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Metasurfaces forge new paths in quantum spaces

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Abstract: The notion of a path in quantum mechanics has fuelled many debates on the very nature of what quantumness is. Although traditionally associated with physical paths, such as double slits, it can be far more abstract. Now Yan Wang and colleagues demonstrate exotic trajectories in an abstract quantum space built from the Bloch sphere of a locally entangled photon, while shaping the path using its non-local entangled partner as a control. The steering and directing along these new paths is enabled by cascaded metasurfaces, demonstrating the myriad of possibilities that emerge when structured matter meets quantum structured light.

Keywords: structured light; quantum structured light; metasurfaces; entanglement

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The ability to control single photons and entangled states in all their degrees of freedom (DoFs) has unleashed the potential of quantum structured light[1], driving new functionality and enhanced applications. For instance, using spatial DoFs such as orbital angular momentum (OAM) has imbued quantum states with the benefits of dimensionality[2], for higher resilience to noise, cloning and errors in quantum communications, more modes for imaging and more cluster states for computing. When space and time are jointly exploited, the potential is enormous. Equally topical is the mixing of DoFs to form multi-dimensional states, with polarisation and OAM a popular combination, giving access to multiple four-dimensional spaces in which to play. It is not only dimensionality to be gained, but the benefits of the basis itself: such hybrid states are natural modes of free-space and optical fibre, making them particularly attractive for quantum communication[3].

Driving this revolution in quantum structured light is a highly sophisticated toolkit. Metasurfaces as nanostructured artificial atoms have emerged as core elements, imbuing light with exotic properties and offering unprecedently potential for creation and control of quantum states[4,5]. They have been used to produce exotic sources of quantum light as well as novel approaches to detection, while pointing a new route towards efficient state preparation by exploiting resonant metasurfaces with a nonlinear response[6]. Although the use of metasurfaces in quantum experiments is now gaining traction, experiments have largely replicated their classical counterparts in single pass and single element shaping of a single input to a single output, with few venturing into the territory of studying the interaction of quantum states holistically with structured matter, and none considering the sequential use of multiple metasurfaces as quantum operators.

To address the challenge of generating and flexibly controlling high-dimensional entangled states, Yan Wang and colleagues introduce an approach based on ultra-thin non-commutative metasurfaces interacting with entangled photons[7], as illustrated in Fig. 1. They begin by generating a polarisation-entangled state in free space. The entangled photons were spatially separated such that the idler photon remained in free-space for remote polarisation control while the signal photon was directed through a pair of cascaded geometric-phase metasurfaces. One metasurface carried a uniform optical axis distribution, while the other was designed as a q-plate; together they converted the polarisation superposition of the signal photon state into a spin-orbit hybrid state representable on a distinct Higher-Order Poincaré Sphere (HOPS)[8]. As the idler photon's state was collapsed along a cardioid trajectory on the Poincaré sphere, the structured signal photon non-locally mirrors this exact path on a distinct HOPS of order m. This non-local mirror-

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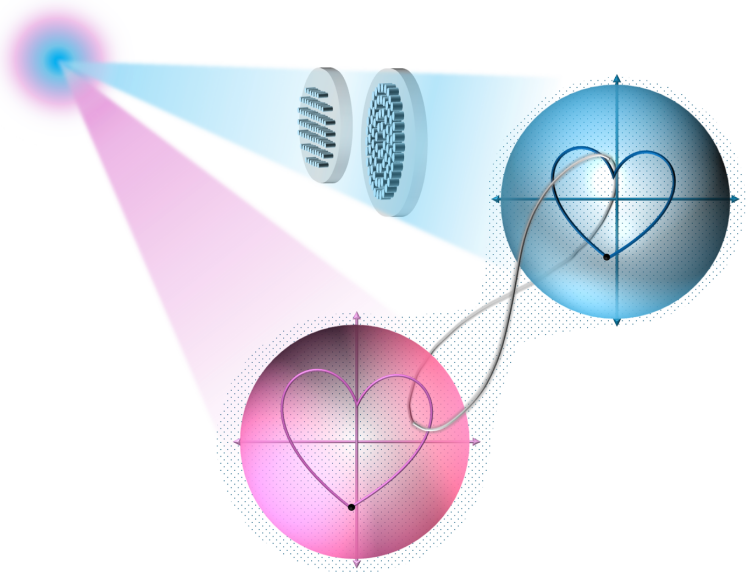

Fig. 1 | Correlated paths in abstract quantum spaces. Two polarisation entangled photons are created by spontaneous parametric downconversion. One is passed through a sequence of metasurfaces with differing transformation rules that perform spin-to-orbit coupling, producing hybrid states in polarisation and orbital angular momentum (OAM). Controlling the polarisation of one photon moves its state around the Poincare Sphere (pink sphere) in an arbitrary path (heart shaped trajectory), while the entanglement ensures that its partner mirrors this movement in the new High-Order Poincare Sphere (HOPS) space spanned by hybrid quantum states (blue sphere). The order of the metasurfaces matter: changing their order, form or number changes the very nature of the blue sphere and thus the type of states created during an arbitrary trajectory.

ing of paths is known as quantum path entanglement. Consequently, since the two metasurfaces are non-commutative this means reversing their cascaded order produces a fundamentally different Jones matrix and thus switching the entanglement path between higher-order spheres of opposite orders, e.g., from $m = 2$ to $m = -2$.

Building further on this, the authors extended the approach to three cascaded metasurfaces, showing that diverse quantum path entanglement can be switched not merely between HOPS of opposite orders ($m = \pm1, \pm2$) but across a broader library of non-opposite orders ($m = 1, 3, -1$), each accessed by a different permutation of the metasurface sequence. The non-commutativity of metasurfaces thereby provides an additional degree of freedom for quantum entanglement manipulation. Experimental complex polarisation patterns were reconstructed via Stokes parameter measurements show excellent agreement with simulated results across multiple entangled path geometries, with each point along an entangled path constituting a distinct mutually entangled two-photon basis state. This capability enables flexible control over a wider range of diverse entangled quantum states, each carrying multiple degrees of freedom simultaneously.

The work by Yan Wang and colleagues opens up the potential for abstract structuring of quantum states, here by an abstract path in a space spanned by two DoFs of one photon, steered by the entanglement of its partner. The result is a complex state that is formed by the noncommutative nature of the metasurfaces, that is, simply altering their order has a material impact on the states that can be created. Their beautiful demonstration traverses both single and multi-DoFs spheres, creating hybrid entangled states of exotic local structure. In the future it is highly conceivable that this approach might produce new topological forms of quantum light, smoothly moving from entangled to single photon topologies. This has become a highly topical field in quantum structured light, offering resilience to noise and entanglement decay through topology[9]. Their work may also find immediate application for rapid switching of states in quantum communications protocols[10] and might be the versatile new tool to allow fast detection of all states in quantum state tomographies. These applications are sure to follow in more directed experiments.

At its heart is the study of what path means in the context of exotically structured quantum states, clearly demonstrating that abstract trajectories can be tailored to traverse multiple single photon and entangled states. Here it is not a question of particles or waves, but how superposition principles of entangled states can be used to mirror single DoF paths to multi-DoF paths, raising fundamental questions on the notion of path entanglement itself.

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