Using Two Mode Squeezing to Enhance Quadrature Quantum Sensing

Rodrigo Estrada Torrejon, Electrical Engineering

Mentor: Kanu Sinha, Adjunct Faculty

School of Electrical, Computer, and Energy Engineering

Research question: How can using two-mode squeezed entangled photons help enhance the quantum detection of quadratures of an arbitrary state?

Background:

Squeezed states enable the reduction of a quantum state quadrature uncertainty below that of the minimal uncertainty state. This project proposes a homodyne detection setup with the intention of using a squeezed state of entangled photons to help improve the sensitivity of quadrature detection of an arbitrary quantum system by enhancing the contrast between the two half modes.

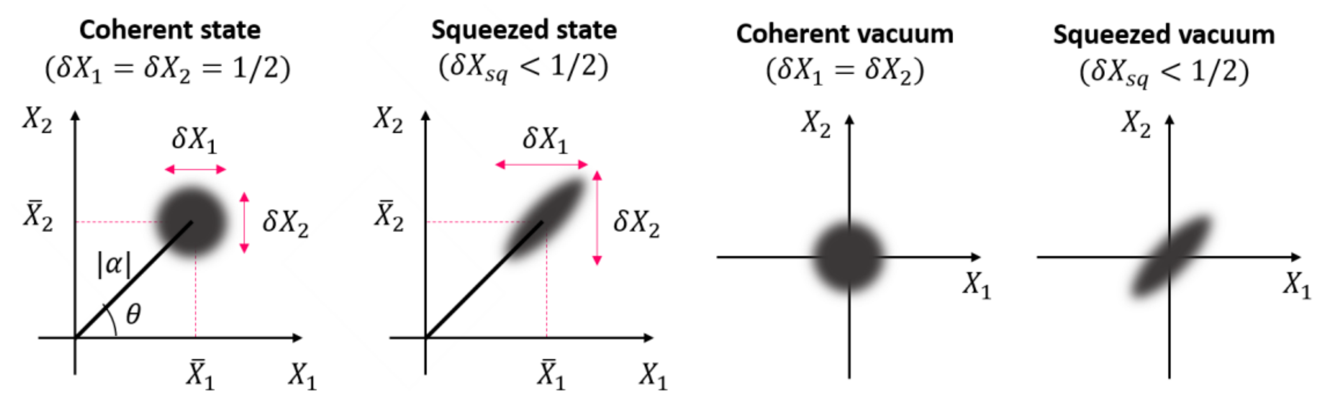

Figure 1: Phase diagrams of different quantum states with illustrated quadrature fluctuations. [1]

