Universidade de Aveiro
2017-2018

Quantum Noise

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Quantum Noise

Quantum noise is an intrinsic property of light, it is a manifestation of the fluctuations of the quantum vacuum field.

The objective of this work is to model quantum noise in a double homodyne detection system and validate the numerical model with experimental data.

Quantum Noise - Theoretical Introduction

A Coherent states can be defined in the number state basis $\{|n\rangle\}$ as

$$|\alpha\rangle = e^{-\frac{|\alpha|^2}{2}} \sum_{n=0}^{\infty} \frac{\alpha^n}{\sqrt{n!}} |n\rangle$$

in which the complex number $\alpha = |\alpha|^{i\theta_\alpha}$ is the sole parameter that defines it. The parameter $|\alpha|$ is equal to square root of the number of photons and θ_α is the signal's phase difference to a reference oscillator.

A number state $|n\rangle$ has exactly n photons. The action of the creation $\hat{a}^\dagger$ and annihilation $\hat{a}$ operators are

$$\hat{a}\,|n\rangle = \sqrt{n}\,|n-1\rangle \qquad \hat{a}^\dagger\,|n\rangle = \sqrt{n+1}\,|n+1\rangle$$

$$\hat{n}\,|n\rangle = n\,|n\rangle$$

in which $\hat{n} = \hat{a}^\dagger \hat{a}$, is the number operator.

Quantum Noise - Theoretical Introduction

The measurement of quadratures is based in the quantum operators $\hat{X} = \frac{1}{2}\left(\hat{a}^{\dagger} + \hat{a}\right)$ and $\hat{Y} = \frac{i}{2}\left(\hat{a}^{\dagger} - \hat{a}\right)$, which have the expected values

$$\langle\alpha|\hat{X}|\alpha\rangle = \mathrm{Re}(\alpha), \qquad \langle\alpha|\hat{Y}|\alpha\rangle = \mathrm{Im}(\alpha)$$

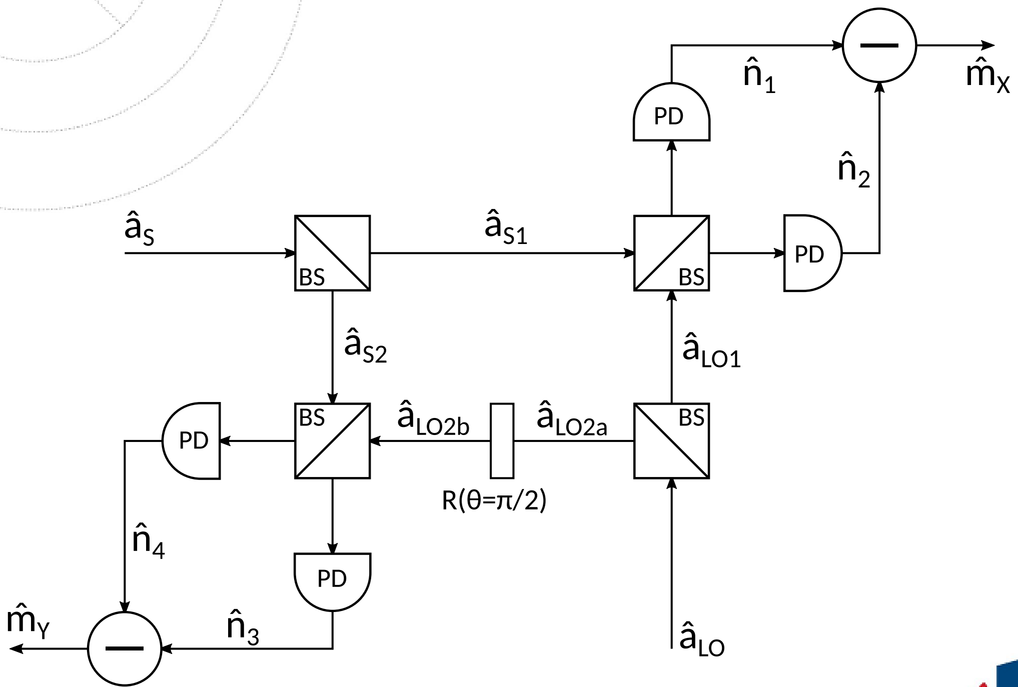
and a variance

$$\mathrm{Var}(\hat{X}) = \mathrm{Var}(\hat{Y}) = \frac{1}{4}$$

This result shows that for both quadratures, the variance of measurement is the same and independent of the value of α.

