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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 xxxxx

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 xxxxx

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:

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

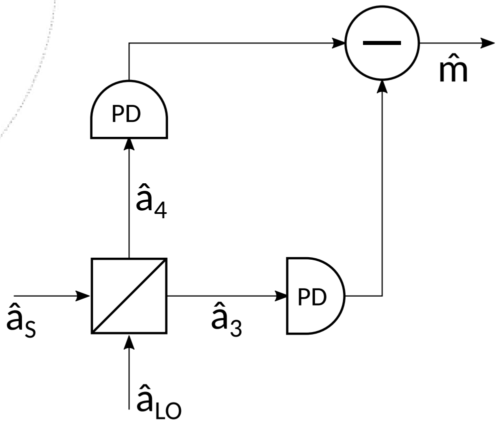
And the variance is

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

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 illustration:



This technique basically measures the phase difference between a input signal S and a local oscillator LO. Figure xx shows the quantum mechanical description of the technique, in which $\hat{m}$ is the operator of the output difference between the photocurrents.

Homodyne Detection

Given the input signal given by the state $|\alpha\rangle$ ($\alpha = |\alpha|e^{i\theta_\alpha}$) and the local oscillator given by state $|\beta\rangle$ ($\beta = |\beta|e^{i\theta_\beta}$), the expected value of $\hat{m}$ and it's variance will be

$$\langle m\rangle = 2|\alpha||\beta|\cos(\theta_\alpha - \theta_\beta) \quad (1)\ , \qquad \mathrm{Var}(m) = |\alpha|^2 + |\beta|^2 \quad (2)$$

If we normalize the units of m by $2|\beta|$ and knowing that $\alpha \ll \beta$, then it can be simplified to

$$\langle m\rangle = |\alpha|\cos(\theta_\alpha - \theta_\beta) \quad (3)\ , \qquad \mathrm{Var}(m) \approx \frac{1}{4} \quad (4)$$

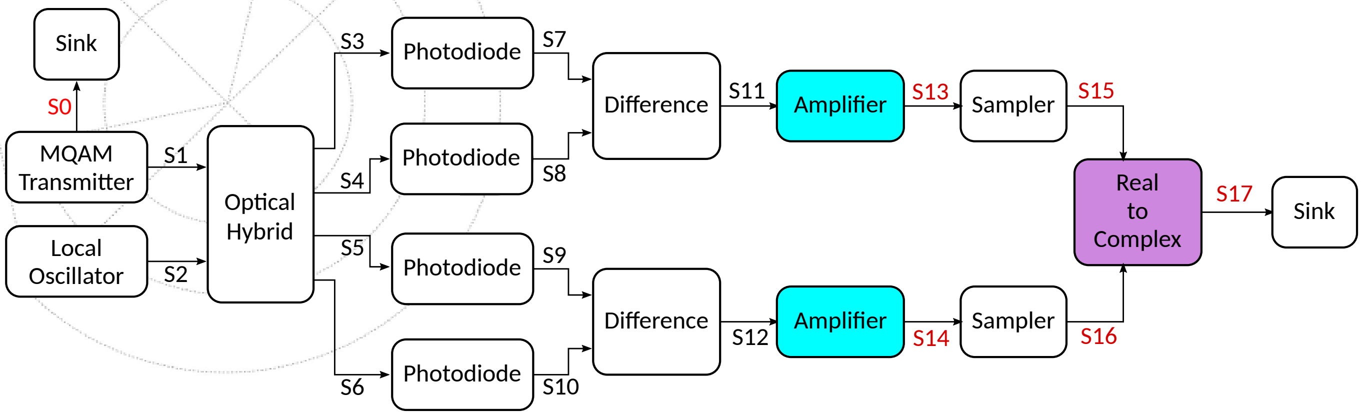
Double Homodyne Detection

In fact, we can measure the two quadratures X and Y at the same time, using the double homodyne detection. This tecnique consists in simply divide the signal in two beams with half the power of the original one and one of them is measure in-phase with the local oscillator, and the other is measured with a phase difference of $\pi/2$ relative to the first one???????

$$\langle m_X \rangle = \left| \frac{\alpha}{\sqrt{2}} \right| \cos(\theta_\alpha - \theta_\beta) \quad (5) \ , \qquad \mathrm{Var}(m_X) \approx \frac{1}{4} \quad (6)$$

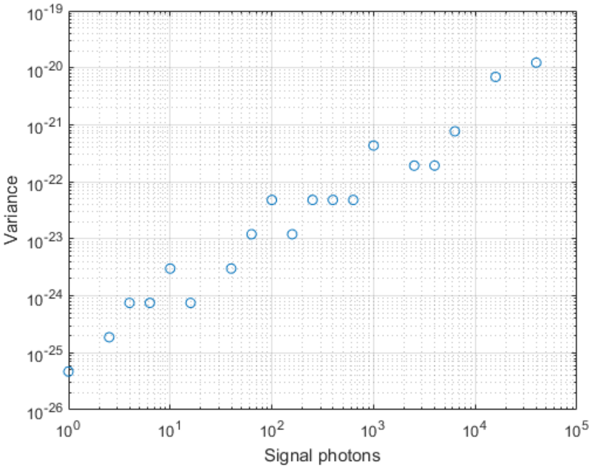
$$\langle m_Y \rangle = \left| \frac{\alpha}{\sqrt{2}} \right| \sin(\theta_\alpha - \theta_\beta) \quad (7) \ , \qquad \mathrm{Var}(m_Y) \approx \frac{1}{4} \quad (8)$$

