Entangling macroscopic light states via delocalized single photon addition

Nicola Biagi[1,2], Luca S. Costanzo[1,2], Marco Bellini[1,2] and Alessandro Zavatta[1,2]

[1]Istituto Nazionale di Ottica (INO-CNR), L.go E. Fermi 6, 50125 Florence, Italy
[2]LENS and Department of Physics, University of Firenze, 50019 Sesto Fiorentino, Florence, Italy

The coherent addition of a single photon to two distinct field modes, 1 and 2, entangles them. In general, the amount of entanglement produced by the balanced superposition of photon creation operations $\hat{a}_1^\dagger + e^{i\varphi}\hat{a}_2^\dagger$ depends on the states of light already present in the modes. If both are originally in a vacuum state, one simply obtains a single-photon mode-entangled state of the kind [1]

$$|\psi\rangle_{12} = \frac{1}{\sqrt{2}}(|1\rangle_1|0\rangle_2 + e^{i\varphi}|0\rangle_1|1\rangle_2). \qquad (1)$$

If different quantum states originally populate the field modes, the state resulting from delocalized photon addition may present different features. For example, injecting a vacuum and a coherent state in the two input modes give rise to a so-called hybrid discrete/continuous-variable entanglement of the two output modes [2].

Here we study the effect of delocalized single-photon addition on two input modes containing identical coherent states $|\alpha\rangle$, as schematically illustrated in Fig.1.

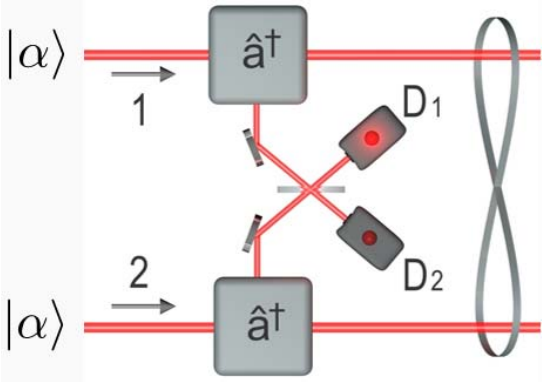

Figure 1: Simplified view of the experimental setup used to perform a coherent single-photon addition on two different input modes, both containing a coherent state $|\alpha\rangle$. A click in a single-photon detector D_1, placed after a balanced beam-splitter mixing the herald modes of two photon-addition modules based on parametric down-conversion, generates entanglement between the two output modes.

It is easy to show that the degree of entanglement of the final state depends on the sign of the superposition and on the amplitude α of the coherent states. In particular, while the entanglement negativity of the even superposition is expected to quickly deteriorate for larger α, the odd state is seen to preserve maximum negativity independently of the amplitude of the input coherent states. Ideally, a high degree of entanglement should thus be maintained even between modes containing macroscopic states.

The odd superposition entangled states

$$|\psi(\alpha)\rangle_{12} = \mathcal{N}(\hat{a}_1^\dagger|\alpha\rangle_1|\alpha\rangle_2 - |\alpha\rangle_1\hat{a}_2^\dagger|\alpha\rangle_2), \qquad (2)$$

where $\mathcal{N}$ is a normalization constant, are therefore a very interesting testbed for studying the robustness and detectability of entanglement for states of growing macroscopicity. It should be noted that this particular superposition is equivalent to the result of an equal phase-space displacement operation $D(\alpha)$ on both modes of a delocalized single-photon state, and its entanglement properties have already been theoretically discussed in Ref.[3].

We experimentally generate states of the form of Eq.2 starting from different coherent state amplitudes α, and perform a quantum tomographic analysis based on data from two-mode homodyne detection. We use the reconstructed density matrices to extract the degree of entanglement of the states (the negativity of the partial transpose) as a function of their 'macroscopicity'. Finally, we compare the experimental results with simulations including the known efficiencies and instabilities.

---

[1] A. Zavatta, M. D'Angelo, V. Parigi, and M. Bellini, Remote preparation of arbitrary time-encoded single-photon ebits, *Phys. Rev. Lett.* **96,** 020502 (2006).

[2] H. Jeong, A. Zavatta, M. Kang, S. Lee, L.S. Costanzo, S. Grandi, T.C. Ralph, and M. Bellini, Generation of hybrid entanglement of light, *Nat. Photon.* **8,** 564 (2014).

[3] P. Sekatski, N. Sangouard, M. Stobińska, F. Bussières, M. Afzelius, and N. Gisin, Proposal for exploring macroscopic entanglement with a single photon and coherent states, *Phys. Rev. A* **86**, 060301(R) (2012).