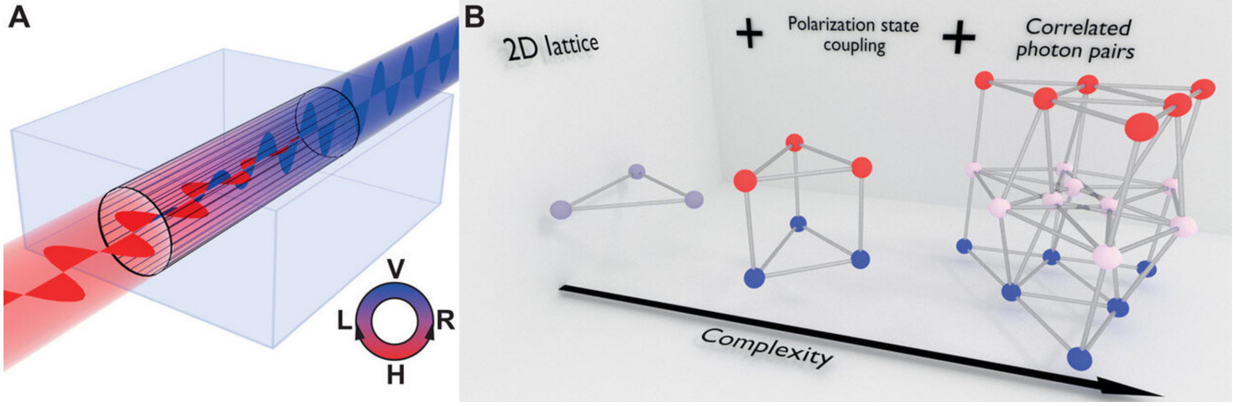
Exploring complex graphs using three-dimensional quantum walks of correlated photons

