論 文 の 内 容 の 要 旨

論文題目　Study on the Manipulation of Optical Spin Texture based on the Optical Spin–Orbit Interaction in Photonic Nanostructures
（フォトニックナノ構造における光スピン軌道相互作用に基づく光スピン構造の制御に関する研究）

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The spin angular momentum (SAM) of light, or optical spin, is a fundamental property of light and is associated with the polarization degrees of freedom. The orbital angular momentum (OAM) is the other important angular momentum and is associated with the spatial phase and intensity distribution of light. Optical fields in which these two angular momenta are coupled to each other often exhibit spatially non-uniform optical spin distributions or so-called optical spin textures. Light beams with optical spin textures are generally known as vector beams and are distinguished from conventional scalar light beams with uniform polarization distributions. Vector beams and their optical spin textures have been of great interest because of their rich physics and of the promise for novel applications in photonics. In particular, the topological properties of optical spin textures have been intensively studied in recent years. For instance, radially-polarized vector beams have been analyzed as topologically-nontrivial optical spin vortices. More recently, various topological spin textures in light, including optical skyrmions and knots, have been discovered. These states are of significance in strong relevance to condensed matter physics, in which topology has been a key concept for the last decade. Such topological states of light will also offer a great opportunity in the development of new photonic applications.

The coupling of SAM and OAM in an optical field, which is imperative to generate an optical spin texture, can be realized via the spin–orbit interaction (SOI) of light. The SOI of light is known to typically occur in optical elements with anisotropic and inhomogeneous refractive index distributions, such as q-plates. The SOI is known to become stronger with rapidly modifying the refractive index in space. In this regard, nanophotonic structures, such as photonic crystals or metasurfaces, are suitable for generating giant SOI compared to bulk optics, and thus are deemed to be an excellent platform to engineer optical spin textures. Nanophotonic structures are also advantageous in downsizing optical devices and implementing them on chip and thereby in finding practical applications. So far, there are some reports using nanophotonic structures that synthesize light beams with topological spin textures, such as a cylindrical vector beam. Nevertheless, there remains a huge space to explore the generation of various types of topological spin textures from nanophotonic structures, in particular from the structures suitable for on-chip integration.

In this thesis, photonic nanostructures that generate light beams with various topological spin textures through controlling the angular momenta of light with the aid of the optical SOI are studied. It was found that microring structures augmented with angular gratings can generate light beams with various optical spin textures including optical skyrmion beams. This structure was also applied to synthesizing higher- and hybrid-order Poincaré sphere beams. In addition to these, a method to generate an optical skyrmion crystal beam are also studied, in which a two-dimensional array of optical skyrmions is created. The microring cavity itself was also engineered for maximizing the SOI, opening the path for exciton spin-dependent directional optical amplification and unidirectional lasing, which are vital to construct active topological beam generators. These findings brought by this thesis will deepen the understanding of optical spin textures with topological properties and will broaden the range of their applications.

In Chapter 1, the research background and objective are introduced. The outline of this thesis is also shown at the end of this chapter.

In Chapter 2, the basic physics of optical spin–orbit interaction is introduced. At first, the spin and orbital angular momenta of light are discussed. Similarities and differences between the photonic and electronic spin--orbit interactions are reviewed considering the correspondence between Maxwell's equations and the Dirac equation.

In Chapter 3, an optical microcavity-based optical skyrmion beam generator is discussed. An optical skyrmion beam characterized with an arbitrary skyrmion number was generated as a superposition of two beams with orthogonal SAMs and different OAMs. Microring resonators patterned with double angular diffraction gratings are studied for simultaneously controlling both SAM and OAM. The angular gratings are placed on chiral lines induced by strong SOI in the resonator, resulting in out-of-place radiation with controlled SAM. The number of the grating elements was carefully chosen so that the diffracted light carries a designed OAM. The inner workings of the device were analyzed by developing a theoretical toy model consisting of arrays of dipole radiators. The operation of the device is also verified by finite-difference time-domain calculations.

In Chapter 4, nanophotonic structures that generate either higher-order or hybrid-order Poincaré sphere beams are studied. It was analytically and numerically shown that the state defined on a point on a higher (or hybrid)-order Poincaré sphere can be synthesized from a microring cavity assembling two angular gratings. To realize arbitrary state generation, the phase and intensity of the diffracted light from each angular grating are controlled by modifying the relative azimuthal rotation and the relative size of the two gratings.

In Chapter 5, a scheme for generating an optical skyrmion crystal beam is discussed. It was found that such a beam can be generated by arranging multiple radiation sources with controlled polarizations and phases in a two-dimensional array. The radiation from the sources interferes in the far field and forms a skyrmion lattice in the beam cross section. The device operation was firstly analyzed with a toy model and further verified with a numerical model consisting of coupled ring cavities with each possessing a double angular grating.

In Chapter 6, the fabrication and optical characterization toward the realization of the proposed devices are described. The devices were fabricated by electron-beam lithography and reactive ion etching. For high precision arrangement of angular diffraction grating on the microring, a technique resembling grayscale lithography was developed. Optical microscopy was performed and observed the generation of an optical skyrmion beam from the fabricated device. The remaining challenges that were identified from these experiments are also discussed.

In Chapter 7, an optical microring resonator that enables the directional emission depending on the spin-state of the embedded quantum dots is studied. It was found that spin-polarized emission from the quantum dot ensemble can be converted to unidirectional emission via the SOI of light when carefully introducing spatial asymmetry in the cross-section of the waveguide constructing the microring. The capability of unidirectional lasing in the structure is also studied.

In Chapter 8, the conclusions of this thesis are presented. An outlook for future development is also given.