Homodyne Detection

The simultaneous measurement of the X and Y quadratures can be made by the double balanced homodyne technique. The quantum description of the detection is described by the following diagram



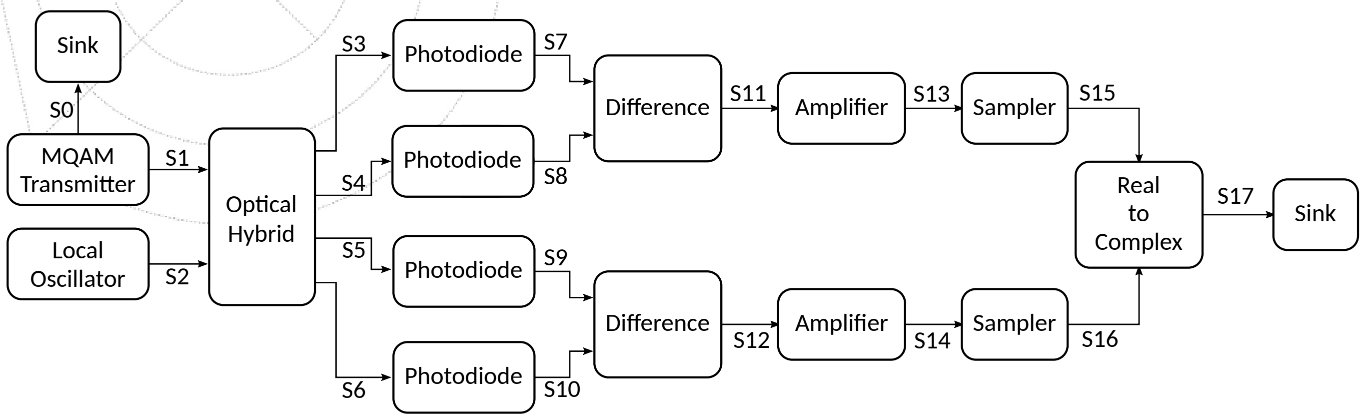
Double Homodyne Detection

One of the beams is measures in-phase with the local oscillator, and the other is measured with a phase difference of $\pi/2$ relative to the local oscillator. Given the input signal state $|\alpha\rangle$, the expected values of $\hat{m}_X$ and $\hat{m}_Y$ in shot noise units will be

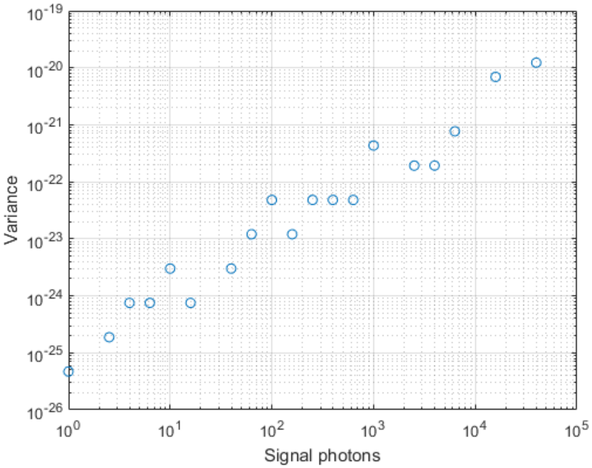
$$\langle \hat{m}_X \rangle = \left|\frac{\alpha}{\sqrt{2}}\right| \cos(\theta_\alpha), \qquad \mathrm{Var}(\hat{m}_X) = \frac{1}{4}$$

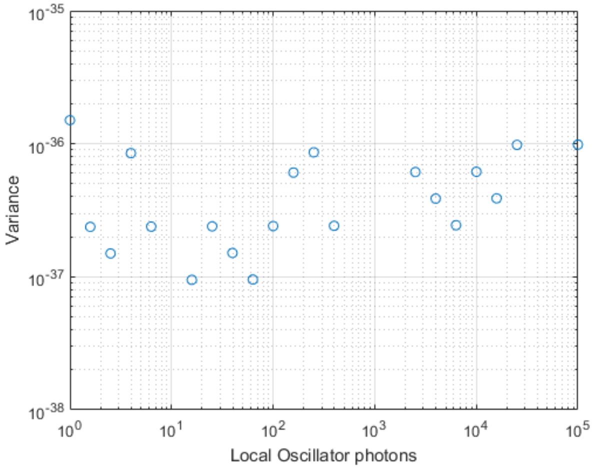
$$\langle \hat{m}_Y \rangle = \left|\frac{\alpha}{\sqrt{2}}\right| \sin(\theta_\alpha), \qquad \mathrm{Var}(\hat{m}_Y) = \frac{1}{4}$$