March 16 2021, by Thamarasee Jeewandara

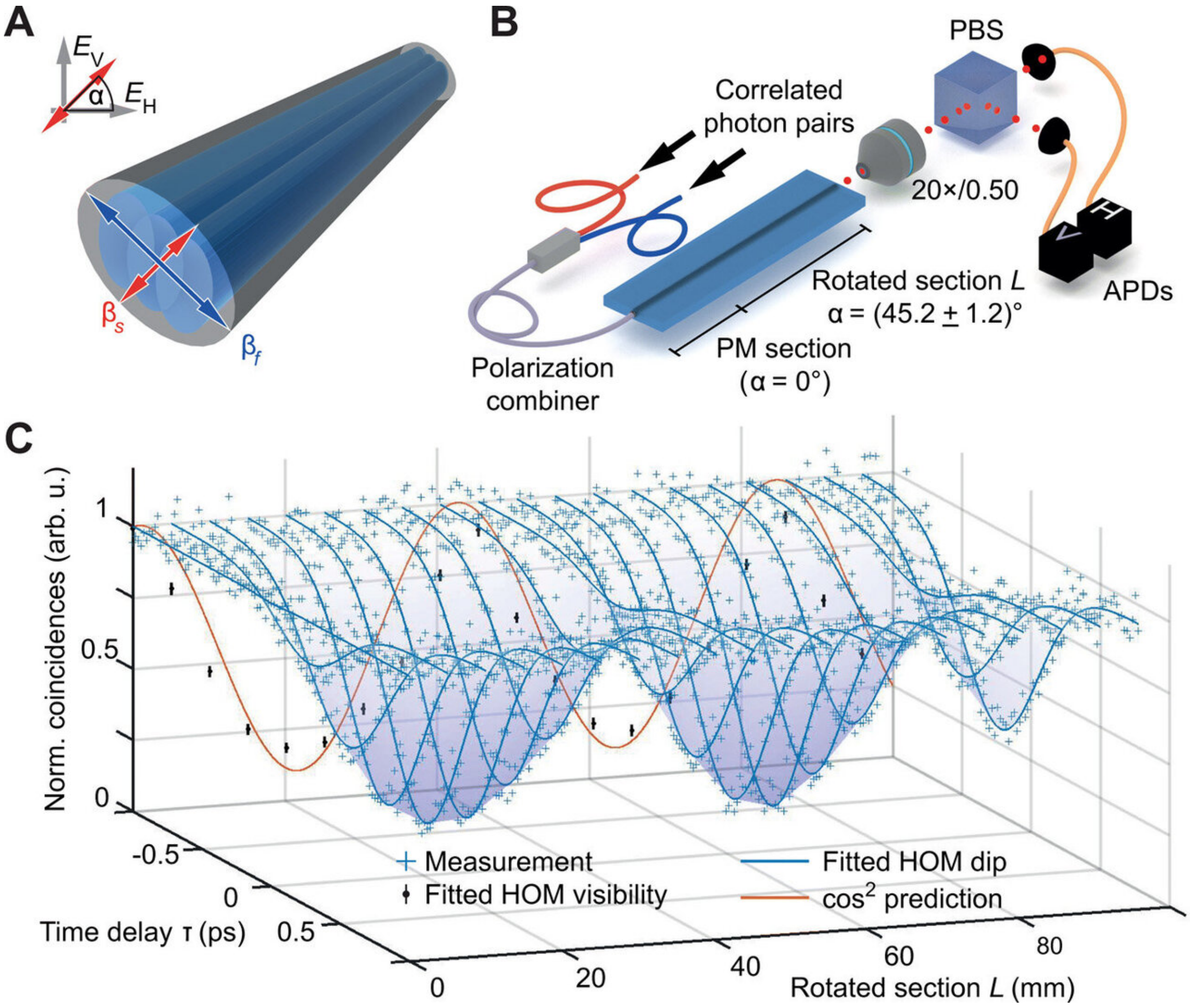


Using polarization as an additional synthetic dimension. (A) A single waveguide with tailored birefringence coherently couples its horizontally (red) and vertically (blue) polarized modes of the electromagnetic field. (B) Planar graphs (left) acquire an additional dimension due to the coupling of two polarization states (middle). The Hilbert space of photon pairs on 3D graphs takes the form of a yet more complex graph (right). Credit: Science Advances, doi:10.1126/sciadv.abc5266

Graph representations can solve complex problems in natural science, as patterns of connectivity can give rise to a magnitude of emergent phenomena. Graph-based approaches are specifically important during quantum communication, alongside quantum search algorithms in highly branched quantum networks. In a new report now published on *Science Advances*, Max Ehrhardt and a team of scientists in physics, experimental physics and quantum science in Germany introduced a hitherto unidentified paradigm to directly realize excitation dynamics associated with three-dimensional networks. To accomplish this, they explored the hybrid action of space and polarization degrees of freedom of photon pairs inside complex waveguide circuits. The team experimentally explored multiparticle quantum walks on complex and highly connected graphs as testbeds to pave the way to explore the potential applications of fermionic dynamics in integrated photonics.

Complex networks

Complex networks can occur across diverse fields of science, ranging from biological signaling pathways and biochemical molecules to exhibit efficient energy transport to neuromorphic circuits across to social interactions across the internet. Such structures are typically modeled using graphs whose complexity relies on the number of nodes and linkage patterns between them. The physical representation of a graph is limited by their requirement for arrangement in three-dimensional (3D) space. The human brain is a marked example of scaling behavior that is unfavorable for physical simulation due to its staggering number of 80 billion neurons, dwarfed by 100 trillion synapses that allow the flow of signals between them. Despite the number of comparably miniscule volume of nodes, discrete quantum systems faced a number of challenges owing to complex network topologies, efficient multipartite quantum communications and search algorithms. However, such physical implementations are thus far constrained to two dimensions (2D). Researchers typically use quantum walks to study the transport properties of connected graphs. For example, they had previously used linear one-dimensional (1D) chains across a range of technical platforms. In this work, Ehrhardt et al. showed controlled quantum walks of correlated photons on 3D graphs. To realize the graph structure, they used a new hybrid approach of 2D photonic lattices of spatially coupled waveguides inscribed into fused silica using femtosecond laser writing. The approach opens new avenues to explore the quantum dynamics of highly complex graphs that play a significant role across numerous scientific disciplines.

