— Supplementary Material —
Reduction of Classical Measurement Noise via Quantum-Dense Metrology

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QUANTUM-DENSE METROLOGY

Here we give a brief review of quantum-dense metrology and explain how this technology gave us simultaneous access to two orthogonal quadratures of the signal with sub shot-noise sensitivity without violating Heisenberg's uncertainty relation.

Referring to Figure 1, let us assume the following setup. We send orthogonally squeezed vacuum fields into the two input ports of a Mach-Zehnder interferometer with symmetric beam splitters. If we keep the phase inside the interferometer the same for both paths, then the second beam splitter exactly undoes the action of the first beam splitter, and we re-obtain the two orthogonally squeezed fields in the two output ports at balanced-homodyne detectors BHD 1 and 2. To be in line with our experiment, we further assume that the initial squeezed states are aligned such that BHD1 receives a phase-squeezed state, while BHD2 receives an amplitude-squeezed state.

In a second step, we modulate an arbitrary signal $\varphi(t)$ onto the field in one arm of the interferometer. Half of the signal power reaches BHD1, which can now perform a phase quadrature measurement on this part, while the other half of the signal reaches BHD2, which can simultaneously perform an amplitude quadrature measurement. As the quantum noise at BHDs 1 and 2 is phase- and amplitude-squeezed, respectively, both detectors can perform their individual measurements with sub-shot noise sensitivity. For squeezing levels exceeding 3 dB, the loss of signal power is compensated (but see the main text for an improvement of this situation in the presence of optical loss).

While this simultaneous sub-shot noise measurement of two orthogonal quadratures might appear to contradict Heisenberg's uncertainty relation, this description makes it clear that this is not the case. The measurements of the amplitude and phase quadratures are performed on two separate (and indeed separable) states.

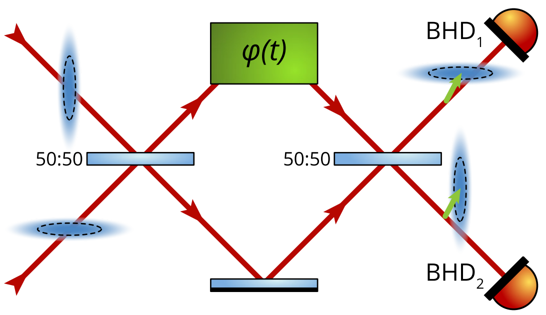

Figure 1: Simultaneous sub shot-noise readout of two orthogonal quadratures of light. Two orthogonally squeezed states of light are sent into the two input ports of a Mach-Zehnder interferometer. A signal $\varphi(t)$ is modulated onto the field in one arm. After recombination, the squeezed fields are re-obtained in the two output ports, each displaced by half the signal power (indicated by the green arrows), and allow for reading out the respective signal quadrature with sub shot-noise accuracy.