Optical entanglement of co-propagating modes

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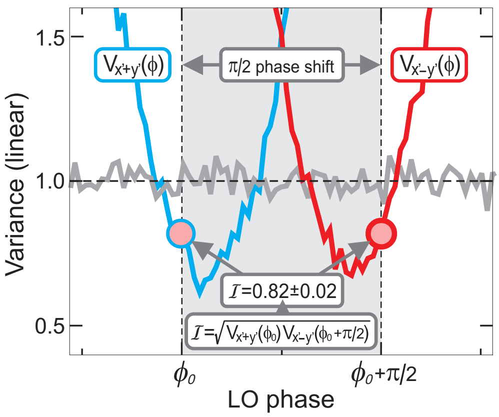

Fig. 1: Results for inseparability. Measurement of the variance for the sum $V_{x'+y'}(\phi)$ and difference $V_{x'-y'}(\phi)$ for the 45° rotated fields. The data, both below the QNL, are combined to one value for the inseparability of $\mathcal{I} = 0.82 \pm 0.02$, demonstrating significant entanglement between two orthogonal spatial modes within one optical beam.

Optical entanglement is a key requirement for many quantum communication protocols. Conventionally, entanglement is formed between two distinct beams, with the quantum correlation measurements being performed at separate locations. Such setups can be complicated, requiring the repeated combination of complex resources, a task that becomes increasingly difficult as the number of entangled information channels, or modes, increases. We pave the way towards the realization of optical multimode quantum information systems by showing continuous variable entanglement between two spatial modes within one beam [1], see Fig. 2. Our technique is a major advance towards practical systems with minimum complexity. We demonstrate three major experimental achievements. First, only one source is required to produce squeezed light in two orthogonal spatial modes. Second, entanglement is formed through lenses and beam rotation, without the need for a beamsplitter. Finally, quantum correlations, see Fig. 1, are measured directly and simultaneously using a multipixel quadrant detector.

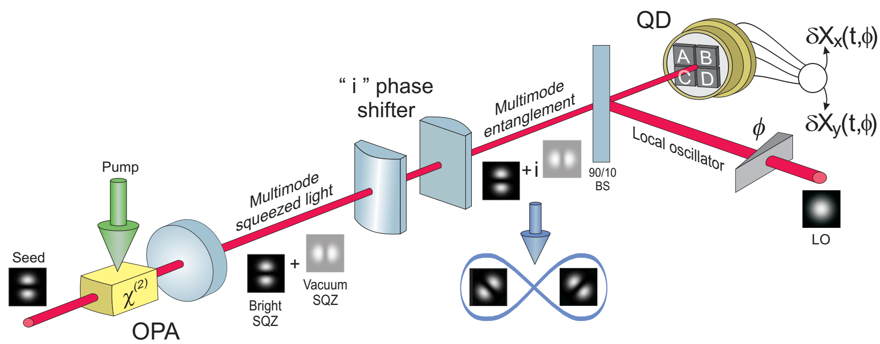

Fig. 2: Multimode entanglement experimental setup. We use a degenerate OPA for generating two squeezed higher-order modes. An optical system made of cylindrical lenses imparts a $\pi/2$ phase shift on one of the modes. Entanglement between 45° rotated spatial modes is analyzed using a QD set to a correct basis. $\delta X_x(t,\phi)$ is equivalent to $\delta X_{(A+B)-(C+D)}(t,\phi)$, and $\delta X_y(t,\phi)$ is given by $\delta X_{(A+C)-(B+D)}(t,\phi)$. OPA: optical parametric amplifier; LO: local oscillator; HD: homodyne detection; QD: quadrant detector.

References

[1] J. Janousek et al., Nature Photonics **3**, 399 (2009).