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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

~~The studied communication system is based on the transmission of coherent states.~~ 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 α is the sole parameter that characterizes it.

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 following quantum operators:

$$\hat{X} = \frac{1}{2}\left(\hat{a}^{\dagger} + \hat{a}\right), \qquad \hat{Y} = \frac{i}{2}\left(\hat{a}^{\dagger} - \hat{a}\right)$$

In fact, the expected value of this two operators are:

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

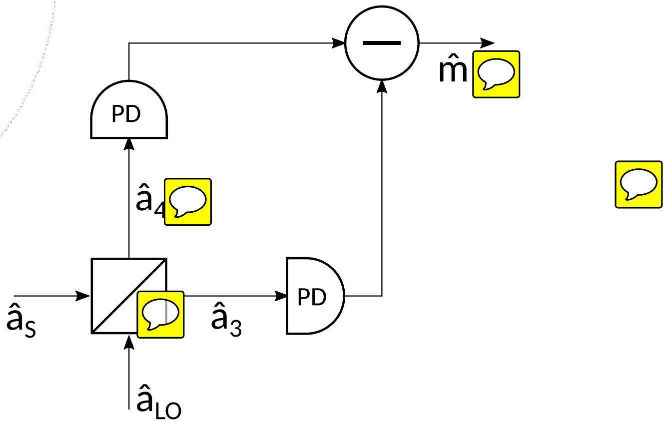
And the variance is

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

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

Homodyne Detection

The measurement of quadratures is made by the homodyne technique. The quantum description of the detection is described by the following diagram



This technique basically measures the phase difference between a input signal (S) and a local oscillator (LO). The figure shows the quantum mechanical description of this technique, based in annhihilation operators, in which $\hat{m}$ is the operator of the output difference between the photocurrents.

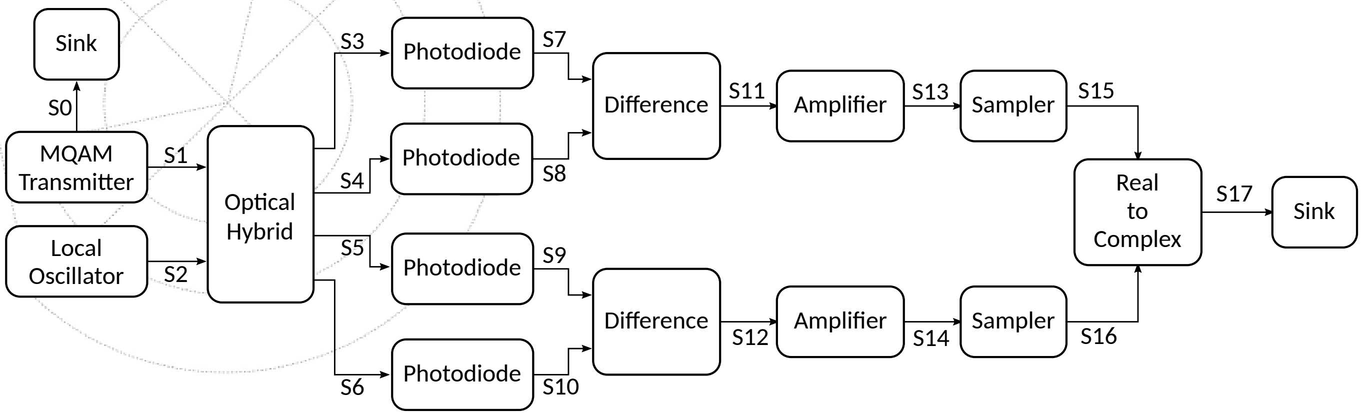
Double Homodyne Detection

The used technique is the double homodyne technique which starts by dividing S in two beams of equal power. One 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 $|\alpha\rangle$ ($\alpha = |\alpha|e^{i\theta_\alpha}$) and the local oscillator state $|\beta\rangle$ ($\beta = |\beta|e^{i\theta_\beta}$), the expected value for the two quadratures operators $\hat{m}_X$ and $\hat{m}_Y$ is

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

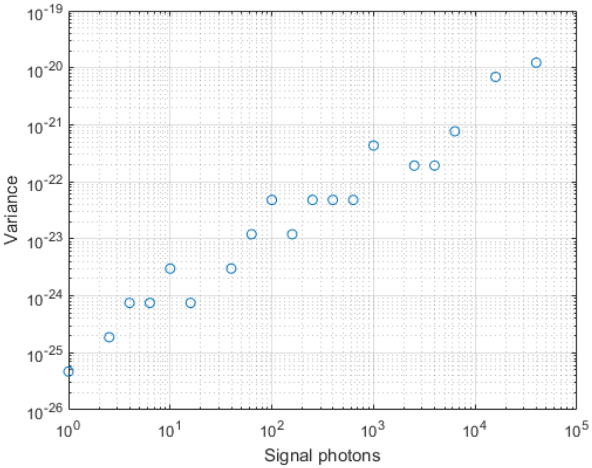
$$\langle \hat{m}_Y \rangle = \left| \frac{\alpha}{\sqrt{2}} \right| \sin(\theta_\alpha - \theta_\beta), \qquad \mathrm{Var}(\hat{m}_Y) \approx \frac{1}{4}$$

