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TOPOLOGICAL LASERS

Multitudes of twists

Multiplexing increases the capacity of optical communication, but it is limited by the number of modes and their orbital angular momentum. A robust vortex laser now solves this problem by emitting several beams, all carrying large topological charges.

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Optical vortex beams carrying orbital angular momentum are characterized by a helical phase front and a phase singularity in the beam centre. The number of twists of the phase fronts around the axis of propagation within one wavelength gives the beam's topological charge. And vortex beams with different topological charges are orthogonal, which suggests that high-dimensional multiplexing is possible. This has been exploited for applications in optical communication and quantum information processing. In theory, the multiplexing dimension is limited by only how high a topological charge one can create; in practice, that's not an easy task. Writing in *Nature Physics*, Babak Bahari and colleagues now introduce a method to directly generate multiplexed vortex beams carrying a topological charge as large as 276 using a robust topological vortex laser[1].

There are many methods to convert a normal laser beam to a vortex beam, which use spiral phase plates, metasurfaces, synthesized holograms, plasmonic nanostructures and photonic crystals[2]. A compact vortex emitter can be directly constructed by engineering the eigenmode of a microscale laser itself[3–5]. The chiral eigenmodes of a whispering gallery mode resonator can serve as a natural source because they share the azimuthal phase factor of a vortex beam propagating in free space[6,7], which controls the topological charge of the emitted vortex beam.

However, it has been a long-standing challenge to construct a robust chiral whispering gallery mode that circles in only one direction. At a certain resonant frequency, there are usually two degenerate chiral modes travelling in opposite directions. Any backscattering, for example, from bending and defects, will cause coupling between the two, which turns the circling waves to standing waves. Because the counter-propagating modes carry opposite topological charges, they cancel each other and result in zero orbital angular momentum in the emission (Fig. 1a). To lift the degeneracy in whispering gallery mode lasers and directly generate a vortex beam, one needs to break this symmetry. Both parity–time symmetric refractive index modulation and the photonic quantum spin Hall effect with its spontaneous symmetry breaking have been employed to this end[3,8,9]. However, fabrication challenges and mode competition limit the emission of these vortex lasers to beams with small topological charges.

In their work, Bahari and co-authors tackled this challenge by using the photonic quantum Hall effect to realize a one-way circling wave that is robust against backscattering inside their vortex emitter (Fig. 1b). The key was to introduce a magneto-optic material close to a structured semiconductor membrane. Under a static external magnetic field, the magneto-optic material breaks time-reversal symmetry in the system, and a topologically non-trivial photonic crystal can form in the structured

