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Abstract

We report an intriguing Poynting vortex street produced by 3D vectorial superposition of two counterpropagating modes in different mode orders on silicon-based waveguides. Importantly, this Poynting vortex street can produce composite topological textures characterized by spin skyrmion (bimeron) array overlapped with momentum vortices yielding local transverse orbital angular momentum. The transverse and longitudinal shifts of these topological textures can be controlled by modulating the relative amplitudes and phases (or frequency shift) between the counter-propagating modes, respectively. These on-chip manageable topological spin and momentum flows may open new doors to optical manipulation, classical or quantum information processing, and optofluidic techniques on integrated photonic platforms.

Full Text

On-Chip Topological Spin-Momentum Flows

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We introduce photonic spin-momentum topologies on silicon-based waveguides characterized by spin skyrmion (meron-antimeron) arrays overlapped with momentum vortices that yield local transverse orbital angular momentum. These composite textures are induced from Poynting vortex streets produced by the superposition of two counter-propagating modes in different mode orders. Importantly, they can be dynamically controlled to undergo transverse shifts and longitudinal flows by modulating the relative amplitudes and phases (or frequencies) between the counter-propagating modes. These on-chip controllable topological spin-momentum flows may enable new opportunities for optical manipulation, waveguide quantum electrodynamics, and optofluidic techniques on integrated photonic platforms.

Topologically nontrivial textures refer to configurations that cannot be continuously deformed into trivial smooth shapes [1-3]. Such topological structures have increasingly advanced basic and applied research in hydrodynamics, aerodynamics, cosmology [4], mathematics, and physics [5]. For example, magnetic skyrmions as classical topological textures may be potentially applied to nanoscale information storage and spintronic devices due to their topological stability [6-8]. From a wave perspective, topological structures can be readily formed in electromagnetic waves because of their rich vectorial nature, typically characterized by various vortices [9-13], Möbius strips [14,15], skyrmions or merons [16-20], and hopfions [21,22]. Additionally, they can also be constructed using familiar water waves [23,24] and acoustic waves [25,26]. Particularly, as analogues of magnetic skyrmion topologies, various kinds of optical skyrmions have been uncovered by fully exploiting photonic degrees of freedom (DoFs), such as spin angular momentum (SAM) [16,19], electromagnetic vector [3,27], Poynting vector [28], and Stokes vector [29-31]. All these topological structures may offer new opportunities for many potential applications in multidimensional or ultraprecise metrology, super-resolution imaging, versatile particle manipulation, classical and quantum information processing or communications, and beyond [32-42].

Electromagnetic fields tightly confined to the scale of their wavelengths typically manifest strong vectorial nature, for example in highly focusing and strongly guiding cases [43-51]. These scenarios provide ideal platforms for constructing and studying photonic topological structures. For instance, the transverse spin within tightly structured fields can form spin skyrmions [16,19]. So far, the discovered photonic topologies have been mostly realized on free-space bulk optical systems [22,43-47], metal surfaces via surface plasmon polaritons [3,27,48-51], and 2D dielectric materials or metasurfaces [52,53]. However, until now, little attention has been paid to the topological nature of light transmission systems on integrated photonic platforms. It is known that electromagnetic modes strongly guided by high-index contrast waveguides exhibit three-dimensional (3D) vectorial distributions as well. These fields can also form photonic transverse spin with spin-momentum locking effects and spin singularities under evanescent field coupling [54-58].

In this letter, we first introduce an interesting Poynting vortex street in optics constructed by Poynting energy flow that features repeating swirling patterns, analogous to a classical Kármán vortex street caused by flow separation of a fluid around blunt bodies (Fig. S1 [59], [62-64]). This Poynting vortex street can be produced by electromagnetic superposition between two counter-propagating modes in different mode orders on optical waveguide platforms [59]. Surprisingly, we find that it can inherently generate composite spin-momentum topologies containing spin skyrmions overlapped with momentum vortices (Fig. 1 [Figure 1: see original paper]). The latter can further yield local transverse orbital angular momentum (OAM) perpendicular to the modal propagation directions. Note that beyond conventional standing waves with nodes and antinodes under destructive and constructive interference, respectively, the counter-propagating 3D waveguide mode superpositions in different mode orders produce no nodes and antinodes, but instead generate intriguing topological textures. It is worth emphasizing that these resulting composite topological spin-momentum structures possess remarkable advantages compared with those in other photonic platforms. One is controllability that can be easily realized by modulating the relative amplitudes and phases (or frequencies) between the counter-propagating modes. The other is the silicon-based platform capability to produce near-field topologies that may open new opportunities for developing on-chip light-matter interactions, waveguide quantum electrodynamics, versatile optical manipulation, and optofluidic techniques [65-68].

