Vortex photonics

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Taming twisted light with topology

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Mode coupling and purity degradation have long challenged vortex photonics. A topological disclination lattice waveguide with dual topological protections now offers a solution, enabling robust vortex transmission and precise mode filtering.

The rectilinear propagation of light is evident in everyday phenomena, such as shadows, flashlight beams and eclipses. However, the discovery in 1992 that light can carry orbital angular momentum (OAM) profoundly transformed our understanding of photonics[1]. Vortex beams, which possess a helical phase structure characterized by a topological charge l, the number of phase twists per wavelength around the propagation axis, allow each photon to carry a discrete OAM of $l\hbar$, where $\hbar$ is the reduced Planck constant. This additional degree of freedom has driven breakthroughs in imaging resolution, optical data multiplexing, optical trapping and manipulation, and quantum information encoding. Despite these advances, practical implementation of vortex beams has faced significant challenges, especially for high-order modes ($l > 1$). High-order vortex beams are more vulnerable to environmental disturbances, structural imperfections and mode coupling, making it difficult for them to preserve their complex phase structure and purity during propagation.

Now, reporting in *Nature Photonics*, Zhichan Hu and colleagues introduce a topologically protected transport scheme that ensures the stability of vortex modes, even at high orders[2]. This innovation provides critical insights into achieving robust vortex beam control and marks a substantial step toward scalable vortex photonic technologies.

Both waveguides and laser cavities support stable optical eigenmodes. In a laser cavity, these modes are typically confined in all three spatial dimensions, while in a waveguide they are confined only in the transverse plane and extend freely along the waveguide's longitudinal axis. To generate and maintain vortex modes, the eigenmode must include a factor $e^{il\varphi}$, where l is an integer, indicating an optical field with orbital angular momentum – a characteristic feature of chiral whispering gallery modes. A long-standing challenge in realizing vortex lasers lies in breaking time-reversal symmetry to enable a robust, unidirectional chiral mode. Recent advances in the design and implementation of topological vortex lasers[3,4], inspired by analogies to the quantum spin Hall and quantum Hall effects, have successfully overcome this challenge.

In waveguides, by contrast, time-reversal symmetry is typically preserved, ensuring that both clockwise and counterclockwise chiral modes can propagate. Instead, the principal challenge lies in maintaining the purity of the chosen vortex mode during propagation, particularly when structural imperfections are present[5–8]. Even slight defects can induce two primary forms of degradation: (1) scattering of the vortex mode into delocalized modes and (2) scattering into other vortex modes, especially those with opposite handedness but identical frequency. Another persistent challenge is developing effective vortex mode filters – waveguides that transmit only the desired vortex mode.

Hu and colleagues have tackled these challenges by developing a topological disclination lattice waveguide that confines and transports

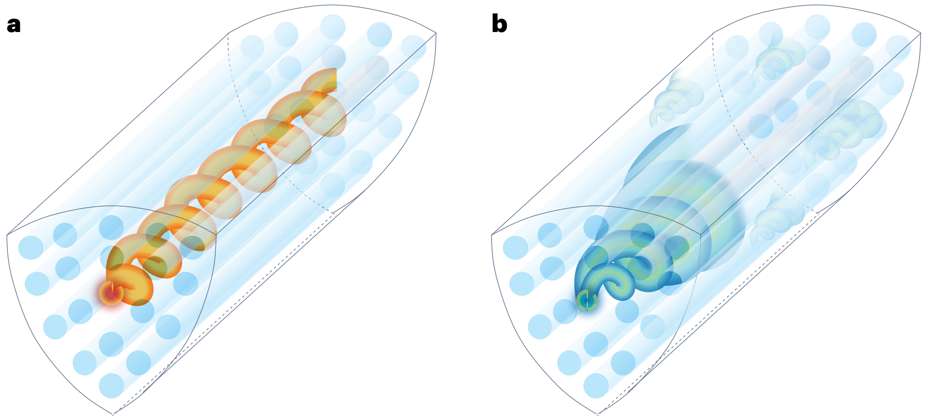

Fig. 1 | Topological disclination lattice waveguide. a,**b**, The waveguide features dual topological protection, simultaneously enabling the robust propagation of vortex modes through topological properties in both momentum space and real space. Schematics illustrating the propagation of a protected vortex mode (**a**) and an undesired vortex mode (**b**). The protected vortex mode propagates within the waveguide, with its energy strongly localized at the single-site core at the centre of the structure (**a**). By contrast, the undesired vortex mode lacks protection and becomes scattered into delocalized modes during propagation (**b**).

vortex modes within a single-site core at the centre of the structure, as shown in Fig. 1. This innovative waveguide provides dual topological protection, simultaneously enabling the robust propagation of vortex modes through topological properties in both momentum space and real space.

In momentum space, their design ensures that the two-dimensional disclination lattice[9,10] retains chiral symmetry[11]. The lattice comprises two sublattices, A and B, where optical coupling occurs only between sites in A and B, with no coupling between sites within the same sublattice. This symmetry guarantees the existence of zero-energy topological modes, located at the centre of the photonic bandgap. From a frequency perspective, these modes are farthest from the delocalized bulk states, minimizing their coupling with such states under perturbation. During waveguide transmission, the frequency of the input vortex mode can be fixed, allowing the zero-energy topological modes in frequency space to correspond to specific wavevectors in propagation wavevector space. These wavevectors are also farthest from the delocalized bulk-state wavevectors, minimizing scattering into bulk states.

In real space, Hu and colleagues introduce a new topological invariant protected by a vorticity-coordinated rotational symmetry[2]. This symmetry ensures that scattering between two zero-energy vortex modes can be forbidden by destructive interference. For instance, in a disclination lattice with threefold rotational symmetry (C_3 symmetry), the structure remains invariant under a 120-degree rotation about its central axis. This symmetry divides the lattice into three identical 120-degree sectors. Each sector scatters the input zero-energy vortex mode into its counterpart with opposite chirality, but the scattered components destructively interfere, resulting in complete cancellation of net scattering. This innovative mechanism highlights the critical role of real-space topological protection in achieving robust vortex mode transmission.

The authors have further demonstrated that the topological disclination lattice waveguide offers vortex mode filtering functionality. By carefully tuning the lattice's rotational symmetry and lattice constants, only two zero-energy vortex modes are protected by chiral symmetry. At the zero-energy frequency, unwanted vortex modes with wavevectors not protected by chiral symmetry couple to delocalized bulk modes, enabling effective filtering. This topological approach overcomes a long-standing challenge in vortex transmission, ensuring robust propagation of the desired vortex mode while effectively suppressing unwanted modes.

The results presented by Hu and colleagues underscore the remarkable potential of topology in shaping and stabilizing vortex beams. By harnessing chiral symmetry and vorticity-coordinated rotational symmetry, their design achieves robust vortex transmission while effectively filtering out unwanted modes. This breakthrough unlocks new possibilities for reliable vortex photonic technologies, including advanced optical communication systems and on-chip quantum information processing. While opportunities remain to enhance tolerance to structural imperfections for preserving the desired symmetry and to scale the system for broader applications, these challenges represent exciting pathways for innovation and advancement in this rapidly evolving field.

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Competing interests

The authors declare no competing interests.