Interference of two intense entanglement sources:
continuous variable entanglement swapping and multi-partite entanglement

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Quantum entanglement is the basic resource for quantum communication and networking applications. By using continuous quantum variables of intense beams one can take advantage of efficient controllable sources and detectors. An important protocol is entanglement swapping, i. e. the teleportation of entanglement with continuous variables. Furthermore, for more complex applications in the field of quantum networking, such as quantum secret sharing or telecloning, multi-partite entanglement is necessary. A first experiment towards entanglement swapping is reported here. In the progress of this experiment we showed that by the interference of two entangled systems 4 highly correlated modes can be created. As preliminary theoretical calculations suggest, the state of the whole 4-beam system is indeed multi-partite entangled [1].
The basic ingredient for entanglement swapping is the generation of two pairs of entangled beams. The generation process utilizes the non-linear Kerr effect in an optical fibre for the creation of squeezing. In an asymmetric fibre Sagnac interferometer (non-linear optical loop mirror NOLM) two orthogonally polarized amplitude squeezed beams can be generated. Two squeezed beams are used to produce entanglement [2]. Using two separate NOLMs, two pairs of entangled beams are created. For an entanglement swapping experiment it is necessary to interfere one beam of each entangled system with another one from the other system, here labeled EPR 2 and EPR 3 (see fig. 1). The Bell state measurement can be performed in direct detection without local oscillator and is completed by detecting the two resulting output modes. The sum and difference of the signals measured at the output ports of the beam splitter should then be used to modulate amplitude and phase of one of the remaining beams, here EPR 4. After that, beams OUT 1 and OUT 2 can be checked for correlations to verify the success of the entanglement swapping process.

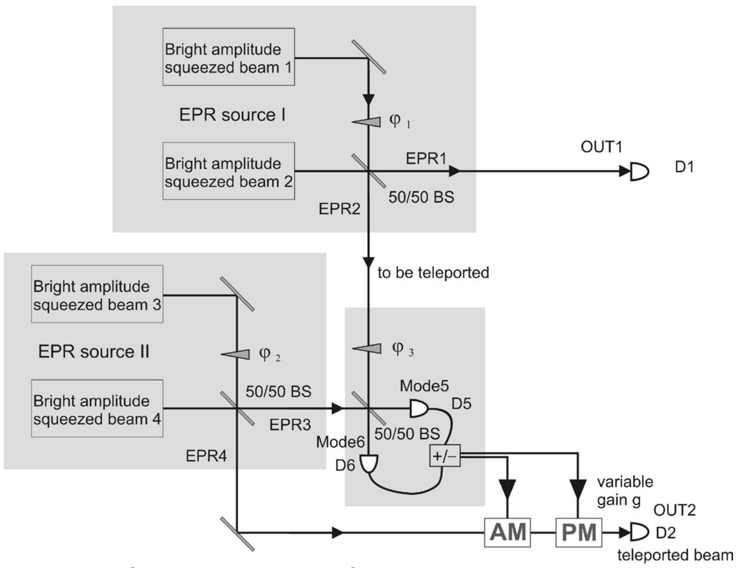

Fig. 1. Left: Experimental setup for continuous variable entaglement swapping

We achieved interference between EPR 2 and EPR 3 with a visibility of more than 80%. As a first step towards entanglement swapping, we performed a direct analysis of the photocurrents imposing the result of the amplitude Bell measurement on EPR 4 not optically but electronically. We checked for correlations in the amplitude quadrature created by the entanglement swapping process. The amplitude correlations between the photocurrents of D1 and (D2+D5+D6) are detected. The relative variance of the sum photocurrent ($i1+(i4+i_{Bell})$) of all modes (D1+D2+D5+D6) was at the level of the shot noise of two beams (see figure 2).

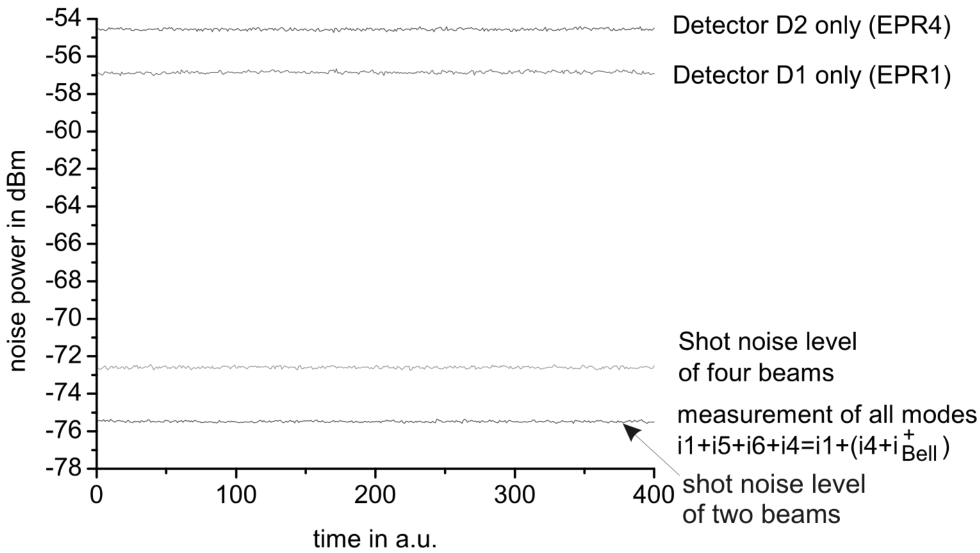

Fig. 2:Experimental results verifying the swapping of amplitude correlations after the Bell measurement and the generation of the 4-fold quantum correlations prior to it. The sum signal of all 4 modes accidentally coincedes with the shot noise level of two beams.

Thus, the correlations between EPR 1 and EPR 2 and the sum Bell signal from Mode 5 and Mode 6 are 1.77dB below the level that is expected by a classical teleportation of EPR 2, where two units of extra vacuum have to be taken into account, similar to the argumentation by Furusawa [3]. This is the first hint that successful teleportation of a highly nonclassical state in continuous variables is possible. The full proof of entanglement swapping needs also the characterization of the phase quadrature, thus taking into account the difference Bell measurement from Mode 5 and Mode 6.
The obtained results are also interesting in the context of multipartite entanglement. The four mode state (EPR 1, EPR 4, Mode 5 and Mode 6) created by the interference of entangled sources exhibits strong quantum correlations. The sum signal of those modes is 3dB below the shot noise level of four equally bright coherent beams. All other possible measurement combinations of the four modes result in high excess noise. The generated 4-mode state exhibits clear multipartite quantum correlations. To prove a four fold entanglement experimentally, homodyne detection techniques are necessary as proposed in Ref. [4] where conditions similar to the Duan criterion are derived. However, those criteria cannot be readily be applied to intense beams due to detector saturation and simple criteria to prove multi-partite entanglement in direct detection are still missing. Neverthless, it was shown that for pure input states, the Wigner function of the generated four-mode state cannot be written as a product state[1], thus indicating that indeed an four-partite entanglement was produced.

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[3] A. Furusawa, J. L. Sorensen, S. L. Braunstein, C. A. Fuchs, H. J. Kimble, E. S. Polzik, Science **282**, 706, (1998)

[4] P. van Loock and A. Furusawa, quant-ph/0212052v1