The Poynting momentum of electromagnetic fields can be divided into canonical (orbital) and spin momentum parts [70,71], i.e., = o + , where = Re(∗ ×)/(2 2) is the Poynting momentum, = Im[∗ ( )) + (∗ ( ))]/(4) is the canonical momentum, = × /2 is the spin momentum, and = Im[∗ × + ∗ ×]/(4) is the SAM density. Here denotes the angular frequency of the electromagnetic fields, is the speed of light in a medium, and and denote the absolute permittivity and permeability of the medium, respectively. The transverse spin within electromagnetic guided waves satisfies the spin-momentum relationship [50]. We have verified that such relationship is also suitable for the case of counter-propagating electromagnetic mode superposition [59]. Therefore, the on-chip photonic spin and canonical momentum densities, both associated with the Poynting vortex street, can be respectively described as:

= + where = / is the wave number. Actually, these SAM and orbital momentum of the evanescent fields meet a direct spin-momentum relationship, i.e., ^{2} + 4 ^{2} = 2 × .

[Figure 2: see original paper] Local transverse OAM arrays induced by Poynting vortex street. (a) Electric and (b) magnetic parts of the canonical momentum, respectively. The red circles indicate the circulating directions of canonical momentum vortex cells. The background represents the phase distributions of the electric field component (Ez) in (a) and the magnetic component (Hy) in (b).

[Figure 1: see original paper] Schematic of topological spin-momentum flows on a silicon chip. (a) and (b) Upward and downward spin-momentum cells enlarged from A and B in the topological flows shown in (c). (c) The produced on-chip Poynting vortex street and spin meron-antimeron texture, which can be dynamically controlled to transverse shift and longitudinal flow by modulating the amplitude ratios and phase (or frequency) differences between the counter-propagating TM0 and TM1 modes, respectively.

Here we focus on transverse-magnetic (TM) modes because of their more considerable evanescent electric fields compared to transverse-electric modes that are available outside the waveguides. We first investigate the vectorial dynamics of the superposed electromagnetic fields (and) between two counter-propagating TM modes in different mode orders and polarization ellipses [59]. The dynamical 3D electric field oscillations are shown in Movie 1. Unlike uniform elliptic planes of paraxial polarized light, the polarization ellipses given by 3D field superposition over time manifest as inhomogeneous distributions that contain L lines (Figs. S4 [59]). The normal vectors of these elliptic planes intuitively determine the spin textures with fractional skyrmion numbers. As mentioned above, the Poynting vortex street manifests as periodical vortex pairs with opposite handedness resulting from the superposition dislocation of counter-propagating modes in different orders. These energy vortices can associate with topological stability because of their lowest energy states at the singularities [69]. The details of mathematical derivations and additional calculation results are presented in [59]. Here the electromagnetic fields were numerically calculated by the Finite-Difference Time-Domain method at a wavelength of 1550 nm. The silicon waveguide with 0.22 m thickness and 1.2 m width is placed on a silicon dioxide (SiO2) substrate [Fig. 1(c)]. The monitor position is 0.025 m above the air-waveguide interface.

From Eq. (1), on the one hand, the Poynting vortex pairs with opposite handedness contribute to topological spin textures with opposite fractional skyrmion numbers (Fig. 1). The topological number of spin skyrmion textures can be calculated as:

( ) , (3)

where = /| | denotes the 3D unit vector. For the counter-propagating TM0 and TM1 mode superposition with equal amplitudes, the skyrmion numbers of the resulting spin textures with closed units are `$±$1/2`, referring to bimerons (meron-antimeron) [Fig. 3 Figure 3: see original paper]. In particular, the relation between the and components within these cells is governed by the right-hand screw rule [Figs. 1(a) and 1(b)].

On the other hand, from Eq. (2), this Poynting vortex street naturally gives rise to local canonical momentum vortices that circulate with opposite handedness in the upper and lower rows [Fig. 2]. The topological charge of the vortices is defined as = 1/(2) , where is the orientation angle of momentum vectors in the x-y plane and C is a closed path around the singularities in the counterclockwise direction. Accordingly, the topological charge of these vortices can be calculated as = +1. Note that anti-vortices (= −1) also exist between two vortices with singularities marked by red dots in the same rows (Fig. S3(C) [59]).

