Displacement-enhanced continuous-variable entanglement concentration

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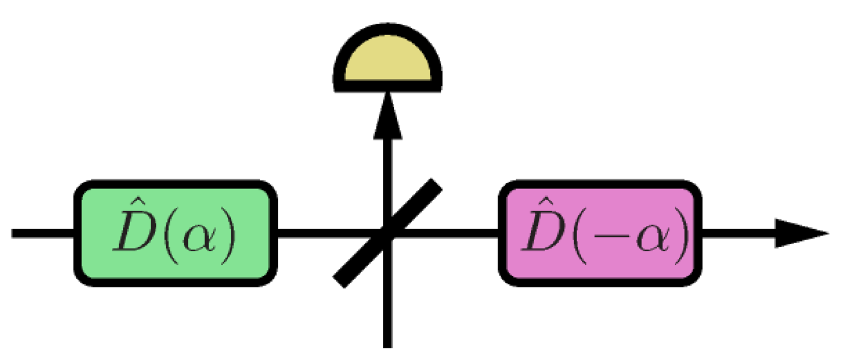
Introduction

Gaussian states and transformations represent an interesting counterpart to two-level photonic systems, due to both efficient theoretical description and easy experimental manipulation. Gaussian operations are not, however, sufficient to distill Gaussian entanglement and a non-Gaussian operation, such as photon subtraction, is required [1]. Gaussian operations can, nevertheless, enhance entanglement concentration based on photon subtraction [2, 3]. Here, we investigate enhancing entanglement concentration based on photon subtraction by coherent displacements [4]. The input state we consider is obtained by mixing a single-mode squeezed vacuum state mixed with vacuum on a beam splitter, making the protocol experimentally more feasible than using two-mode squeezed vacuum state.

The protocol

Photon subtraction can be achieved by reflecting a small part of the incoming light onto a single photon detector whose click heralds a successful subtraction. In our protocol, photon subtraction is combined with two displacements, $\hat{D}(\alpha)$, $\hat{D}(-\alpha)$, leading to the operation $\hat{F} = \hat{a} + \alpha$.

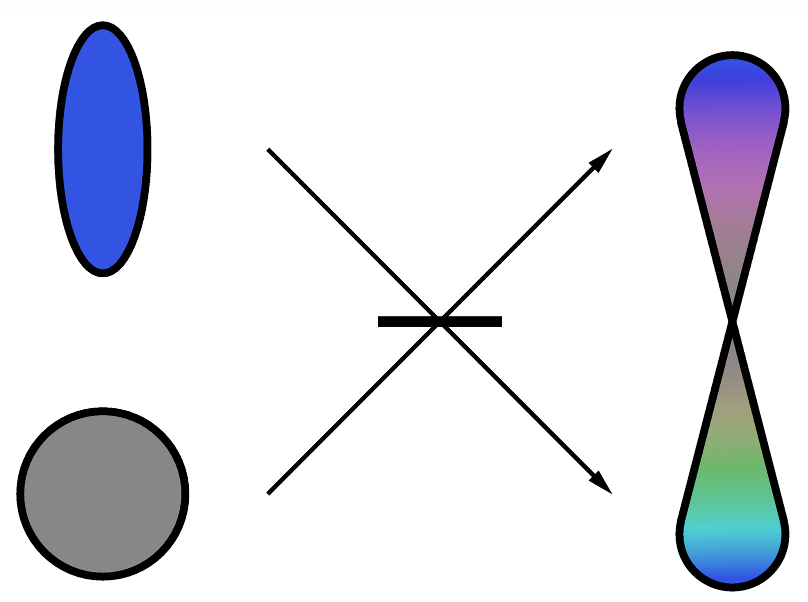


The filter can be applied to only one of the modes, leading to the operation $\hat{F}_1 = (\hat{a} + \alpha) \otimes \hat{\mathbb{I}}_B$, which is experimentally easier. Alternatively, displacement-enhanced photon subtraction can be performed on both modes, resulting in the operation $\hat{F}_2 = (\hat{a} + \alpha) \otimes (\hat{b} + \beta)$, which brings another degree of freedom for protocol optimization.

