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Orbital angular momentum

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A photonic equivalent to disclination in crystals has been used to produce orbital angular momentum laser light directly on-chip, ushering in compact and efficient twisted-light lasers.

Light can carry orbital angular momentum (OAM) through its spatial structure, where each twist to its phase imbues light with additional quanta of OAM[1]. Light's OAM is an essential resource across many disciplines and applications, driving the need for solutions at the source. Imparting this twist is easily done in bulk systems with high efficiency using a sophisticated toolbox, even directly from lasers[2]. However, harnessing OAM from compact at-the-source solutions comes with additional challenges, at once prohibiting the use of existing bulk solutions while suffering from large scattering loss and high lasing threshold due to the lack of suitable mechanisms for high-quality OAM light confinement.

Reporting in *Nature Photonics*, Min-Soo Hwang and colleagues demonstrate the smallest and lowest threshold on-chip OAM laser reported to date[3]. To do so, they borrow concepts from crystal disclination — rotational, rather than translational, defects in materials, replacing atoms with air holes so that the structure is photonic. They demonstrate a laser cavity formed by a topological disclination that can produce on-demand vectorial combinations of OAM light. This development raises the notion of disclination in topological photonics — which to date has only been demonstrated in bulk OAM systems[4], as a result of efforts to miniature on-chip photonic systems — heralding a new state of the art in OAM nano-laser design.

Orbital angular momentum lasers can be traced back to the early days of the laser, specifically to studies of Laguerre–Gaussian modes in cylindrically symmetric laser systems, although at that time OAM was not associated with light's spatial structure and thus not mentioned in these studies. OAM laser advances followed only much later when it was established that the infinite alphabet of OAM could be created by judicious twisting of light's phase about the azimuth, paradoxically requiring some form of symmetry breaking inside the laser despite the rotational symmetry of OAM modes. In many lasers this is easily done by insertion of appropriate symmetry breaking elements, for instance, spiral phase plates[5] and metasurfaces[6], but on-chip lasers prohibit the use of this bulky toolbox.

On-chip lasers can be made by exploiting the natural rotational symmetry of whispering gallery modes in micro-ring resonators[7] aided with scattering-based angular grating for output and have been made handedness-selective by external modulation with chiral light[8]. Even though such micro-lasers are typically hundreds of times larger than the wavelength volume (λ^3), the tiny volume and OAM lasing mechanism require a high lasing threshold owing to low modal confinement and high scattering loss. It is natural to ask whether there is a fundamental limit to how small an OAM laser can be. For instance, how would a sub-wavelength cavity discern the handedness of the OAM wavefront, clockwise or anticlockwise, if this itself is twisted per unit wavelength?

To address these challenges and make their ultra-small and efficient laser, Hwang and colleagues introduce a new confinement notion made possible by borrowing concepts from defects in solids and translating them to a photonic solution[3]. Imagine cutting a material along one side, for instance, a cylinder along the long side, to open two exposed long edges. If these edges are displaced by some translation, left–right or up–down relative to one another, then the defect is a dislocation, a topic extensively studied in the last century. A more interesting example is if the edges are rotated relative to one another. Such rotational defects form what is known as a disclination and can support topologically protected currents at their edges. In photonics, they have the potential to support optical states that are robust to perturbations, offering a new path to light manipulation through topology[9].

With these notions in mind, Hwang and colleagues started with a four-fold symmetrical lattice and created a lower symmetry disclination cavity with three-fold symmetry by removing a quarter of the structure and stitching the rest together by rotating the edges to meet, thus filling the missing gap. They also created a higher symmetry cavity by rotating the original structure to form a wider gap to accommodate additional sectors, one additional sector for five-fold symmetry, two sectors for six-fold symmetry, and so on, as illustrated in Fig. 1. Rather than a lattice of atoms, they used a lattice of air holes to ensure the structure was photonic in nature. Just as an atomic disclination would support charge confinement at the atomic sites and stable current modes on the edge, so too does the photonic version, this time with a confined z component of the magnetic field vector in the air holes with a transverse phase sweep around the edge of the defect (depicted as the connected red air holes in Fig. 1). Since the transverse electric field structure is derived directly through the gradient of the magnetic component, the electric field is similarly structured in phase, supporting vectorial OAM states, that is, opposite handedness OAM coupled to opposite handedness polarization, so-called vector vortex beams. The entire structure has a volume of less than λ^3, with each air hole only ~90 nm in radius, about 270 nm apart (centre-to-centre) and sitting on a ~275 nm slab, making it an ultra-compact on-chip OAM laser. The OAM confinement mechanism allowed Hwang and colleagues to report a new state of the art in measured lasing threshold, which is 10 times lower than the best reported value to date[8]. These are very impressive performance numbers for a first reporting of this new laser.