Simulation setup



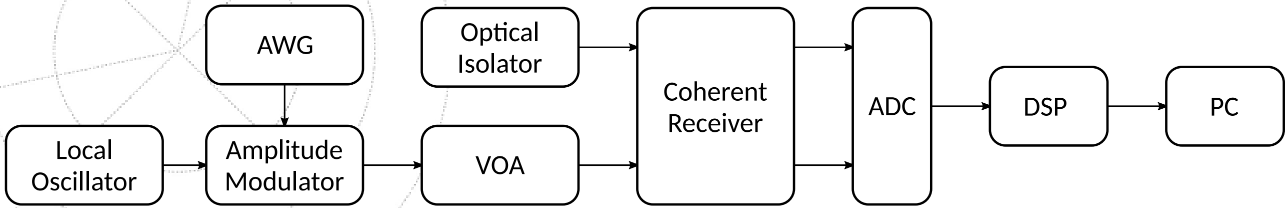
Simulation results - REVIEW





These plots show the variance of $\hat{m}$ in function of signal power (left) and local oscillator power (right). Given that there is no implementation of noise, these plots show only fluctuations of numerical errors. We see that these values are very close to 0.

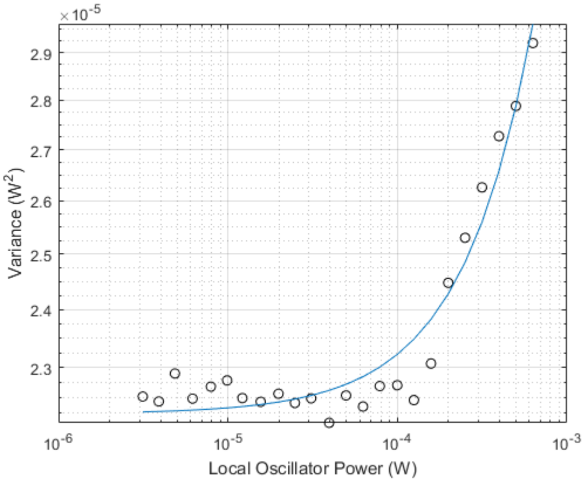
Experimental setup

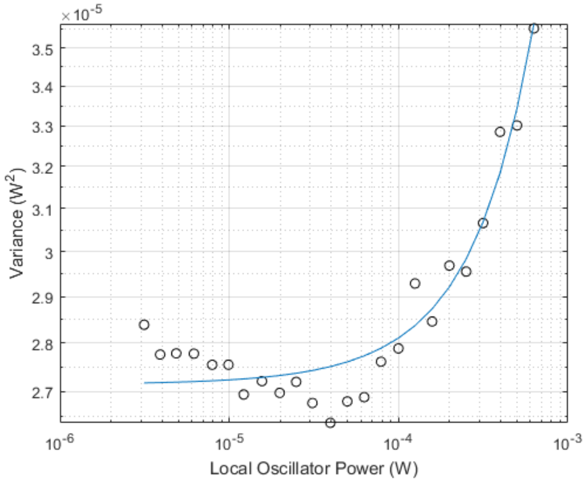


A signal is produced by modulating and attenuating a laser beam. This signal and a vacuum signal are used as the inputs of the Coherent Receiver, which outputs two voltages, proportional to each quadrature of the double homodyne detection.

Reference: Yuemeng Chi, L Tian, B Qi, L Qian, and HK Lo. High speed homodyne detector for gaussian-modulated coherent-state quantum key distribution. University of Toronto, 2009.

Experimental results





These plots of the variance of the quadratures, X and Y, show a constant value for low power of LO, and a growth proportional to the square of the power of LO for higher power. This is not in conformity with the theory and can be attributed to the noise generated by the electronic devices.

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