When choosing the displacement ( ) from the vortex centers (singularities) as coordinate origins, each canonical momentum vortex cell yields a local transverse OAM perpendicular to the waveguide surface, and its integral value can be given as:

$\langle \ \rangle = \quad \times \quad$, (4)

where is the integral domain covering the vortex cells denoted by [Fig. 2]. Here the electric transverse OAM is much larger than the magnetic transverse OAM under the broken electromagnetic distributional symmetry in the highly guiding condition [59]. Such transverse OAM from the electric part is determined by the local helical phase of the dominant Ez component [Movie 1], while its magnetic counterpart is determined by the Hy component [Fig. 2], arising from the superposition of counter-propagating TM modes in different mode orders. Notably, the phase singularities of the dominant vertical electric component correspond to conventional nodes, also aligning with the centers of Poynting vortices with the lowest energy (Fig. S3 [59]).

Despite the existing local transverse OAM array, the overall integral transverse OAM over the superposition region is zero because the local OAM cells with opposite directions in the upper and lower rows cancel each other out. Nevertheless, this near-field transverse OAM may be used for on-chip optical manipulation, for example, driving particle rotation [72,73].

[Figure 3: see original paper] Controllable skyrmion numbers and transverse shifts of topological spin-momentum texture. (a) The 3D spin vectors within alterable skyrmion cells can be mapped from a northern or southern hemisphere starting from the pole to specific latitudes via stereographic projection. (b) The skyrmion numbers (left y-axis) and transverse distances between opposite spin skyrmions (right y-axis) versus the amplitude ratios $0/\ 1$ of TM0 and TM1 modes. (c) and (d) The spin skyrmion cells with different mean skyrmion numbers and transverse shifts under $0/\ 1 = 1$ and 0.4, respectively.

We next demonstrate the controllability of these topological structures enabled by the relative amplitudes and phases (or frequencies) between the two counter-propagating modes. The relative amplitude affects the collective distributions of the topological textures, thereby changing both the skyrmion numbers and center positions. Here we define a complete skyrmion cell encircled by a contour line of the angle α of the 3D spin vector with respect to the 2D plane that forms the maximum closed area [Figs. 3(c) and 3(d)]. These spin skyrmions can be visually described by mapping the 3D vectors on a northern or southern hemisphere onto the defined texture regions starting from the north or south pole to a specific latitude via stereographic projection [Fig. 3(a)]. This latitude gives the fractional value of skyrmion number:

$= \pm\ (1 - \cos\alpha)/2$, (5)

which is determined by the amplitude ratios (/) of TMn to TMm modes, where the polar angle is given by $\alpha = \tan^{-1}(\sqrt{(\ ^2 + \ ^2)}/\ )$ [59], and the sign '+' or '-' depends on the northern or southern hemisphere, respectively. For example, the spin textures with average skyrmion numbers of about $±$0.50 (bimerons) and $±$0.31 given by the 0° (equator) and $±$23° latitudes on the hemispheres are presented in Figs. 3(c) and 3(d), which are produced by the counter-propagating TM0 and TM1 modes with amplitude ratios of $0/\ 1 = 1$

and 0.4, respectively. Despite the drop-shaped boundaries, the spin textures can be quantified by the skyrmion number as a topological invariant when stereographically projected from the hemispheres. We further investigate the changeable skyrmion numbers versus amplitude ratios shown as the curve (left y-axis) in Fig. 3(b), where the pentagrams indicate values calculated by the angle α, while the triangles represent values obtained by the defined skyrmion number via integral operation.

[Figure 4: see original paper] Controllable longitudinal flows of topological spin-momentum textures by modulating the relative phases (or frequencies) between the counter-propagating TM0 and TM1 modes. The instantaneous spin-momentum textures at (a) t=0 ps, (b) t=1.33 ps, and (c) t=2.67 ps, respectively, when the frequency shift is $\Delta \ = 250$ GHz.