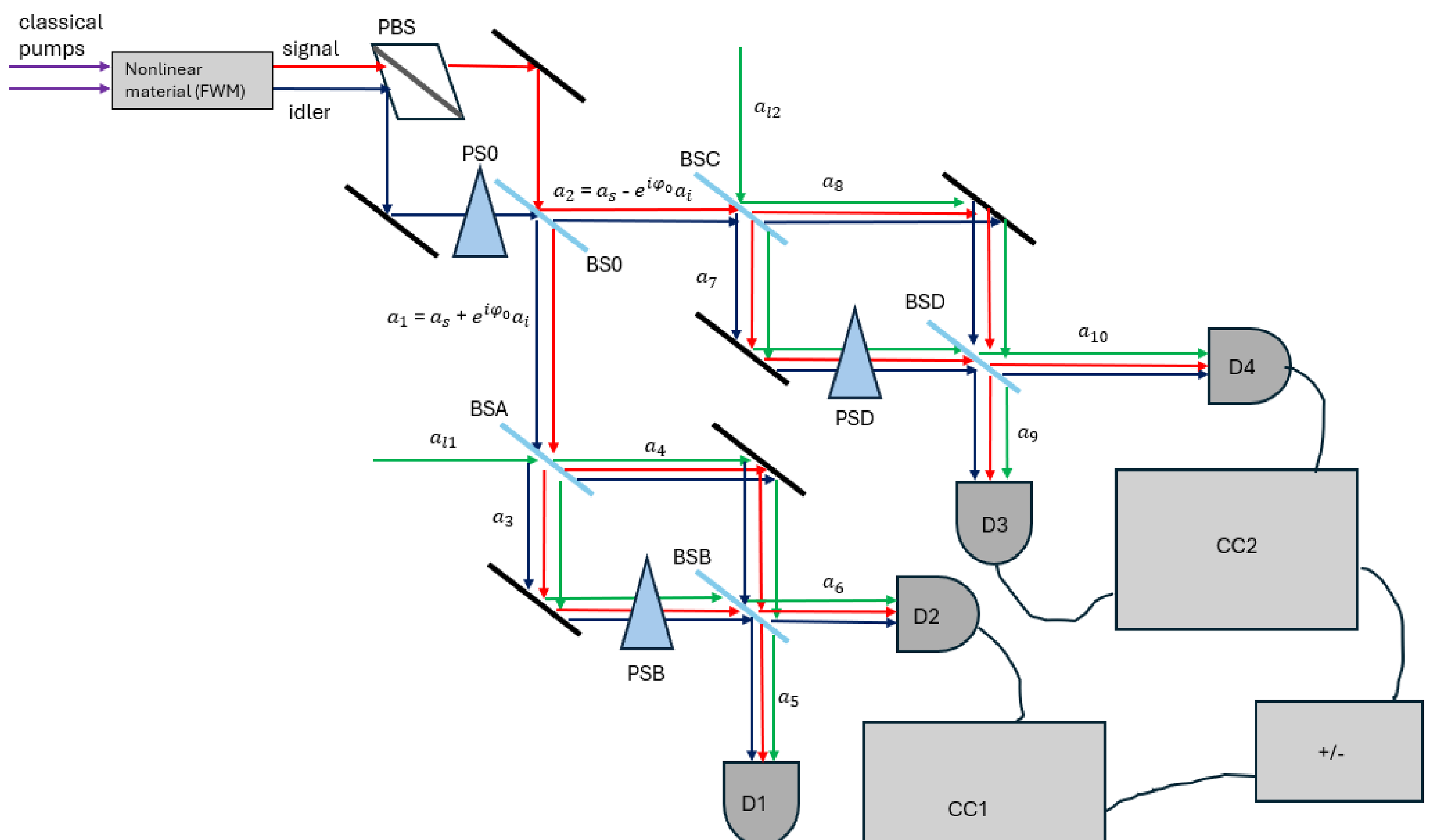

Figure 2: Proposed experimental setup

Conclusions:

While we can see in the results section that we arrived at the difference operators in terms of quadratures of signal and idler, this setup does not provide a mixing of the local oscillators 1 and 2 and therefore is not ideal for the results intended. We will explore another setup to conduct a joint measurement in which we will mix paths 4 with 7 and 3 with 8.

Procedure:

- Generation of two-mode squeezed states:

$$\hat{H}_I = -\int dV \epsilon_0 \chi^{(3)} \mathbf{E}_p^2 \hat{E}_s \hat{E}_i$$

Time-independent Interaction Hamiltonian

$$\hat{H}_I = \frac{\hbar\sqrt{\omega_s\omega_i}}{2}\chi^{(3)}\left(\mathcal{E}_{p_1}^*\mathcal{E}_{p_2}^*\hat{a}_{\vec{k}_{sx}}\hat{a}_{\vec{k}_{ix}} + \mathcal{E}_{p_1}\mathcal{E}_{p_2}\hat{a}^\dagger_{\vec{k}_{sx}}\hat{a}^\dagger_{\vec{k}_{ix}}\right)$$

$$\begin{aligned}|\psi\rangle &= U(t)\,|0,0\rangle \\ &= e^{-iHt/\hbar}\,|0,0\rangle \\ &= \exp\left[-it\left(\eta^*\hat{a}\hat{b} + \eta\hat{a}^\dagger\hat{b}^\dagger\right)\right]|0,0\rangle\end{aligned}$$

Two-mode Squeezing Operator as Time Evolution Operator

- Number operators at each detector:

$$\begin{aligned}n_5 = &\frac{1}{4}(\hat{a}_s^\dagger\hat{a}_s + e^{i\phi_0}\hat{a}_s^\dagger\hat{a}_i + e^{-i\phi_0}\hat{a}_i^\dagger\hat{a}_s + \hat{a}_i^\dagger\hat{a}_i)(1+\cos\phi_B) \\ &+ i\frac{1}{2\sqrt{2}}(\hat{a}_s^\dagger\hat{a}_{l1} + e^{-i\phi_0}\hat{a}_i^\dagger\hat{a}_{l1})\sin\phi_B \\ &- i\frac{1}{2\sqrt{2}}(\hat{a}_{l1}^\dagger\hat{a}_s + e^{i\phi_0}\hat{a}_{l1}^\dagger\hat{a}_i)\sin\phi_B \\ &+ \frac{1}{2}(\hat{a}_{l1}^\dagger\hat{a}_{l1})(1-\cos\phi_B)\end{aligned}$$

