Continuous Variable Entanglement over Different Degree of Freedom for Entanglement Multiplexing

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ABSTRACT

Continuous variable entanglement is usually set between pairs of optical modes sharing the same geometrical property where distinguishability is demanded to polarization and/or frequency. Thus, the inherent non-local correlation shows-up in quantum quadratures relative to two distinct *e.m.* modes. In this contribution we will show how the polarization d.o.f. of a pair of entangled modes is coupled to the optical orbital angular momentum giving, at the end, a pair of entangled modes that have orthogonal OAM and polarization. We also show how this experimental scheme can be extended to give more than a pair of entangled modes paving the way to CV entanglement multiplexing.

Keywords: quantum information, entangled state generation, quantum characterization, homodyne detectors.

1. INTRODUCTION

Realising multipartite and/or multiple bi-partite entangled states, *i.e.* having entanglement established between many nodes [1] or having at disposal more than one entangled pair at the same time [2], is more than a conceptual challenge. It promises to increase the complexity of feasible quantum communication (QC) tasks.

In Continuous Variable (CV) QC, field quadratures are usually the encoding degrees of freedom (d.o.f) while polarization is used to distinguish the entangled modes. The latter represent a bi-dimensional Hilbert space so that, unless extra d.o.f. are exploited, only a pair of entangled modes at a time can be realised. Usually, in continuous wave (CW) sources, CV bipartite entangled states are efficiently produced by parametric down-conversion in Optical Parametric Oscillators (OPO) working below threshold [3]-[6]. To pave the way to a multi-mode approach a possible implementation is to provide entangled modes to be distinguishable by an additional discrete d.o.f.: the Orbital Angular Momentum (OAM). It spans an infinite-dimensional Hilbert space made of a class of transverse optical modes whose photons have non-zero OAM. These modes co-propagate along the same path intrinsically preserving their distinguishability [7]. Beams carrying OAM are paraxial beams characterized by the presence of an azimuthal angle phase dependence of the form $e^{im\varphi}$. They show helical wavefronts and a phase singularity, where the field vanishes, on the axis. The integer number m represents the topological charge of the vortex and corresponds to the amount of OAM (in unit of ħ [8]) carried by each photon in the beam. In ref. [9] we presented the generation of a Gaussian bipartite CV entangled state carrying OAM. There we endowed the Gaussian bipartite entangled state generated by a standard below-threshold type-II OPO with non-zero OAM. The CV entanglement, established between orthogonally polarized modes, is, then, imprinted between non-zero OAM modes by using a liquid crystal-based optical device commonly known as "q-Plate" (qP) [10]. Afterwards, the state is completely characterized by means of a reconfigurable Homodyne Detector (HD) capable of measuring quadratures relative to helical modes. In this way, we have provided a complete characterization of a multi-distinguishable polarization-OAM CV entangled state.

In this contribution, together with a discussion on the results therein presented, we will show how properly tuning a qP would allow to distribute the initial entanglement among more than a pair of modes. This is possible exploiting the fact that CV quantum correlation does not vanishes even in presence of high losses.

2. THE EXPERIMENT

CV entanglement between two orthogonally polarized TEM_{00} modes is established by means of a triply resonant below-threshold OPO [11]. Then the two linearly polarized beams are converted into circularly polarisation by a QWP and enter the qP whose action on the mode operators is given by

$$\hat{Q}k_{L,m}\hat{Q}^{+} = \cos\frac{\delta}{2}\,k_{L,m} + i\sin\frac{\delta}{2}\,k_{R,m+2q}$$
$$\hat{Q}k_{R,m}\hat{Q}^{+} = \cos\frac{\delta}{2}\,k_{R,m} + i\sin\frac{\delta}{2}\,k_{L,m-2q} \qquad (1)$$

where q is the qP topological charge and δ an experimentally tuning parameter. If $\delta = \pi$ then the qP simply provide the incoming $m = 0$ beams of opposite, $\pm 2q$ OAM value. In this case the beams at its output are still in an entangled state and they got an extra distinguishability d.o.f..

The entanglement manipulation scheme is reported in Fig. 1. A qP sandwiched between two quarter-wave-plates (QWP) allows to endow a pair of cross polarised entangled modes with a second distinguishability d.o.f..