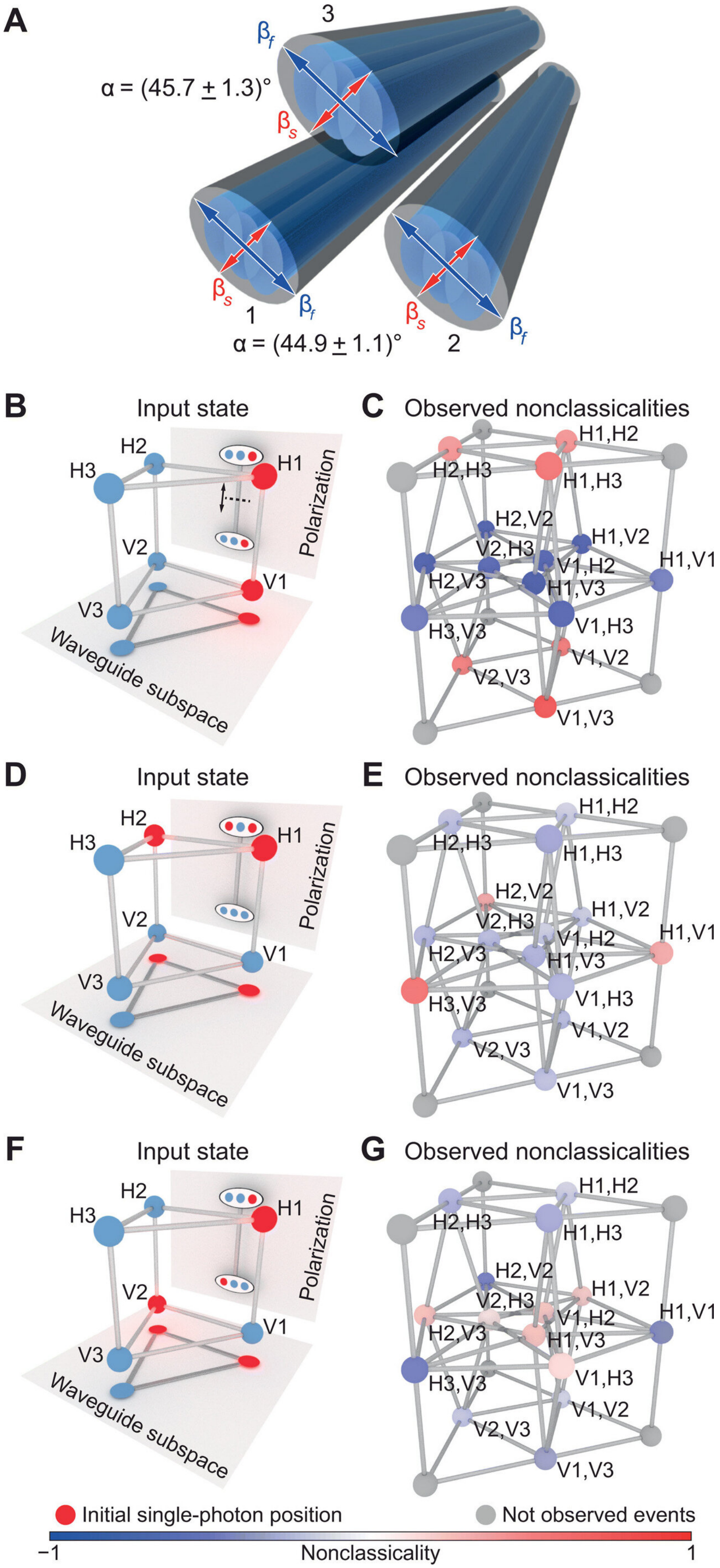


Quantum interference in a polarization coupler. (A) Triple-pass femtosecond laser–written waveguides enable control over both magnitude and orientation of the birefringence. Changes to the angle α of the slow axis allow for polarization-maintaining (PM) sections to be included at will. (B) Correlated photon pairs combined in a single waveguide exhibit HOM interference due to a coupling of the horizontal and vertical polarization modes in a section with rotated fast and slow axes of length L. (C) Coincidence rate measured as a function of the time delay τ between the photons' arrival time and length L of the rotated section. The displayed cos2 prediction fits the data for τ = 0 and a visibility limited only by the photon source to (92.3 ± 1.1)% (see Materials and Methods for details). The largest observed visibility was (84.2 ± 2.1)%. arb. u., arbitrary units. Credit: Science Advances, doi:10.1126/sciadv.abc5266