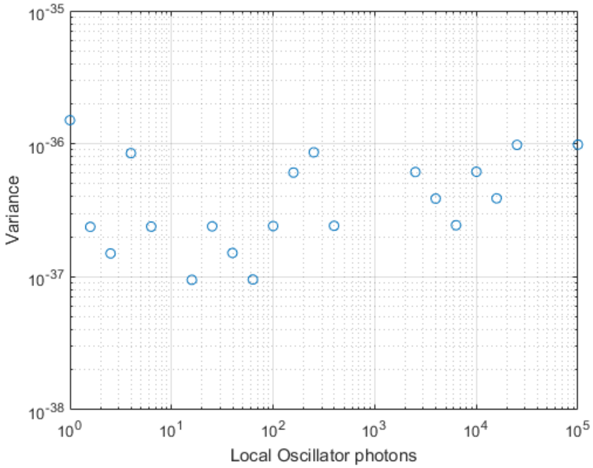
Simulation setup



A state is generated in the MQAM which is then mixed in the Optical hybrid with a local oscillator. The 2 pairs of output optical signals are then converted to photocurrents. The difference between the currents of each pair is obtained and then sampled. Finally the two signals are combined in a complex number which will be the final output.

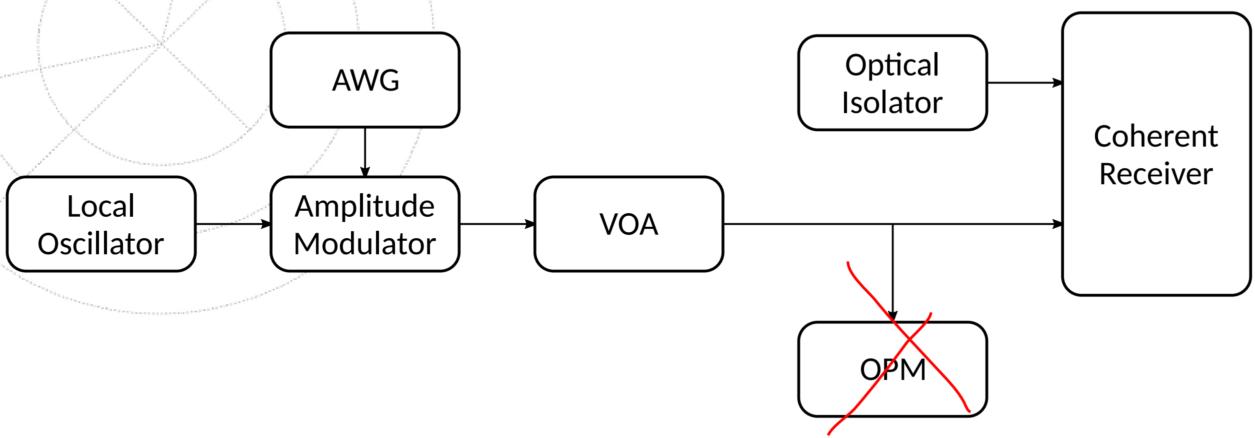
Simulation results - REVIEW





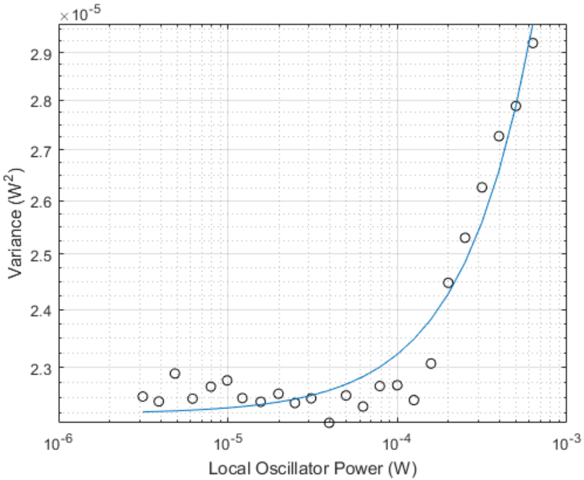
These plots show the variance of $\hat{m}$ in function of signal power (left) and local oscillator power (right). Given that there is no implementation of noise, these plots show only fluctuations of numerical errors. We see that these values are very close to 0.

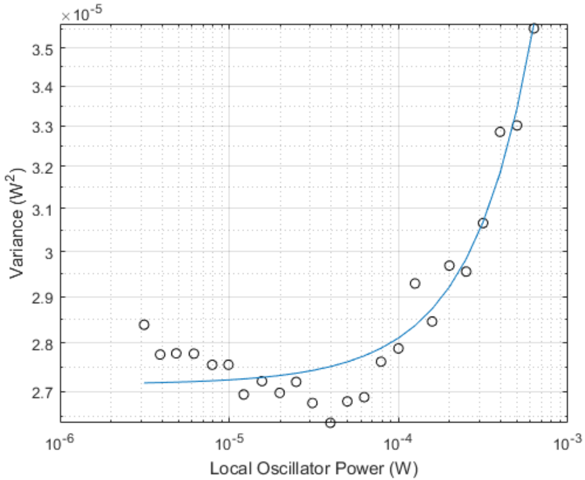
Experimental setup



A signal is produced by modulating and attenuating a laser beam. This signal and a vacuum signal are used as inputs of the Coherent Receiver, outputing a voltage proportional to the homodyne detection.

Experimental results





These plots of the variance of $\hat{m}$ plots, for two quadratures, 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 simulation.

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