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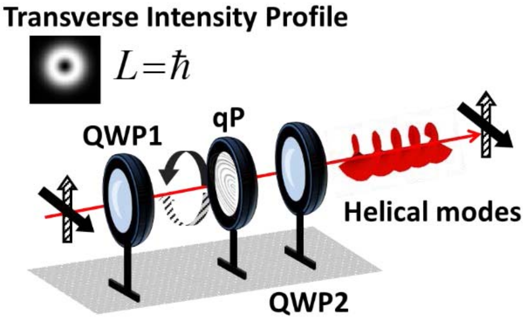

Figure 1. Entanglement manipulation scheme. A tuned q-plate is sandwiched between two quarter-wave-plates (QWPs). This combination of linear optical elements is placed at the ouput of a sub-threshold OPO that generates a pair of othogonally linearly polarised beams. Then, QWP1 transform their polarisation into circular and they enters the tuned q-plate to acquire opposite value of OAM and kleeping their polarization distinguishability.

In Ref. [9] (see therein for more details) we have reported a method for the full characterization of such a doubly distinguishable entangled pair measuring quadrature correlation by an homodyne detector tailored in the OAM space. The state we have measured, whose covariance matrix pictorial view is given in Fig. 2, is still entangled at the end of the process as proved by the use of both Duan and PPS entanglement criteria for Gaussian states.

3. The ***Q-Plate*** for distributing entanglement over more a pair of modes

As seen the qP couples different d.o.f.. If tuned at $\delta = \pi$ (see Eqs. (1)) it act as a beam splitter between two input and two output modes. In a more general view, for $\delta \neq 0$ or π it couples 4 modes at the input with 4 modes at the output. The full quantum version of Eqs. (1) is

$$\hat{Q} k_{L,m} \hat{Q}^{+} = \cos\frac{\delta}{2}\, k_{L,m} + i \sin\frac{\delta}{2}\, k_{R,m+2q}$$

$$\hat{Q} k_{R,m+2q} \hat{Q}^{+} = \cos\frac{\delta}{2}\, k_{L,m} + i \sin\frac{\delta}{2}\, k_{R,m+2q}$$

$$\hat{Q} k_{R,m} \hat{Q}^{+} = \cos\frac{\delta}{2}\, k_{R,m} + i \sin\frac{\delta}{2}\, k_{L,m-2q}$$

$$\hat{Q} k_{L,m-2q} \hat{Q}^{+} = \cos\frac{\delta}{2}\, k_{R,m} + i \sin\frac{\delta}{2}\, k_{L,m-2q}$$

This feature (see Ref. [14] for more details) would allow to distribute the quantum correlation initially shared by a pair of modes, at the OPO output, among four modes that are entangled in pairs. Straight forward calculations show that starting from an entangled pair in the [(L,0),(R,0)] modes ends up with four modes [(L,0),(R,0),(L,-1),(R,+1)] where (L,0) and (R,+1) are in a separable state while they are singularly entangled with (R,0) and (L,-1) and vice-versa. In this way it would be possible to realise a bipartite four-modes entangled state.

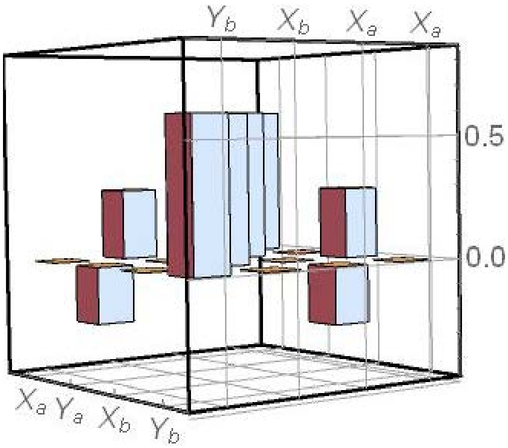

Figure 2. Chart representing the covariance matrix of the entangled state after it passes through the OAM manipulation scheme sketched in Fig. 1. Matrix elements mean values are {0.61,0.61,0.60,0.60} on the diagonal and +0.29 and -0.23 for the out of diagonal ones respectively. The latter are a signature of the quantum correlation established between the two entangled parties.

4. CONCLUSIONS

We have presented the experimental characterization of a bipartite CV entangled state where the carrier modes are vortex beams with non-zero OAM. The state is measured by an OAM reconfigurable single homodyne detector scheme. Moreover, we propose the use of a q-Plate for distributing a bipartite state among four modes pairwise entangled. The resulting state can be used in multi-parties' quantum communication tasks and local operations in quantum Gaussian channel [15].

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