Working principle

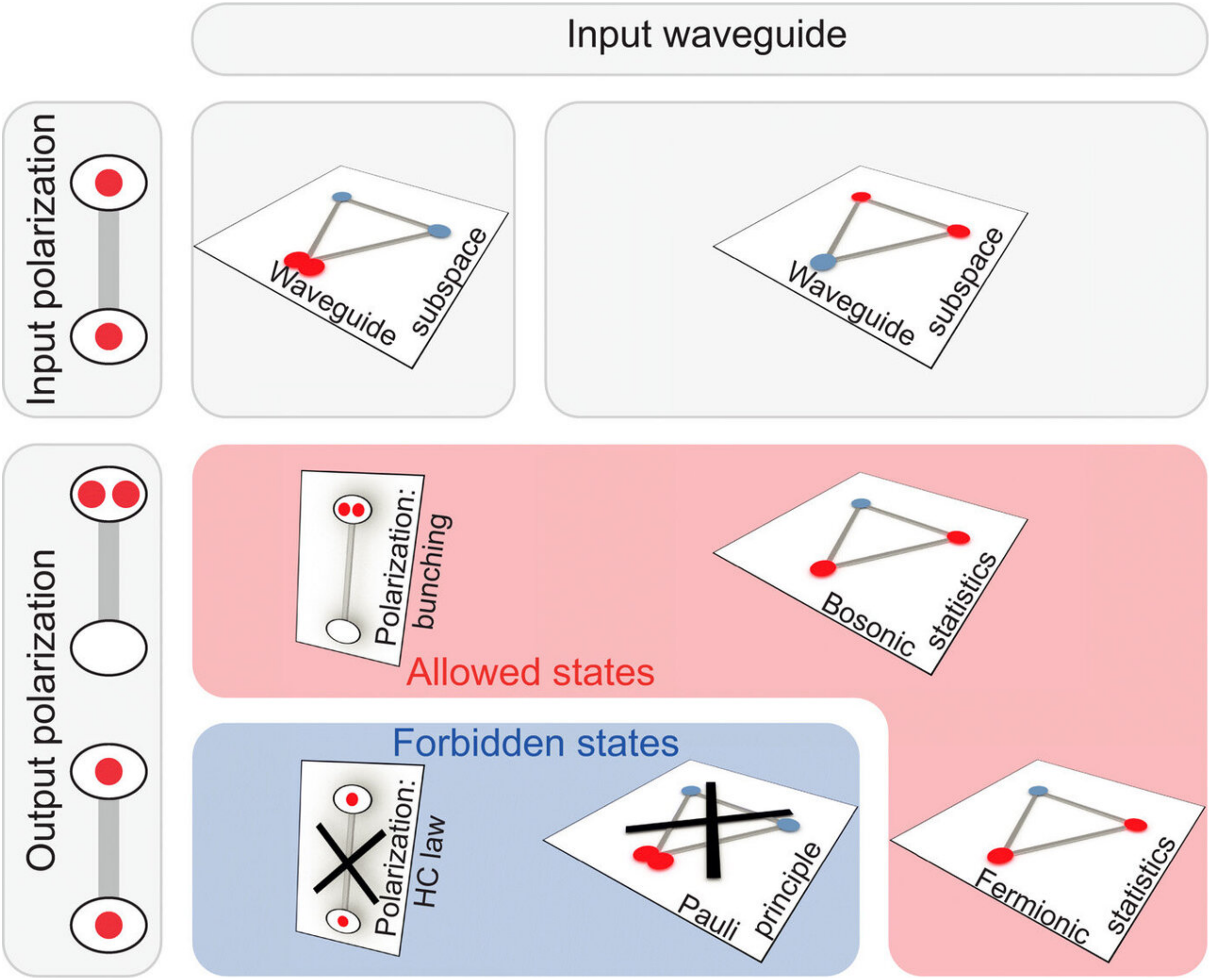
The setup contained spatially coupled waveguides inscribed into fused silica and a synthetic dimension encoded in the photons' polarization. They established the dynamics within the synthetic dimension by harnessing the intrinsic birefringent properties of elliptical waveguides historically used as polarization active cores of individual single-mode optical fibers. The team arranged for continuous coupling between two orthogonal polarization states to take place within the waveguides relative to an external reference frame. They illustrated the working principle to show the hallmark of two-particle interference using the Hong-Ou-Mandel (HOM) effect, which arose in the polarization degree of freedom of a single waveguide. The direct laser-written waveguides in fused silica were intrinsically birefringent and individually described by a Hamiltonian with bosonic annihilation (creation) operators for photons on the slow/fast principal axis with a propagation constant. They oriented the axes at an angle alpha (α) toward the horizontal or vertical frame of reference. Any deviations in the polarizations states of photons propagating along the z direction according to the Heisenberg equation of motion represented the strength of birefringence - the optical property of the material with a refractive index depending on the polarization and propagation direction of light. This mathematical structure was fully equivalent to the dynamics in a coupled and detuned two-waveguide system. The team used a polarization-duplexed input state synthesized from photon pairs generated through parametric down-conversion (SPDC) and injected it into a polarizaton-maintaining waveguide with an angle of 45 degrees and custom length. Using the experimental setup, the scientists obtained a 2D "HOM landscape" for 20 different lengths.

