Shaping the Spatial Coherence of Quantum Source

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There has been immense research interest in quantum entanglement due to its ability to generate stronger-than-classical nonlocal correlations.[1,2] These strong, nonlocal correlations form the backbone of various quantum information protocols. One of the core principles of quantum entanglement is quantum coherence, which provides deep insights into the statistical correlations among quantum particles.[3–5] Quantum coherence reflects the wave-like properties of quantum particles, enabling them to exhibit interference and unique quantum behaviors. Higher-order quantum coherence, involving correlations beyond simple intensity patterns, reveals more complex statistical relationships among quantum particles.[6,7] For instance, while first-order coherence is linked to classic interference fringes, second-order coherence explores correlations in arrival times (temporal) and positions (spatial). However, actively controlling second-order spatial quantum coherence has long been an elusive goal for physicists.

Recently, Shuang-Yin Huang and colleagues at Nanjing University have demonstrated the active manipulation of second-order spatial quantum coherence using entangled photons.[8] Huang and colleagues proposed a novel method for manipulating second-order spatial quantum coherence. They predicted and then demonstrated the switching between photon bunching and anti-bunching spatially. Their framework involved mapping the entanglement of spatially structured photons to the second-order spatial quantum coherence, a process that allows precise control over spatial quantum coherence. The experimental process involved converting global polarization entanglement into spatial entanglement using entanglement transfer units (ETUs).

The ETUs played a critical role in their experiment. The researchers designed two types of ETUs: one for transferring polarization to orbital angular momentum (OAM) and the other for transferring polarization to a patterned phase. These units converted the polarization entanglement into either OAM entanglement or patterned-phase entanglement. By carefully selecting polarization coincidence channels and applying structured phases to the photons, the team could actively manipulate the second-order spatial quantum coherence.

As shown in Fig. 1, the experiments demonstrated that the spatial structure of the coherence function could be precisely controlled by engineering the phases of the spatially structured photons. For example, when using the OAM entangled state, the degree of second-order spatial quantum coherence exhibited diagonal fringes with an experimental visibility of 0.6 within the range $g^{(2)} \in [0, 2]$, even though the single-photon intensity distribution in one path had an azimuthal uniform doughnut pattern. Moreover, the team observed three different $g^{(2)}(\varphi, \varphi') = 0, 1, 2$ for the letter N representing anti-bunching, non-correlation, and bunching of two photons, using the ETUs designed.

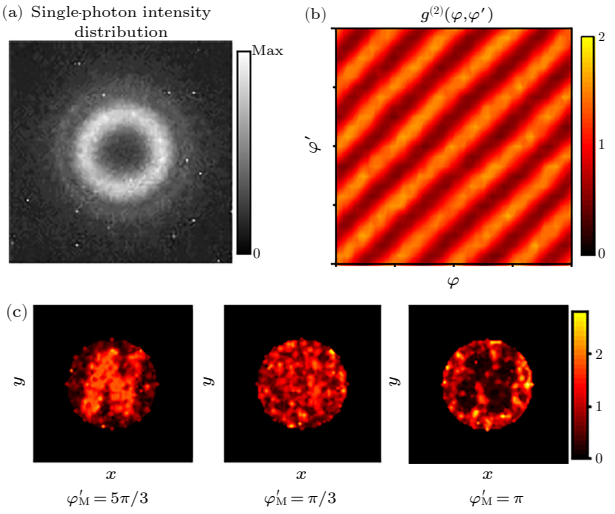

Fig. 1. Manipulation of the second-order quantum coherence of spatially structured entangled photons.[8] (a) The single-photon intensity distributions in one path of the entangled photons. (b) The corresponding interference fringes when measuring the degree of second-order spatial quantum coherence $g^{(2)}(\varphi, \varphi')$. (c) The experimental results of the patterned-phase entangled state, displaying the letter N with anti-bunching ($g^{(2)}(\varphi, \varphi') = 0$), non-correlation ($g^{(2)}(\varphi, \varphi') = 1$), and bunching ($g^{(2)}(\varphi, \varphi') = 2$) properties.

Huang and colleagues' approach can also be extended to control higher-order quantum coherence, such as fourth-order spatial coherence involving more photons. By demonstrating the active manipulation of second-order spatial quantum coherence, they have opened up new av-

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enues for quantum technology. Manipulating quantum coherence, particularly in higher orders, enables precise control over quantum systems.[2] This capability is crucial for developing advanced quantum technologies. For example, in quantum imaging and holography, high-order coherence can significantly enhance image resolution and reduce noise.[9,10] In quantum communication, it can increase data capacity and security by encoding information in multiple dimensions.[11] Moreover, controlling quantum coherence is fundamental for quantum computation, where it can be used to develop new quantum gates and algorithms.[12,13]

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