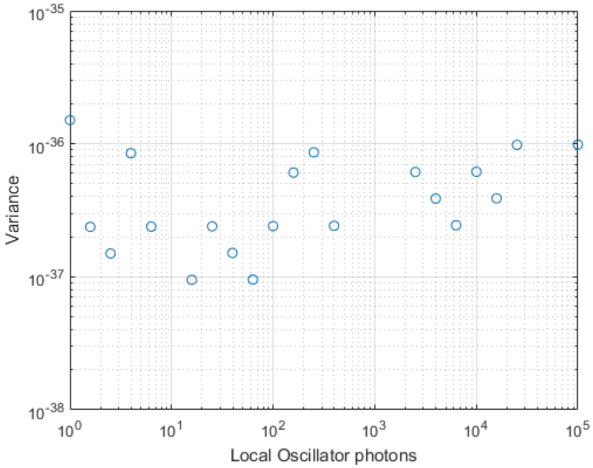
Simulation setup



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 signals of each pair is obtained and then is sampled.

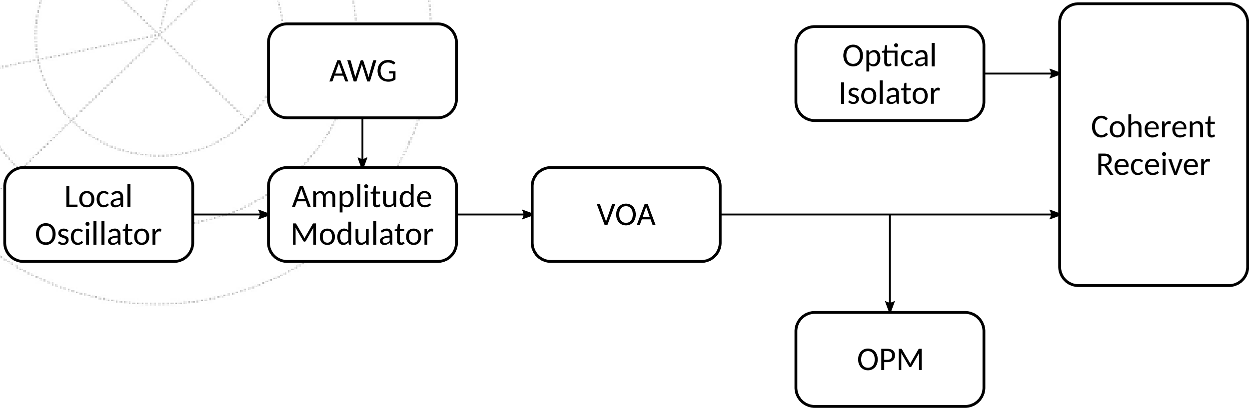
Simulation results





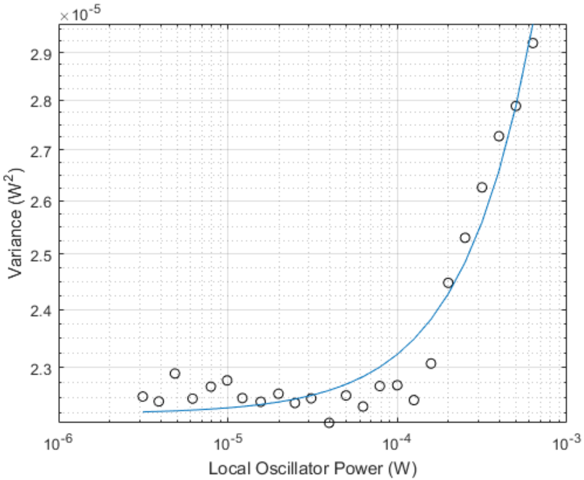
These plots show the variance of $\hat{m}$ in function of signal power (left) and local oscillator power (right). Given that there is no implementation of noise, these plots show only fluctuations of numerical errors. We see that these values are very close to 0.

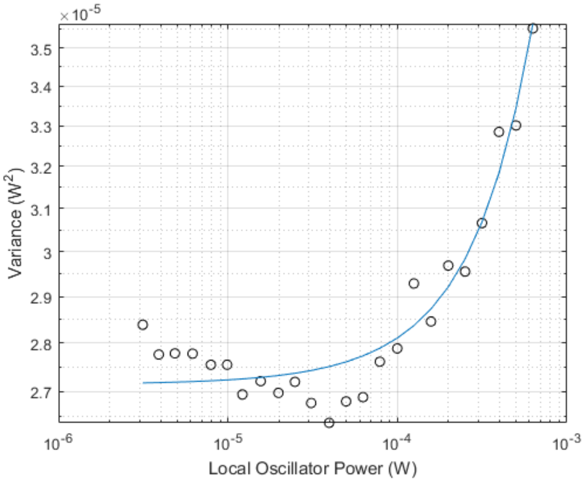
Experimental setup



A signal is produced by the mopulation of a laser beam and attenuated. The Coherent Receiver uses this signal and a vacuum signal as input, 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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