The entangling power of a beamsplitter

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A beamsplitter (BS) is frequently used as a continuous-variable entangler, however a BS is passive and can only create entanglement from a squeezed Gaussian state. Here we demonstrate experimentally that a BS can create entanglement even from modes which do not possess such squeezing, provided that they are correlated to, but not necessarily entangled with, a third mode.

We demonstrate the entangling power of a BS on two protocols depicted in Fig. 1. In the first protocol, mode C is a vacuum state, whereas in the second, it is a squeezed state. In both protocols the initial squeezing is destroyed by modulation of the squeezed quadratures. This modulation is accompanied by modulation of an additional mode B that is correlated to the modulations applied to modes A and C. This creates a fully separable, but correlated, three-mode state prior to the BS. The BS then acts on modes A and C, which creates a two-mode separable state at the outputs since modes A and C are unsqueezed. However, including mode B, the full three-mode state possesses entanglement.

The experimental implementation is realised using Stokes observables and measurements. All the involved modes are created with a soliton laser (Origami, Onefive, center wavelength: 1559 nm, pulse length: 200 fs, repetition rate: 80 MHz). The individual pulses are squeezed using the non-linear Kerr-effect of both axes of a polarization maintaining single mode fiber (FS-PM-7811, Thorlabs, 13 m). This initial squeezing is destroyed by modulation in the direction of the squeezed quadrature. This is done by first applying a sinusoidal voltage (frequency: 18.2 MHz) to an electro-optical modulator (EOM), which slightly modulates the state of polarization. After measurement, the results from different displaced modes are digitally mixed, leading to a mixed Gaussian state. Modes A and C are then combined on a BS and the covariance matrix (CM) of the three-mode state is measured with Stokes measurements.

The measured CM is called $\gamma_{1(2)}$ for the first (second) protocol. $\gamma_{1,2}$ are then used to determine the three-mode separability properties of the final states. The results are presented in Table I, where a negative minimum eigenvalue indicates entanglement across that splitting. For the first protocol, the table shows that the BS has created entanglement across the $A|BC$ and $C|AB$ splittings, whereas the state is separable across the $B|AC$ splitting. However, modes A and C are still separable from each other as required. For the second protocol, the state is entangled across the $A|BC$ splitting, but separable for any other partition.

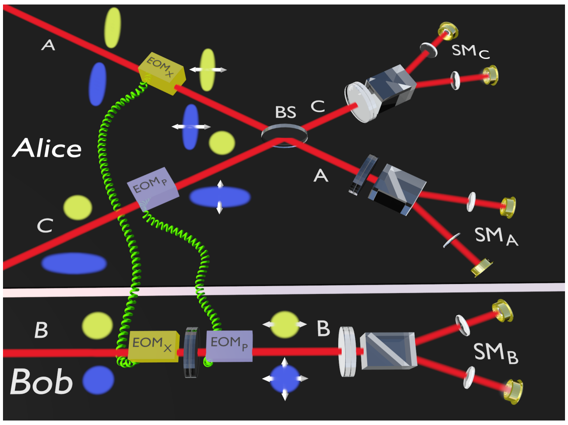

FIG. 1: Experimental scheme. EOM$_i$: electro-optical modulator displacing quadrature i, BS: balanced beam splitter, SM$_j$: Stokes measurement on mode j. The upper yellow (lower blue) circles and ellipses represent the states of protocol 1 (2).

TABLE I: Minimum eigenvalue $\lambda_k^{(T_j)} := \min[\mathrm{eig}(\boldsymbol{\gamma}_k^{(T_j)} + i\boldsymbol{\Omega}_3)]$.

j	A	B	C
$\lambda_1^{(T_j)} \times 10^2$	-2.2 ± 0.1	6.9 ± 0.1	-2.2 ± 0.1
$\lambda_2^{(T_j)} \times 10$	-1.44 ± 0.01	5.28 ± 0.03	3.51 ± 0.02

We have demonstrated two protocols where a BS can create entanglement from unsqueezed modes, provided that the modes are part of a suitable three-mode system. The two protocols differ only in the preparation of the initial states. The created entanglement does not occur between the output modes of the BS but instead it emerges between one output mode and the remaining two modes taken together. This phenomenon is a key element of the protocols for entanglement sharing [1] and entanglement distribution [2] with separable states.

Finally, we have shown that the states created after the BS can be used for a collaborative dense coding scheme similar to that in [3]. Therefore the entanglement created by the BS has a practical use for quantum communication.

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