Engineering Tunable Band Structures and Spin-Orbit Coupling in Photonic Potentials Using Birefringent Optical Cavities

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In solid-state systems broken inversion symmetry gives rise to Dresselhaus and Bychkov-Rashba spin-orbit couplings (SOC), which are crucial for spintronics, topological insulators, and superconductors. Unlike SOC in solid-state materials, which is challenging to manipulate, birefringent optical cavities offer substantial tunability of photonic modes. The properties of polarized electromagnetic waves propagating through one- or two-dimensional structures can be effectively described using a two-mode Hamiltonian, which represents a massive particle with spin 1/2 using Pauli matrices. This approach not only simplifies theoretical descriptions but also facilitates significant advancements in modern photonics by exploiting the mathematical similarities between equations describing electromagnetic waves and electrons in condensed matter. By applying the Green's function technique, based on the Mittag-Leffler expansion with respect to resonant states and the k·p perturbation theory from semiconductor physics, we have obtained results interpretable as effective cavity mode spin-orbit coupling [1] and non-Hermitian Hamiltonians.

We have developed a method to electrically control the SOC of light using specially designed photonic structures – birefringent microcavities. These consist of a 2-3 μm thin liquid crystal (LC) layer enclosed between two parallel distributed Bragg reflectors deposited on transparent electrodes. This setup has enabled the observation of an optical analog of the spin Hall effect and the creation of artificial gauge fields for parameters that extend far beyond those previously considered experimentally and theoretically [2]. We discovered Rashba-Dresselhaus spin-orbit coupling in a photonic system and demonstrated control over artificial Zeeman splitting [3]. Furthermore, we have shown how to structure light so its polarization mimics spins in a ferromagnet, forming half-skyrmions (merons) [4]. We observed optical analogs of persistent spin helix, reciprocal Young's, and Stern-Gerlach experiments [5], and a new type of chiral Rashba-Dresselhaus lasing [6]. Our results illustrate an effective strategy for engineering artificial gauge fields and synthetic Hamiltonians with photons to simulate nontrivial condensed matter and quantum phenomena, promising new directions in topological photonics [7-9], non-Hermitian systems [1,7], and condensates of light. By embedding laser dyes and perovskites within birefringent microcavities, we explore light-matter interactions in both weak [6] and strong coupling regimes [8,9].

Beyond traditional lithographic methods, our approach using liquid crystal cavities enables the creation of self-organizing macromolecular structures, whose sizes and shapes can be controlled by temperature or electric fields. These periodic photonic structures allow for precise control over optical modes, enhancing their functionality and application potential. In the present work, we have developed a self-assembled liquid crystal structure in a planar cavity, which provides a tunable periodic potential and interband SOC between the lattice bands of different parity. We show that doping the LC with dyes allows us to achieve lasing that inherits all the above-mentioned tunable properties of LC microcavity, including dual and circularly-polarized lasing.

References

[1] P. Oliwa et al. *Quantum mechanical-like approach…* Phys. Rev. Research **6**, 013324 (2024)
[2] K.Lekenta, et al., *Tunable optical spin Hall effect..* Light Sci. & Appl. **7**, 74 (2018).
[3] K.Rechcińska, et al. *Engineering spin-orbit synthetic Hamiltonians…,* Science **366**, 727 (2019)
[4] M. Król et al. *Observation of second-order meron polarization textures …,* Optica **8**, 255 (2021)
[5] M.Krol et al. *Realizing Optical Persistent Spin Helix…*, Phys. Rev. Lett., **127**, 190401 (2021)
[6] M.Muszynski, et al. *Persistent-Spin-Helix Lasing…*, Phys. Rev. Appl. **17**, 014041 (2022);
[7] M. Król, I. Septembre et al. *Annihilation of exceptional points…* Nature Commun.**13**, 5340 (2022)
[8] K. Łempicka-Mirek et al., *Electrically tunable Berry curvature …* Sci. Adv. **8**, eabq7533 (2022)
[9] K. Łempicka-Mirek et al., *Electrical switching…* doi.org/10.1515/nanoph-2023-0829 Nanophotonics (2024)