At present, the design approach has an element of trial and error to it, where some 'playing' with parameters, such as air hole positions and spacing, must be carefully adjusted for optimal performance. Furthermore, the laser produces vectorial combinations of OAM for an output with zero net angular momentum, where splitting into preferred handedness, for example, +1 and −1 OAM, would require additional polarization-selective optical elements. Although the actual structure is tiny, the present study required complex

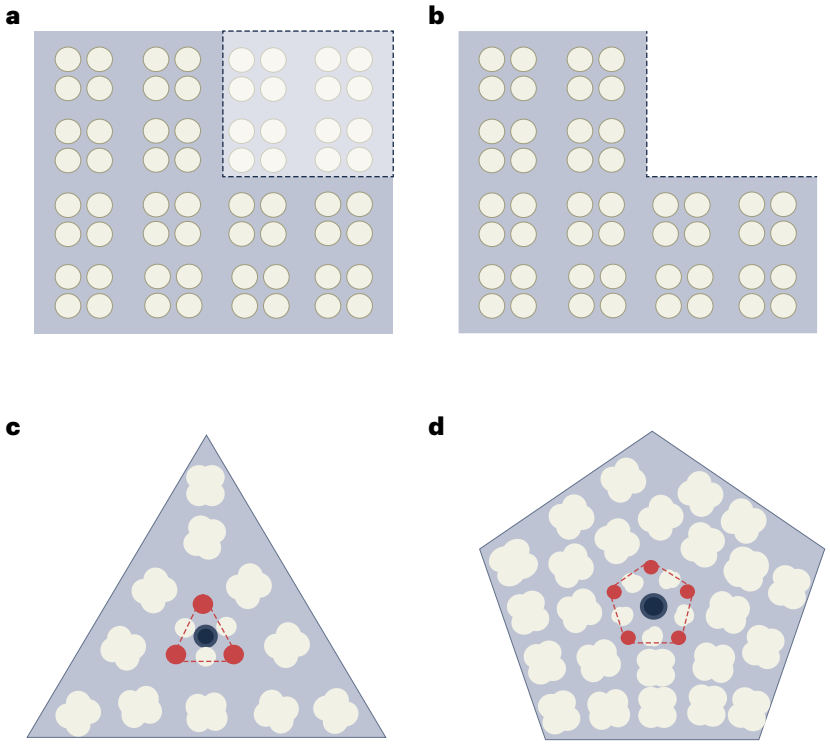

Fig. 1 | Rotational defects for twisted light. A disclination cavity is formed by cutting out a piece of structure made of air holes and rotating the edges to join for a reduced symmetry or to widen to accommodate additional material for increased symmetry. For example, in **a**, a four-fold symmetrical optical cavity made of air holes (circles) in a photonic-crystal arrangement can be contracted by removing a quarter of the structure and rotating the edges, shown as dashed lines in **b**, to form **c**, a three-fold symmetrical optical cavity. Alternatively, additional material can be added, as in **d**, to create a five-fold symmetrical optical cavity. The excitation of edge states (shown as connected red dots) about the defect (central black circle) results in vectorial OAM lasing.

and bulky excitation and collection of optics to exploit the device. These shortcomings could be overcome in the future by a complete on-chip solution with embedded excitation, while a deeper look into photonic disclination cavities and their excitation may provide the answer for direct laser designs with the required symmetry breaking for pure on-demand OAM emission.

Rotational defects in solids were once considered so energy restrictive that they barely received attention, with much more focus on dislocations than disclinations. Today the topic[10] has shed light on the role of topology in many physical systems, from matter to light. Hwang and colleagues have demonstrated a very promising example of how the physics of one system can be translated to another, with rich reward. Their novel nano-laser may just be the solution that sees OAM integrated into on-chip photonic devices, a necessary step if OAM is truly to be used in next generation optical communication systems, exploiting its infinite alphabet to fast-track data rates, while heralding an exciting new method to produce coherent structured light from sub-wavelength devices.

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Competing interests

The author declares no competing interests.