Extending the system


A
3
β_f
α = (45.7 ± 1.3)°
β_s
β_s
β_f
1
β_s
β_f
α = (44.9 ± 1.1)°
2
B
Input state
H2
H3
H1
Polarization
V2
V1
V3
Waveguide subspace
C
Observed nonclassicalities
H1,H2
H2,H3
H1,H3
H2,V2
H1,V2
V2,H3
H1,V1
V1,H2
H2,V3
H1,V3
H3,V3
V1,H3
V1,V2
V2,V3
V1,V3
D
Input state
H2
H3
H1
Polarization
V2
V1
V3
Waveguide subspace
E
Observed nonclassicalities
H1,H2
H2,H3
H1,H3
H2,V2
H1,V2
V2,H3
H1,V1
V1,H2
H2,V3
H1,V3
H3,V3
V1,H3
V1,V2
V2,V3
V1,V3
F
Input state
H2
H3
H1
Polarization
V2
V1
V3
Waveguide subspace
G
Observed nonclassicalities
H1,H2
H2,H3
H1,H3
H2,V2
H1,V2
V2,H3
H1,V1
V1,H2
H2,V3
H1,V3
H3,V3
V1,H3
V1,V2
V2,V3
V1,V3
Initial single-photon position
Not observed events
−1
Nonclassicality
1

3D graph in two spatial dimensions. (A) The graph structure of a triangular prism is realized with three coupled birefringent waveguides arranged in the shape of an equilateral triangle. (B, D, and F) Two-photon input states are illustrated by red nodes on the single-photon graphs and the respective projections on the polarization and waveguide subspaces. (C, E, and G) The corresponding experimentally observed nonclassicalities (coincidence rates are available in fig. S4) are color-coded on a two-photon graph representation for the input states shown on the left-hand side. Gray nodes indicate output states with both photons in the same waveguide and polarization, which are inaccessible in the present experimental setting without photon number–resolving detection. Credit: Science Advances, doi:10.1126/sciadv.abc5266

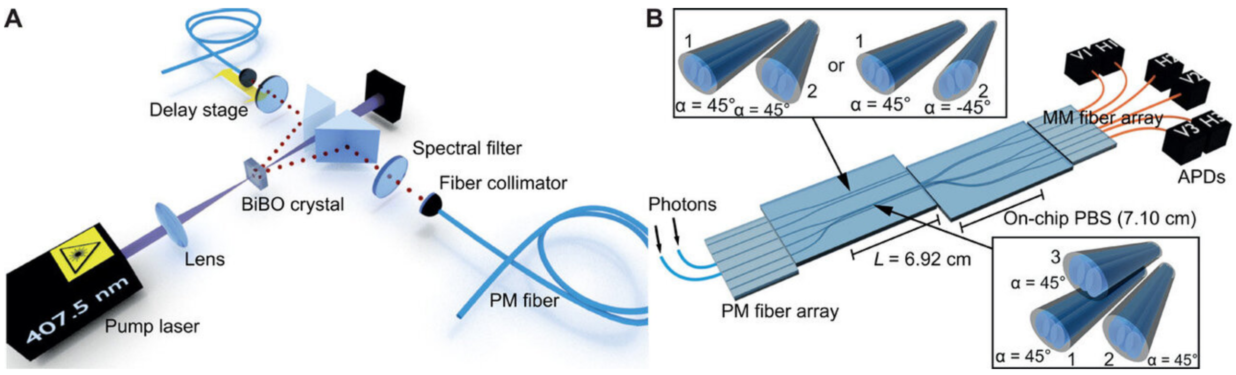
Based on the existing tools, Ehrhardt et al. extended a system of two spatially coupled waveguides to a square lattice. While conventional waveguide couplers are designed for specific input polarization, the different splitting ratio in this instance was dictated by the difference in polarization-dependent coupling strength between the two channels relative to the photon dynamics within the principal axis. The scientists used a 45-degree rotation of the principal axis, to allow simultaneous spatial coupling and well-defined crosstalk between the polarization states within a given waveguide. They also studied the collective dynamics of two-photon input states for all possible arrangements with at most one photon per site. After the transformation in the square lattice, they separated the polarization components using two on-chip polarization beam splitters and detected the photons subsequently using avalanche photodiodes. For distinguishable photons, Ehrhardt et al. noted equally strong couplings between the lattice sites to form a uniform output probability distribution across the entire lattice. They noted how the destructive and constructive quantum interference caused the full suppression and pronounced enhancement for indistinguishable photons.



