Hyperentanglement goes deterministic and large-scale

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Recognized by Einstein, Podolsky, and Rosen in their famous paradox to argue that quantum mechanics must be incomplete,[1] quantum entanglement is now considered a fundamental resource of quantum physics and forms the cornerstone of a variety of quantum information protocols that have the potential to significantly outperform their classical counterparts. Optical fields have a variety of degrees of freedom (DoFs), and many of these DoFs can become entangled under suitable conditions. Recently, much research interest has been drawn to hyperentanglement[2] which is defined as the simultaneous entanglement in multiple DoFs.[3] Hyperentanglement can significantly increase channel capacity and enable demonstrations of interesting and useful quantum information protocols.[4,5]

Until now, hyperentanglement has been extensively explored with discrete variables, such as polarization, spatial mode, time bin, frequency bin, and so on. However, continuous-variable (CV) hyperentanglement is less studied (the only previous demonstration was limited to a very small scale[6]), but it should hold equal potential for exciting quantum information protocols. A valuable feature of CV optical quantum states is that they are generated deterministically without post-selection.[7] Therefore, generating large-scale CV hyperentanglement could trigger the development of high-capacity, deterministic quantum information protocols.

As reported recently in *Advanced Photonics Nexus*,[8] a group led by Jietai Jing from East China Normal University experimentally realized the deterministic generation of large-scale CV hyperentanglement. Their scheme utilizes a third-order nonlinear process, four-wave mixing (FWM) in an atomic vapor, to generate quantum correlated twin beams, each of which contains a number of optical modes defined by multiple optical DoFs. These optical modes are in terms of the quadratures of quantized fields, which have a continuous spectrum, and the entanglement of optical modes is often observed as strong correlations between the fluctuations of field quadratures. By simultaneously entangling optical modes defined by three DoFs (Fig. 1), the authors were able to generate CV hyperentanglement and verify the entanglement of 216 pairs of optical modes in their system.

The first DoF they exploited is the optical frequency of the fields. Frequency has been extensively employed in a multitide of applications[9,10] because its dimension can be considered infinite. In the present experiment, the entanglement in frequency DoF originates from energy conservation in the FWM process, and three separate frequency sidebands within the FWM bandwidth are utilized to demonstrate entanglement. The other two DoFs are based on the spatial modes of optical fields, which recently have attracted a growing interest for applications in both classical[11] and quantum[12–14] photonics. Laguerre-Gaussian (LG) modes, characterized by azimuthal and radial indices, are used to provide two spatial DoFs in this experiment. It should be noted that the two indices of LG modes are independent in terms of mode orthogonality, meaning that these two spatial DoFs are independent from one another. To make a long story short, the three DoFs together are pieces of a larger jigsaw puzzle that completes the large-scale CV hyperentanglement picture.

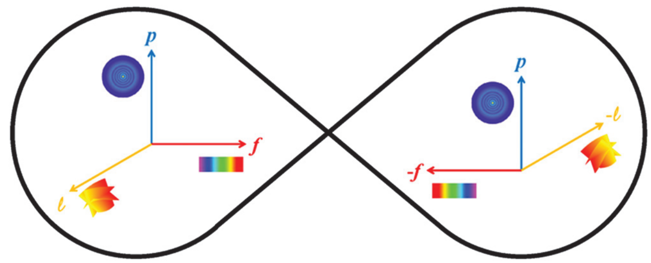

Fig. 1 Schematic of CV hyperentanglement in frequency (f), azimuthal (ℓ), and radial (p) DoFs. Black lemniscata indicates the quantum entanglement between two optical modes.

This work takes an important step towards applying abundant and diverse DoFs of optical fields to the research of quantum information science. In terms of applications, the study sheds new light on constructing novel quantum information protocols. For example, hyperentanglement is an essential resource for realizing multiple-DoF quantum teleportation.[5] Such CV hyperentanglement provides the possibility to realize deterministic quantum teleportation of multiple-DoFs, which has never been reported. In addition, these hyperentangled modes can be efficiently separated from each other, making it particularly useful for parallel, independent quantum communications channels, enabling a wide variety of simultaneous quantum communication tasks.

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Raphael Pooser is an expert in continuous-variable quantum information. He is a distinguished scientist at Oak Ridge National Laboratory (ORNL) and founder of Quantum Advantage Partners. Over the past thirteen years he developed a quantum sensing program and led the quantum sensing group at ORNL from the ground up based on continuous-variable quantum networks. He has been working to demonstrate that continuous variable quantum optics, quantum noise reduction in particular, has important uses in the quantum information field. The deterministic nature of these systems is a strong draw and motivator that leads to practical applications, and this research model uses quantum sensors as a showcase for the technologies that will enable quantum computing. Notable achievements include demonstrations of quantum plasmonic sensors with signal-to-noise ratios that exceed the classical state of the art, the first demonstrations quantum-enhanced read out of atomic force microscope cantilevers, and practical applications of nonlinear interferometry. Prior to his post as a research scientist, he served as a distinguished Wigner Fellow at ORNL. He previously worked as a postdoctoral fellow in the Laser Cooling and Trapping Group at the National Institute of Standards and Technology after receiving his PhD in engineering physics from the University of Virginia.