Optical Bipartite Continuous Variable Entangled States carrying Orbital Angular Momentum

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Efficient production of entangled states is becoming more and more an exciting challenge since these states are the heart of a large number of quantum information protocols. On the other hand Orbital Angular Momentum (OAM), on this regard, allows one to exploit a Hilbert space with, in principle, infinite dimension, leading to an enhancement of both information transmission capacity and security in communications [1]. We present the first generation and complete characterisation of a Continuous Variable (CV) bipartite entangled state constituted by helical modes. The primary entanglement source is a triply resonant type-II Optical Parametric Oscillator (OPO) working below threshold that provides a bipartite entangled state made of a pair of thermal cross-polarised collinear modes. Out of the OPO, the polarisation entangled state is then provided with orbital angular momentum by means of a quarter wave plate and a q-plate (qP) [2], a liquid-crystal optical device that couples polarisation and orbital angular momentum degrees of freedom (see Fig. 1).

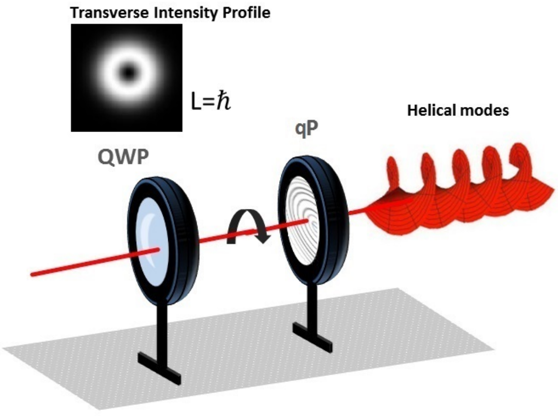

Figure 1: Set up for the OAM imprinting. A quarter waveplate (QWP) and a q-plate (qP) transform the polarisation entangled state into a polarisation/OAM entangled state.

Acting on a circularly polarised Gaussian TEM_{00} mode, a qP reverts its polarisation and changes its geometrical profile to a Laguerre-Gauss-like mode that carries an amount of orbital angular momentum per photon $m = \pm 2q\hbar$ (with q the qP topological charge). The qP we used has $q = \frac{1}{2}$, so it converts the two polarisation entangled Gaussian modes into polarisation/OAM entangled Laguerre-Gauss-like modes carrying opposite amounts of OAM ($\pm\hbar$). In this way the resulting entangled state can be distinguished by both d.o.f.: polarization and orbital angular momentum.

After the OAM imprinting the state is sent to a Homodyne Detector (HD) for characterisation. In order to directly detect the state in the OAM space it is necessary to modify ordinary HD by providing also the local oscillator with the same amount of OAM carried by the beam under scrutiny to obtain a high level of mode matching. A qP and two quarter waveplates allows one to switch the local oscillator between two different OAM values (see Fig. 2).

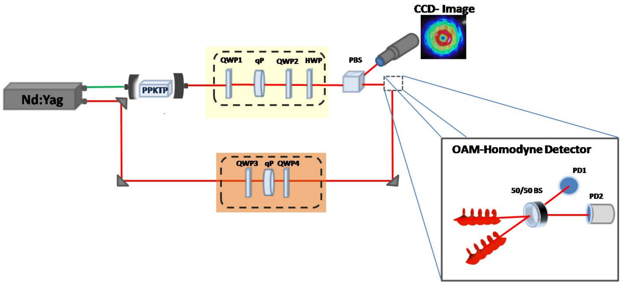

Figure 2: Schematic representation of the experimental setup. A bipartite entangled state is generated by the OPO and then provided with OAM (dotted blank box). The HD local oscillator is provided with the same amount of OAM (dotted pink box) carried by the mode under scrutiny.

Since thermal states are a subfamily of Gaussian ones, i.e. states with a Gaussian Wigner distribution in phase space, their quantum state can be completely characterised by their Covariance Matrix (CM). The full CM of the state has been reconstructed through a single HD scheme [3]:

$$\begin{pmatrix} 0.61 \pm 0.02 & -0.00 \pm 0.02 & 0.29 \pm 0.02 & -0.00 \pm 0.02 \\ -0.00 \pm 0.06 & 0.61 \pm 0.02 & -0.00 \pm 0.02 & -0.23 \pm 0.02 \\ 0.29 \pm 0.02 & -0.00 \pm 0.02 & 0.60 \pm 0.02 & -0.00 \pm 0.02 \\ -0.00 \pm 0.02 & -0.23 \pm 0.05 & -0.00 \pm 0.06 & 0.60 \pm 0.02 \end{pmatrix} \quad (1)$$

CM (1) represents a bipartite entangled state according to the Peres-Horodecki-Simon criterion [4]. The state we generate is a genuine bipartite entangled state in which entanglement is set in OAM as well as in polarisation degree of freedom.

The realization of multi-distinguishable CV entangled state and the direct access to entangled variables by a reconfigurable HD paves the way to the use of OAM beams for multi-partite and hyper-entangled CV states over larger Hilbert spaces.

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