Transformations of continuous-variable entangled states of light

Ondřej Černotík[1,2,3] and Jaromír Fiurášek[1]

[1]Department of Optics, Palacký University, 17. listopadu 12, 77146 Olomouc, Czech Republic
[2]Institute for Theoretical Physics, Leibniz University Hannover, Appelstraße 2, 30167 Hannover, Germany
[3]Max Planck Institute for Gravitational Physics (Albert Einstein Institute), Callinstraße 38, 30167 Hannover, Germany

Motivation

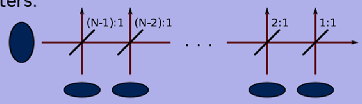
Gaussian states are interesting to both theorists and experimentalists for the ease of their mathematical description and simple experimental manipulation. While very powerful, not everything is known about Gaussian states, e.g., many questions in multipartite entanglement (below, Ref. [1]) are still open. In addition, Gaussian states are not universal. Some tasks, such as entanglement concentration of Gaussian states (right, Ref. [2]) require non-Gaussian operations in order to succeed.

Symmetric Gaussian states

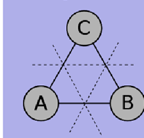
We are interested in transformations of permutation invariant Gaussian states with covariance matrix

$$\gamma = \begin{pmatrix} \nu & \sigma & \dots & \sigma \\ \sigma^T & \nu & \dots & \sigma \\ \vdots & & \ddots & \vdots \\ \sigma^T & \dots & \sigma^T & \nu \end{pmatrix}.$$

Moreover, we assume cannonical form, such that Such states can be prepared using thermal squeezed states and beam splitters.



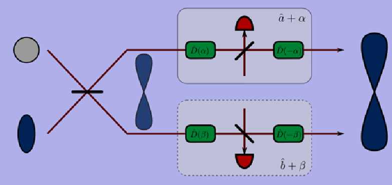
Tripartite Gaussian entanglement



There are three possible bipartitions of tripartite states. From separability properties of these bipartitions, five entanglement classes exist, three of which are relevant for symmetric states [3]. The states can be fully separable, bound entangled or fully entangled.

Displacement enhanced continuous-variable entanglement concentration

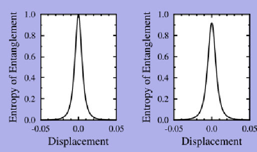
Entanglement concentration with Gaussian states requires non-Gaussian operations (e.g., photon addition or photon subtraction). Gaussian operations can, however, improve entanglement concentration based on photon subtraction [5, 6]. Here, we study entanglement concentration of split single mode squeezed states by photon subtraction enhanced by coherent displacements.



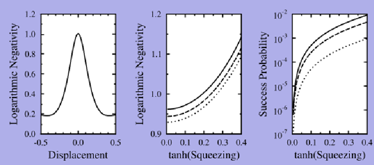
$$|\psi_{\rm in}\rangle \propto \sum_{n=0}^{\infty}\sum_{k=0}^{2n}\frac{\lambda^n}{2^n n!}\frac{(2n)!t^{2n-k}r^k}{\sqrt{k!(2n-k)!}}|2n-k,k\rangle$$

Single mode subtraction

In the weak squeezing limit (considering only vacuum and two-photon contributions), the filtered state is $\lambda t(t|10\rangle + r|01\rangle) + \alpha|\psi_{\rm in}\rangle$, giving maximally entangled state $|10\rangle + |01\rangle$ for zero displacement and a balanced beam splitter.

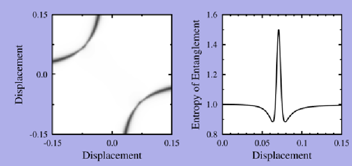


With arbitrary squeezing, we consider a realistic scenario with single-photon detectors with limited detection efficiency and finite transmittance of tap-off beam splitters. For single-mode subtraction, zero displacement is optimal.

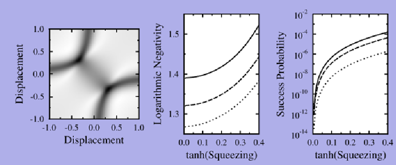


Two mode subtraction

With two-mode filtration, the first displacement is used to eliminate dominant vacuum contribution (dark hyperbole in the left figure). The second displacement is used to eliminate single-photon terms, leading to the state $\sqrt{2}rt|11\rangle + t^2|20\rangle + r^2|02\rangle$.



For two-mode subtraction, the behaviour is similar as in the weak-squeezing regime. The optimal output entanglement is about 0.5 ebit higher than with a single photon subtraction.

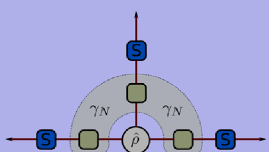


Conclusions

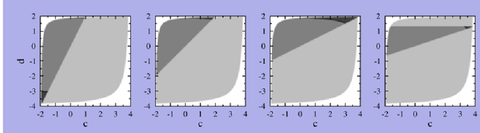
While for single-mode photon subtraction coherent displacement do not provide any improvement, with photon subtraction on both modes, they can lead to an increase in entanglement of the output state. In addition, the effect of state transmission through a lossy channel can be studied [7]. Finally, it can be shown that the resulting entanglement is strictly non-Gaussian, in contrast to the same protocol with two mode squeezed vacuum [7].

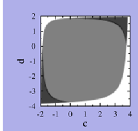
Transformations of symmetric multipartite Gaussian states by Gaussian LOCC

Correlated noise addition



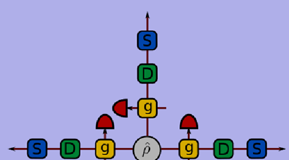
One option of transforming symmetric Gaussian states uses adding correlated noise to one quadrature and subsequent squeezing.



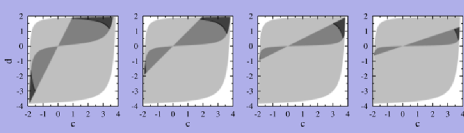


Transformations of entanglement classes are studied for several ratios of quadrature correlations [from left to right, $(n/m, d/c) = (1,2), (1,1), (2,1), (3,1)$]; cf. with classification of input states (right).

Partial non-demolition measurement



Second strategy is based on partial QND measurement, followed by a conditional displacement and squeezing.



With the QND strategy, it appears that entanglement classification is preserved for every input state. In addition, a wider set of entangled states can be transformed using this protocol, making it more universal.

Assisted quantum teleportation

In addition to mere entanglement classification, we are interested in a more qualitative characterisation of entanglement. To this end, we use fidelity of assisted quantum teleportation [4] as a figure of merit. It can be shown [1] that adding correlated noise does not affect the fidelity and squeezing alone determines the fidelity for the first strategy. On the other hand, with partial QND measurement, our numerical calculations suggest that no improvement in teleportation fidelity can be achieved.

References

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