Input state

As input, we consider split single-mode squeezed vacuum, i.e., single-mode squeezed vacuum state mixed with vacuum on a beam splitter which is easier to prepare experimentally than two-mode squeezed vacuum,

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



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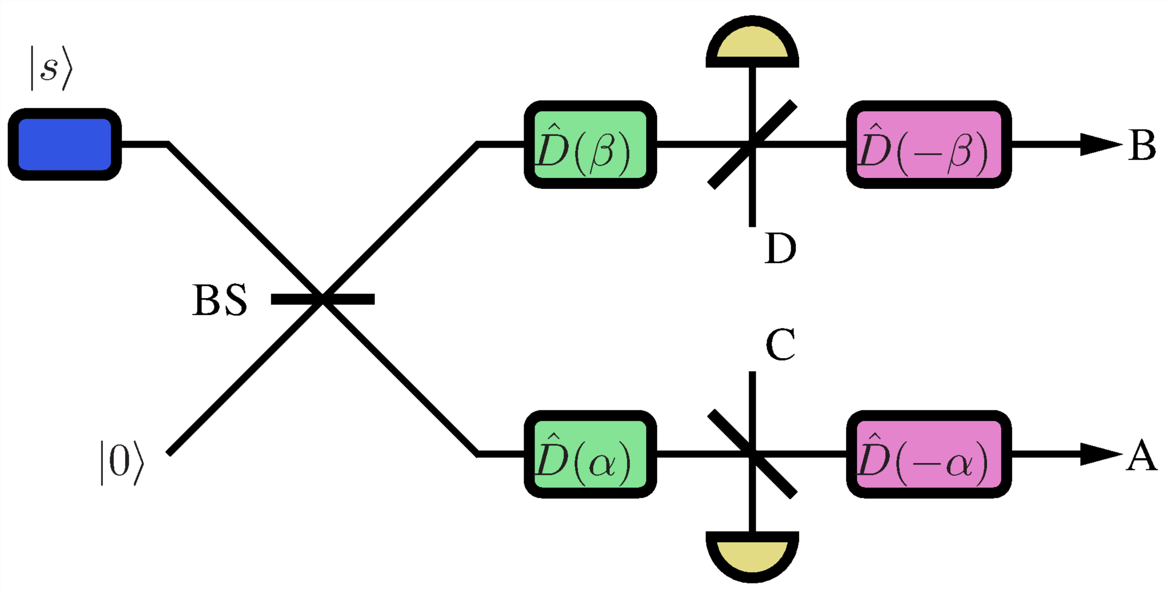
Entanglement concentration



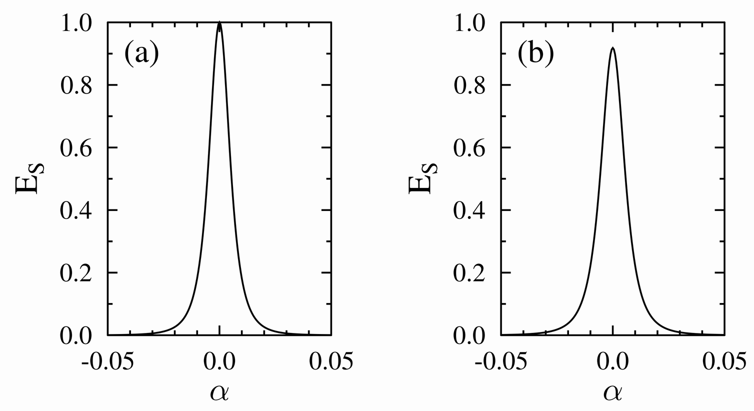
We analyze the protocol in two different regimes. In the weak-squeezing approximation, only vacuum and two-photon contributions are considered, $|\psi_{\rm in}\rangle \approx |00\rangle + \lambda rt|11\rangle + \lambda(t^2|20\rangle + r^2|02\rangle)/\sqrt{2}$, and it can be seen how destructive quantum interference can lead to an enhancement of entanglement. Assuming arbitrary input squeezing, we consider a realistic scenario with binary single-photon detectors with limited detection efficiency and limited transmittance of tap-off beam splitters. For details, see Ref. [4].

