photon wavefront control within a single planar photonic platform.

Translating emitter-scale photonic SOIs in isolated nanostructures into dense photonic integrated circuits remains challenging because hybrid quantum photonic devices require efficient interfaces between quantum emitters, resonant structures, waveguides, and detectors [70]. More generally, scalable integrated quantum photonics requires the on-chip generation, manipulation, routing, and detection of quantum states while minimizing the accumulated optical loss [71]. Recent demonstrations of many-client integrated quantum networks further show that wafer-scale reproducibility, phase stabilization, and system-level control are essential when moving from individual devices to functional quantum networks [72]. At the source-node level, hybrid integration of quantum dots with lithium-tantalate photonics illustrates both the potential of deterministic single-photon routing and the remaining requirements for spatial and spectral alignment, low-loss mode transfer, pump rejection, and cryogenic operation [73]. At the platform level, quantum photonic stacks integrating photon sources, filters, reconfigurable circuits, and single-photon detectors demonstrate a complementary route toward scalable fabrication and packaging [74]. Related progress in photonic quantum computation has also been achieved by integrating nonlinear quantum light sources with coupled resonator lattices and large-scale programmable waveguide networks, including topologically protected entanglement generation [75] and large-scale programmable quantum graph processing [76]. Although these sources are probabilistic rather than on demand emitter-based sources, they provide representative circuit architectures for the future integration of deterministic quantum-source nodes. A practical goal is therefore to develop each emitter–metasurface or emitter–PCS structure as a modular, on-demand quantum-source node with local spectral tuning and a low-loss guided-mode interface to coupled waveguide networks in scalable photonic integrated circuits, and to evaluate the resulting devices using quality factor, Purcell enhancement, collection efficiency, $g^{(2)}(0)$, and photon indistinguishability, as well as system-level metrics such as end-to-end efficiency, fabrication yield, and long-term stability.

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