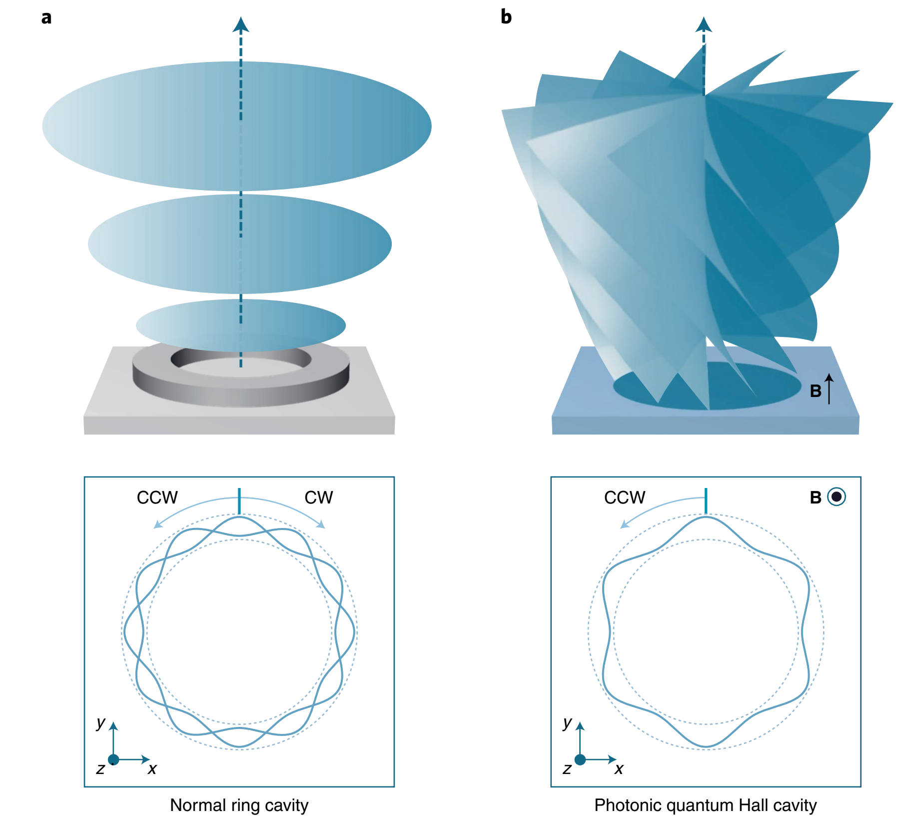

Fig. 1 | Robust light circling for vortex lasing based on the photonic quantum Hall effect. a, At a certain resonant frequency, a normal ring cavity has two degenerate chiral modes travelling clockwise (CW) and counterclockwise (CCW) (bottom). They carry opposite topological charges and therefore cancel each other out, which leads to emission with zero orbital angular momentum (top). **b**, In the presence of a static magnetic field (**B**), a photonic quantum Hall cavity supports a one-way circling mode that is robust against backscattering (bottom). Under optical pumping, the one-way mode above the light cone starts to lase and its azimuthal phase factor transfers to the helical phase front of the radiated vortex beam (top). In **a** and **b**, both phase fronts of 0 and π are plotted in the same colour.

semiconductor membrane. The team then introduced a topologically trivial photonic crystal to surround the non-trivial photonic crystal. The dissimilar topologies of the photonic structures ensure the existence of one-way topological edge modes at their interface.

When the interface has the shape of a ring, a one-way whispering gallery mode forms, the robustness of which originates from the absence of a mode that circulates in the opposite direction at the same frequency. Under optical pumping, the one-way mode above the light cone starts to lase and its azimuthal phase factor transfers to the helical phase front of the radiated vortex beam. Because the topological charge is equal to the azimuthal resonant order of the ring, the size of the ring controls the topological charge of the vortex beam: the larger the ring radius, the higher the topological charge. In this way, Bahari and co-workers successfully demonstrated a vortex emitter with a topological charge of 276 from a ring with a radius of about 34 μm.

This method can easily integrate multiple orthogonal orbital angular momentum beams of alternating chirality on the same chip in a compact manner. By alternating concentric circular interfaces between the two topologically dissimilar photonic crystals, Bahari and co-workers demonstrated a multiplexed vortex emitter consisting of three rings with emissions carrying topological charges of 100, 156 and 276. But the azimuthal resonant order of two neighbouring rings cannot be infinitely close because a minimum number of unit cells is required to achieve the necessary topological properties. Nonetheless, the calculated topological charge difference between the emissions of two neighbouring rings is smaller than ten.

The results reported by Bahari and co-authors show the uniqueness of topology in the design of photonic devices, representing a major step towards practical applications of topological photonics[10,11]. One key issue yet to be solved is how to make electrical contacts to the device. The magneto-optic material used to break time-reversal symmetry has to be in close proximity to the semiconductor photonic crystals, which makes the realization of electrically driven devices difficult. Furthermore, due to the inherently weak magnetic response at optical frequencies, the bandgap that opens in the non-trivial photonic crystal is small, only tens of picometres. Although the narrow gap provides a mode selection mechanism, it has to be matched to a resonant frequency of the cavity, which complicates the design and may limit the modulation bandwidth of the device. ❐

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Competing interests
The author declares no competing interests.