Single-mode subtraction

For single-mode subtraction in the weak-squeezing regime, the output state reads

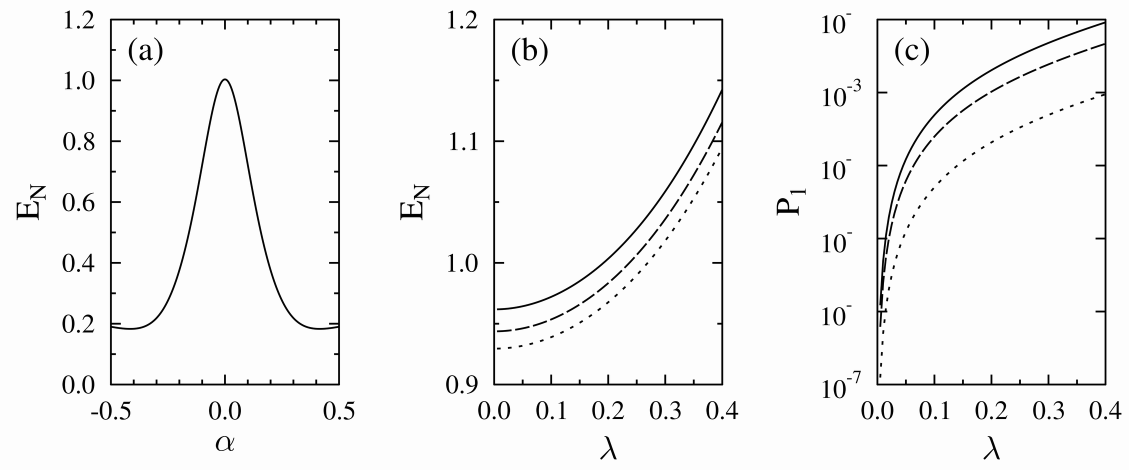
$$|\psi_1\rangle = \lambda t(t|10\rangle + r|01\rangle) + \alpha|\psi_{\rm in}\rangle.$$

The best choice is to use a balanced beam splitter together with no displacement as this gives the Bell state $(|01\rangle + |10\rangle)/\sqrt{2}$.



Single-mode subtraction

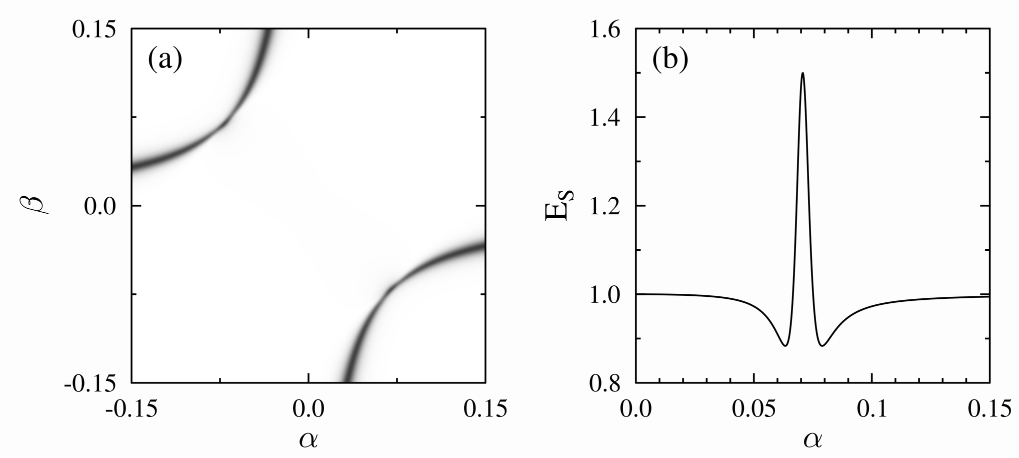
In a realistic scenario with photon subtraction and displacements on one mode, zero displacement is optimal (a). While logarithmic negativity is not affected much by the input squeezing (b), success probability grows rapidly with increased squeezing (c).



