New twist to twisted light

Andrew Forbes*
University of the Witwatersrand, Johannesburg, South Africa

Controlling light in all its degrees of freedom is steadily gaining traction, extending our familiar 2D transverse forms of electromagnetic waves to include 3D control (all three components of the electric field), and spatiotemporal control for 4D forms of structured light.[1] Despite the advances, there still exist solutions to Maxwell's equations that have not yet been demonstrated,[2] hindered by the need to induce higher-order multipoles (beyond dipoles) and toroidal excitations in matter.[3] Reporting in *Nature Photonics*, Qiwen Zhan and colleagues demonstrate the first optical toroidal vortex.[4] They bypass the need for exotic materials and rare electronic transitions by exploiting conformal mapping of a space–time shaped vortex pulse, twisting and folding the optical field to form the familiar toroidal nature. Their approach heralds new spatial and temporal control of structured light, with the potential to impact fields from topology to quantum information.

A toroid is a closed-loop vortex ring found in many physical systems and popularized in the media through smoke "rings" in air by Hobbits and bubble "rings" underwater by dolphins. In material form, whether smoke or air bubbles, the mechanical disturbances needed to create them can be achieved with a little skill, but not so the electromagnetic disturbances for photonic toroidal pulses of light. Just as the rare quadrupole transition needed or orbital angular momentum (OAM) photons held back the field until 1992,[5] so the required exotic higher-order and toroidal multipoles have been challenging to harness for new radiative states of light. To overcome this challenge, Qiwen Zhan and colleagues used an ingenious approach that has the benefit of easy implementation and no exotic materials, leveraging on concepts from spatially twisted light.

Vortex light is created by twisting the phase in the transverse plane (x–y) for a hollow tube of propagating light in the z-direction. In order to confirm the twisted nature of the light, the ring in space can be unfolded to a line, mapping a twisted phase to a tilt (rings to lines), which is easy detected by converting tilt angles to positions with a lens.[6] In the present work, the authors first create a spatiotemporal vortex[7] by giving light a twist in space and time (x–t), rather than the traditional space-only vortex twisted light. This creates a tube of light in one spatial coordinate and a vortex in the plane defined by the other transverse coordinate and retarded time, like a long hollow pipe of space–time light. Unlike the traditional tube of twisted light, this space–time tube of light would propagate across the time field of view. In a critical step, they pass this light tube through a conformal mapping system that does the reverse of the OAM detector, now folding lines to rings. The result is to fold the tube of light in on itself, end to end, forming a toroidal shape in space and time, shown in Fig. 1(a), with a cut-out shown in Fig. 1(b). With these building blocks in place, the authors use an ultrafast laser and computer-generated holograms written to spatial light modulators to alter the space and time (via frequency) components of the light, as well as conventional ultrafast measurement tools for pulse characterization. The visualization of the outcome is impressive, for the first look at this new pulse of light. Detailed analysis reveals its intricate structure, with swirling OAM density around the inner "empty" core, with the surface of revolution defined by a spirally spatiotemporal phase.

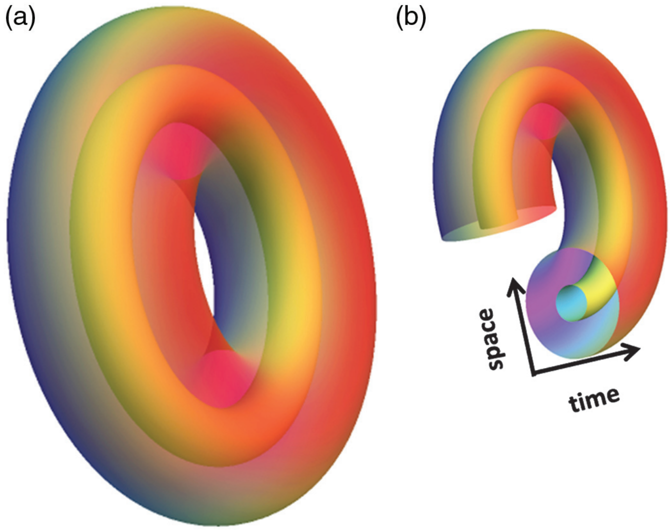

Fig. 1 A new twist on light. (a) By folding a spatiotemporal vortex in space and time onto itself, a toroidal pulse of light is created that exists in space–time, with an inner "hollow" core filled with a swirling orbital angular momentum density. The inset in (b) shows a cut-out, revealing the inner spatiotemporal vortex in space and time.

Conventionally, a toroid is formed by a surface of revolution about a central point so that the dimensions of the inner surface are smaller than the radius of the revolution, e.g., rotating a circle to form a sugar-coated donut or rubber car tire. Now, Qiwen Zhan and colleagues have introduced a novel toolkit for unprecedented control, opening new pathways to explore 4D structured light. In the present work, the surface of revolution was a spatiotemporal vortex with a central null, but one can imaging imbuing it with radial and higher-order azimuthal structure for more exotic forms of light, including topologically trapped Skyrmions and knotted threads of time–light, realizing new forms of light without the need for complex structured matter.

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*Address all correspondence to Andrew Forbes, andrew.forbes@wits.ac.za

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Andrew Forbes is a professor within the School of Physics at University of the Witwatersrand, South Africa, where in 2015 he established the Structured Light Laboratory. He is active in promoting photonics in Africa, as a founding member of the Photonics Initiative of South Africa and initiator of South Africa's Quantum Roadmap. He is a fellow of SPIE, Optica, and the South African Institute of Physics (SAIP), and an elected member of the Academy of Science of South Africa. His outstanding contributions to the field have been recognized by many awards, including the Sang Soo Lee Award from Optica and the Optical Society of Korea, the Georg Forster Research Award from the Alexander von Humboldt Foundation, and the SAIP Gold Medal, the highest award for physics in South Africa.