$$\begin{aligned}n_6 = &\frac{1}{4}(\hat{a}_s^\dagger\hat{a}_s + e^{i\phi_0}\hat{a}_s^\dagger\hat{a}_i + e^{-i\phi_0}\hat{a}_i^\dagger\hat{a}_s + \hat{a}_i^\dagger\hat{a}_i)(1-\cos\phi_B) \\ &- i\frac{1}{2\sqrt{2}}(\hat{a}_s^\dagger\hat{a}_{l1} + e^{-i\phi_0}\hat{a}_i^\dagger\hat{a}_{l1})\sin\phi_B \\ &+ i\frac{1}{2\sqrt{2}}(\hat{a}_{l1}^\dagger\hat{a}_s + e^{i\phi_0}\hat{a}_{l1}^\dagger\hat{a}_i)\sin\phi_B \\ &+ \frac{1}{2}(\hat{a}_{l1}^\dagger\hat{a}_{l1})(1+\cos\phi_B)\end{aligned}$$

$$\begin{aligned}n_9 = &\frac{1}{4}(\hat{a}_s^\dagger\hat{a}_s - e^{i\phi_0}\hat{a}_s^\dagger\hat{a}_i - e^{-i\phi_0}\hat{a}_i^\dagger\hat{a}_s + \hat{a}_i^\dagger\hat{a}_i)(1-\cos\phi_D) \\ &- i\frac{1}{2\sqrt{2}}(\hat{a}_s^\dagger\hat{a}_{l2} - e^{-i\phi_0}\hat{a}_i^\dagger\hat{a}_{l2})\sin\phi_D \\ &+ i\frac{1}{2\sqrt{2}}(\hat{a}_{l2}^\dagger\hat{a}_s - e^{i\phi_0}\hat{a}_{l2}^\dagger\hat{a}_i)\sin\phi_D \\ &+ \frac{1}{4}(\hat{a}_{l2}^\dagger\hat{a}_{l2})(1+\cos\phi_D)\end{aligned}$$

$$\begin{aligned}n_{10} = &\frac{1}{4}(\hat{a}_s^\dagger\hat{a}_s - e^{i\phi_0}\hat{a}_s^\dagger\hat{a}_i - e^{-i\phi_0}\hat{a}_i^\dagger\hat{a}_s + \hat{a}_i^\dagger\hat{a}_i)(1+\cos\phi_D) \\ &+ i\frac{1}{2\sqrt{2}}(\hat{a}_s^\dagger\hat{a}_{l2} - e^{-i\phi_0}\hat{a}_i^\dagger\hat{a}_{l2})\sin\phi_D \\ &- i\frac{1}{2\sqrt{2}}(\hat{a}_{l2}^\dagger\hat{a}_s - e^{i\phi_0}\hat{a}_{l2}^\dagger\hat{a}_i)\sin\phi_D \\ &+ \frac{1}{4}(\hat{a}_{l2}^\dagger\hat{a}_{l2})(1-\cos\phi_D)\end{aligned}$$

Results:

$$\begin{aligned}n_5 - n_6 &= \frac{i}{\sqrt{2}}\left(\hat{a}_s^\dagger\hat{a}_{l1} + e^{-i\phi_0}\hat{a}_i^\dagger\hat{a}_{l1} - \hat{a}_{l1}^\dagger\hat{a}_s - e^{i\phi_0}\hat{a}_{l1}^\dagger\hat{a}_i\right) \\ &= i\left[\left(\frac{\hat{a}_s^\dagger + e^{-i\phi_0}\hat{a}_i^\dagger}{\sqrt{2}}\right)\hat{a}_{l1} - \left(\frac{\hat{a}_s + e^{i\phi_0}\hat{a}_i}{\sqrt{2}}\right)\hat{a}_{l1}^\dagger\right]\end{aligned}$$

$$\begin{aligned}n_9 - n_{10} &= \frac{i}{\sqrt{2}}\left(-\hat{a}_s^\dagger\hat{a}_{l2} + e^{-i\phi_0}\hat{a}_i^\dagger\hat{a}_{l2} + \hat{a}_{l2}^\dagger\hat{a}_s - e^{i\phi_0}\hat{a}_{l2}^\dagger\hat{a}_i\right) \\ &= i\left[\left(\frac{-\hat{a}_s^\dagger + e^{-i\phi_0}\hat{a}_i^\dagger}{\sqrt{2}}\right)\hat{a}_{l2} - \left(\frac{-\hat{a}_s + e^{i\phi_0}\hat{a}_i}{\sqrt{2}}\right)\hat{a}_{l2}^\dagger\right]\end{aligned}$$

References:

[1]M. Guidry, “Exploring the Multi-Mode Structure of Atom-Generated Squeezed Light.” Accessed: Apr. 12, 2024. [Online]. Available: https://www.wm.edu/as/physics/documents/seniorstheses/class2017theses/guidry_melissa.pdf

[2]C. C. Gerry and P. L. Knight, Introductory quantum optics. Cambridge Etc.: Cambridge University Press, 2008.

FURI

Ira A. Fulton Schools of Engineering
Arizona State University