Two-mode subtraction

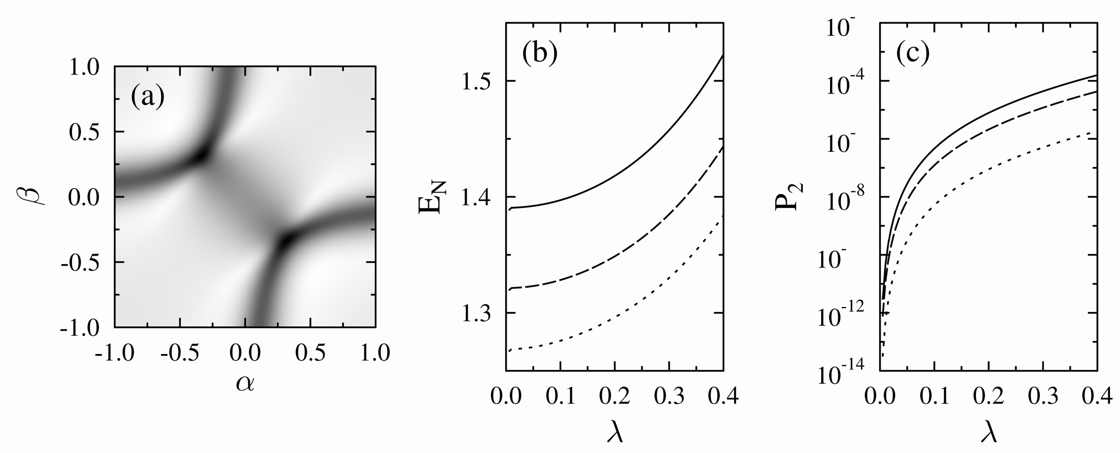
With photon subtraction on both modes, destructive quantum interference leads to an enhancement of entanglement. Choosing $\alpha\beta = -\lambda rt$ [dark hyperbole in (a)], one can eliminate the dominant vacuum term. One-photon terms can be eliminated by choosing $\alpha = \sqrt{\lambda}t$, $\beta = -\sqrt{\lambda}r$, resulting in a two-qutrit state (b)

$$|\psi_2\rangle = \sqrt{2}rt|11\rangle + t^2|20\rangle + r^2|02\rangle.$$



Two-mode subtraction

With photon subtraction performed on both modes, the results are similar to the weak squeezing limit (a). We get about 0.4-0.5 ebit of entanglement more than with single-mode subtraction (b). The cost for this is smaller success probability (c) which is further reduced by limited detection efficiency. This is the main drawback of the two-mode subtraction strategy compared to the one-mode subtraction protocol.



Conclusions and extensions

We studied entanglement concentration of split single-mode squeezed vacuum states by photon subtraction and local displacements. In the weak-squeezing limit, we can see the core of the protocol, destructive quantum interference of dominant terms, while with arbitrary squeezing, we analyze a realistic experimental scenario. While with single-mode photon subtraction, local displacements do not constitute an advantage, subtraction from both modes can be largely improved by displacmenets. While we considered only pure input states, the effect of loss can be also investigated [5]. It turns out that local displacements improve entanglement concentration only for small values of loss and after a certain threshold loss, depending on the input squeezing, simple photon subtraction from both modes is optimal.

References

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[5] A. Tipsmark, J. S. Neergaard-Nielsen, and U. L. Andersen, *Opt. Express* **21**, 6670 (2013).