



## Continuous Variable Entanglement of Orbital Angular Momentum States

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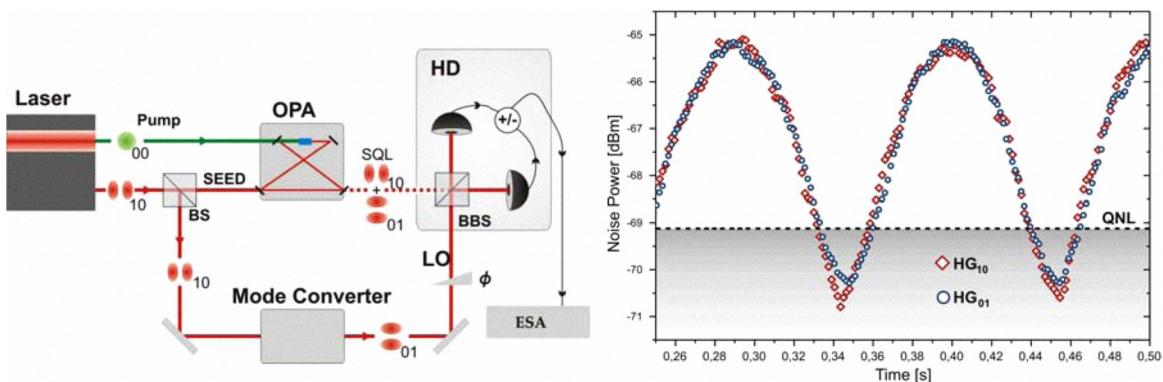
# Continuous Variable Entanglement of Orbital Angular Momentum States

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The simplest spatial mode that can carry orbital angular momentum (OAM) is the first order Laguerre-Gaussian (LG) mode which produce either a left-handed or right-handed corkscrew-like phase front and a ring-like intensity profile. In this contribution we present quadrature entanglement between the two first-order LG modes thereby demonstrating a new type of entanglement from non-degenerate OPOs. The entanglement is manifested in the squeezing of the rotated modes in the Hermite-Gauss (HG) basis, measured with a specially tailored local oscillator.

The most promising application of CV OAM states is their compatibility with atoms, thus allowing for storage of CV quantum information [1].



**Fig. 1** Schematics of the experimental setup to generate amplitude squeezing. Experimental squeezing traces for the HG<sub>01</sub> and HG<sub>10</sub> modes, where the relative phase between the local oscillator and the squeezed beam is scanned. The traces are recorded with an ESA. Resolution bandwidth of 300 kHz and a video bandwidth of 300 Hz at a detection frequency of 5.5 MHz. BBS: Balanced beam splitter (50/50 BS). PBS: Polarizing beam splitter. HWP: ( $\lambda/2$ ) Half-wave plate. QWP: ( $\lambda/4$ ) Quarter-wave plate.

Our OPO consist of a type I phase-matched nonlinear PPKTP crystal in a mode-stable optical cavity, where the polarization, the frequency and the spatial degree of freedom are usually degenerate, which lead to single mode quadrature squeezing as demonstrated by various groups. By optimizing the cavity resonance frequency it is possible to generate the two first order modes simultaneously. This is due to their frequency degeneracy (arising from their identical Gouy phase shifts). This has the consequence that the down-converted signal and idler photons are produced in two distinct orthogonal spatial modes (namely the OAM modes, LG<sup>+1</sup> and LG<sup>-1</sup>), thus quadrature entanglement is generated between these two modes similarly to the production of entanglement between polarization modes.

Therefore to proof the existence of quadrature entanglement between the two LG modes, we measure the quadrature quantum noise of the spatial modes in a rotated basis composed of the first order HG modes, HG<sub>10</sub> and HG<sub>01</sub> [2]. The noise traces for the HG<sub>10</sub> and HG<sub>01</sub> modes, while the phase of the local oscillator is scanned, are depicted in Fig. 1. We measure amplitude quadrature squeezing of -1.6 dB and -1.4 dB for the HG<sub>10</sub> and HG<sub>01</sub> mode, respectively (corresponding to the minima of the squeezing traces). Inserting these values into the entanglement criterion we find [2]:  $V(HG_{10}) + V(HG_{01}) = 1.42 < 2$ .

We thus have shown that the spatially non-degenerate OPO produces quadrature entanglement between the first order OAM modes.

In conclusion, we have generated a new quantum state of light composed of quadrature entangled LG modes. For the generation we used an OPO operating in a new regime where all field parameters are degenerate except for its spatial degree of freedom for which it is two-fold degenerate.

## References

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