Apart from the skyrmion numbers, the relative amplitude also affects the transverse shift (0 coordinate) of the center positions or singularities (0, 0) of the topological textures, which can be approximately deduced from:

$\cos(\ \ 0 - \ \ /2 - \ )\cos(\ \ 0 - \ \ /2 - \ )$, (6)

where (+ 1) / and (+ 1) / denote the transverse wave numbers of TMm and TMn modes with orders and , respectively, = /2 and = /2 determine modal parity distribution, and , = 0,1,2,⋯. The sign '+' corresponds to counterclockwise momentum vortices (or positive spin skyrmions) in the upper row, and vice versa [59]. The transverse distances between opposite topologies in upper and lower rows versus amplitude ratios are given by the curve (right y-axis) in Fig. 3(b). In contrast to transverse shift, the relative phases (or frequency shift) between the counter-propagating modes determine the longitudinal flow (0 coordinate) of these topological textures. For superposition with equal amplitudes, the topological center or singular positions in the upper and lower rows can be approximately given as:

$(\ 0,\ 0)\mathrm{up}\ \ [((2\ +1)\ + \beta\ \ - \Delta\ )/(\beta\ + \beta\ ), (2\ + \ + \ + 1)/(\ + \ + 2)\ ]$, (7)

$(\ 0,\ 0)\mathrm{down}\ \ [(2\ \ + \beta\ \ - \Delta\ )/(\beta\ + \beta\ ), (2\ + \ + \ )/(\ + \ + 2)\ ]$, (8)

where β and β are the propagation constants of TMn and TMm modes, $\Delta\ = \Delta\ 0 + \Delta$ is the overall phase difference induced by the initial phase difference (Δ 0) and frequency shift (Δ), is the waveguide width, is the distance between two modal sources, and the integers M and N denote different topological spin-momentum cells.

Remarkably, these topological textures can be controlled to flow dynamically by simply shifting the frequency (Δ) of the reversely inputted modal sources. The topological spin bimeron and transverse OAM arrays are shown in Figs. 4(a)-4(c) and dynamically demonstrated in Movie 2 under a frequency shift of $\Delta\ = \Delta\ /2\ = 250$ GHz, where the flowing directions depend on the signs of frequency differences between these two modal sources. Note that the frame-by-frame pictures of dynamical electromagnetic structures in Movies 1 and 2 were obtained by subdividing the incident phases from 0 to 2 to replace the time-dependent dynamic phases when simulating modal propagation. Additionally, we present higher-order topological distributions with more transverse periods produced by counter-propagating higher-order TM1 and TM2 modes (Fig. 5 [Figure 5: see original paper]). These on-chip dynamical topological spin and transverse OAM textures may offer new mechanisms or degrees of freedom for optofluidic microsystems used for nanoparticle trapping or manipulation, and topology-based light-matter interactions [74-79].

[Figure 5: see original paper] Higher-order topological spin-momentum flows produced by the counter-propagating TM1 and TM2 modes. (a) and (b) Poynting vortex street with vortex arrays in different viewing angles, where the singularities (red dots) of energy flow vortices form lines in 3D space. (c) and (d) The corresponding topological spin bimeron (meron-antimeron) texture with skyrmion numbers of $±$0.5.

In conclusion, we have demonstrated dynamical topological spin-momentum flows in the propagation system of silicon-based waveguides constructed by counter-propagating modes in different orders, beyond conventional standing waves. The spin textures with fractional skyrmion numbers (bimerons) have an intrinsic relationship with the canonical momentum vortices, both associated with Poynting vortex streets and governed by spin-momentum relationships. Naturally, the canonical momentum vortices can produce local transverse OAM that accompanies the spin merons. These on-chip near-field transverse SAM and OAM show fundamental differences from well-known paraxial vortex fields carrying longitudinal OAM and SAM [70,80]. More importantly, these composite spin-momentum topologies can be dynamically moved by controlling the relative amplitudes and phases (or frequencies) between the counter-propagating modes. We expect that these on-chip controllable spin-momentum topologies in light transmission systems can expand the family of photonic topologies in micro- and nano-photonics, and pave the way toward topology-based light-matter interactions, waveguide quantum electrodynamics, and even optofluidic techniques on integrated photonic platforms.

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relationship, 3D spin and momentum components; the calculation of skyrmion numbers and center positions under different amplitude ratios; more details and numerical results of topological spin and momentum flows in terms of vortex street analogies, schematic sketch, 3D field components, superposed field distributions, topological texture evolution, theoretical verifications, and higher-order topological textures produced by counter-propagating higher-order TM modes.

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