Summary of forbidden and allowed output states. Two photons are launched in different polarization sites (each photon position is indicated by a red node) and in different waveguides (right column) or in the same waveguide (middle column). We classify the possible final two-photon arrangements associated with their input state and their observed hallmarks of quantum interference in allowed (red frame) and forbidden states (blue frame) and same (middle row) and different (bottom row) output polarization states. Credit: Science Advances, doi:10.1126/sciadv.abc5266

Hypercubes and subgraph structures

The team showed how higher-dimensional graphs naturally gave rise to hypercube (HC) symmetries to provide a distinct signature to the evolution of correlated photon pairs. In accordance with the HC suppression law, they noted the emergence of fully destructive quantum interference for two-photon trajectories with specific input-output combinations. Ehrhardt et al. further implemented an experimental 3D quantum walk, in which they transformed an equilaterally coupled triangle of identical birefringent waveguides into a triangular prism. Using the setup, they showed how two bosonic walkers behaved as fermionic walkers on the equilateral triangular waveguide lattice. The division into bosonic and fermionic behavior resulted from a direct consequence of the underlying hypercube structure -similar characteristics can hold for any subgraph structure. As a result, the work indicated how specifically designed waveguide lattices can selectively represent suppression mechanisms relative to bosonic or fermionic two-particle interference on the waveguide subspace.



Experimental setup. (A) Correlated photon pairs are generated by type I SPDC (spontaneous parametric down-conversion). A BiBO crystal is pumped with a focused laser beam. The two horizontally polarized photons and the pump beam are separated with two prisms. After passing spectral filters, the photons are collected by PM fibers. The time delay τ between the photons is set by a delay stage. (B) The generated photon pairs are launched either on the fast or on the slow axes of the fibers in the PM fiber array. After the photons evolve in waveguide arrangements of two or three waveguides with rotated principal axes, they pass an integrated PBS on a second sample. In the end, the photons are collected with multimode (MM) fibers and detected with APDs (Avalanche photodiodes). Credit: Science Advances, doi:10.1126/sciadv.abc5266

Outlook

In this way, the exploration of quantum dynamics on complex graphs are important across varied scientific disciplines. However, the increased dimensionality made their experimental implementation ever more challenging. Max Ehrhardt and colleagues introduced a new approach by expanding the dimensionality of photonic lattices via the polarization degree of freedom to increase the vertices' connectivity in space. Based on proof-of-principle experiments, Ehrhardt et al. observed quantum interference in fully controlled quantum walks of correlated photons on 3D graphs—a longstanding goal in quantum photonics. The established framework can allow a number of fascinating opportunities to arise beyond the context of correlated quantum walks. Based on these results, physicists can emulate quantum dynamics of bilayer 2D materials in photonic model systems. The team expect to further examine other nontrivial topologies more efficiently on optical platforms.

More information: Erhardt M. et al. Exploring complex graphs using three-dimensional quantum walks of correlated photons, *Science Advances*, 10.1126/sciadv.abc5266

Acín A. et al. Entanglement percolation in quantum networks, *Nature Physics*, doi.org/10.1038/nphys549

Paparo G. D. et al. Quantum google in a complex network, *Scientific Reports*, doi.org/10.1038/srep02773

Citation: Exploring complex graphs using three-dimensional quantum walks of correlated photons (2021, March 16) retrieved 18 June 2024 from https://phys.org/news/2021-03-exploring-complex-graphs-three-dimensional-quantum.html