Universidad de los Andes | Facultad de Ciencias Departamento de Física

Óptica Cuántica Uniandes

Characterization of a Balanced Homodyne Detector

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1. Introduction

Homodyne detection is a fundamental technique in quantum optics used to measure fluctuations in the quadratures of a light field. A **balanced homodyne detector (BHD)** consists of two main components: an optical stage, responsible for interference and visibility optimization, and an electronic stage, responsible for differential signal detection and noise analysis. In this work, a Mach–Zehnder interferometer was implemented as the optical backbone of the BHD, while the detector electronics were characterized to distinguish electronic noise, laser intensity noise, and **shot noise**. The measurements presented here constitute a first step towards the future characterization of vacuum and coherent states, as well as the reconstruction of phase-space distributions such as the Wigner function through balanced homodyne detection.

2. Optical Characterization of the BHD

Interference is given by:

$$I(\tau) = I_1 + I_2 + 2\sqrt{I_1 I_2}\cos(\omega_0\tau)|\gamma_{12}(\tau)| \tag{1}$$

Fringe visibility is given by:

$$\mathcal{V} = \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}} \tag{2}$$

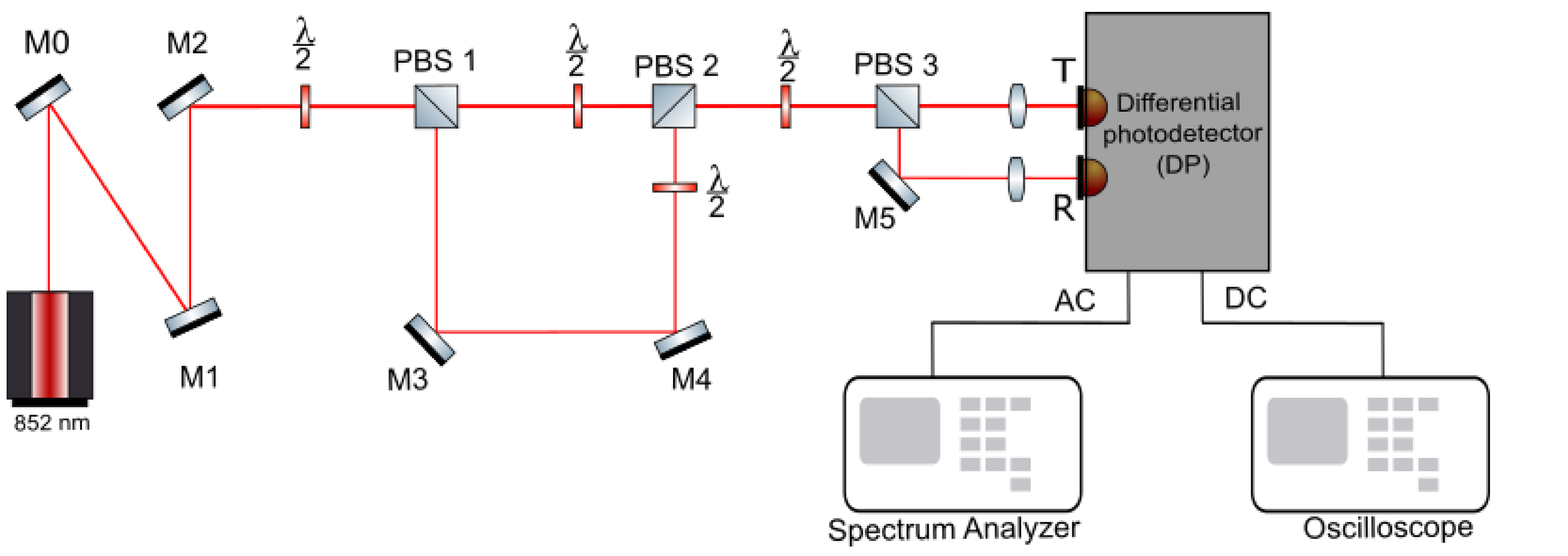

Figure 1. Experimental implementation of the balanced homodyne detector, including the Mach–Zehnder interferometer and the balanced photodetection stage.

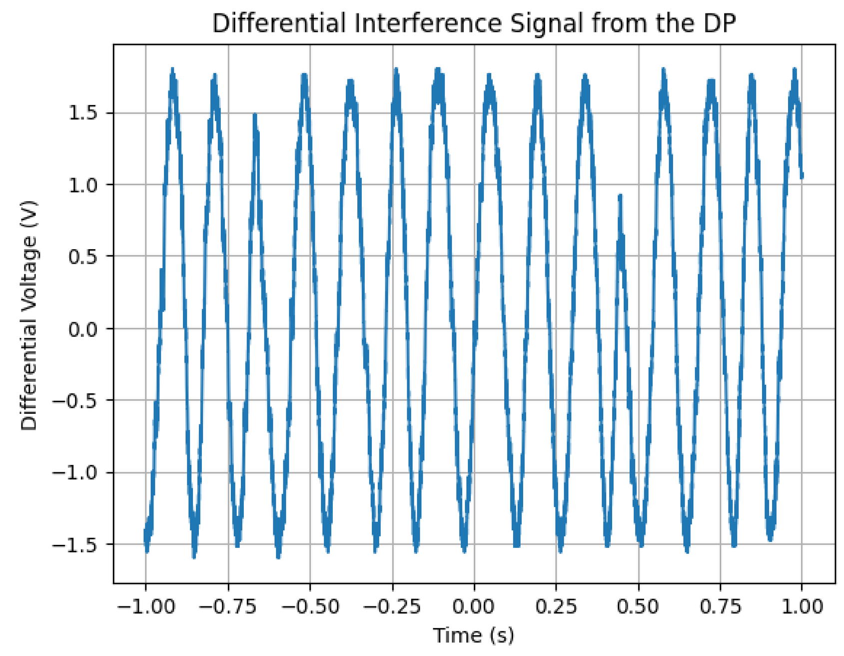

Figure 2. Differential DC output showing the π phase shift between both interferometer outputs.

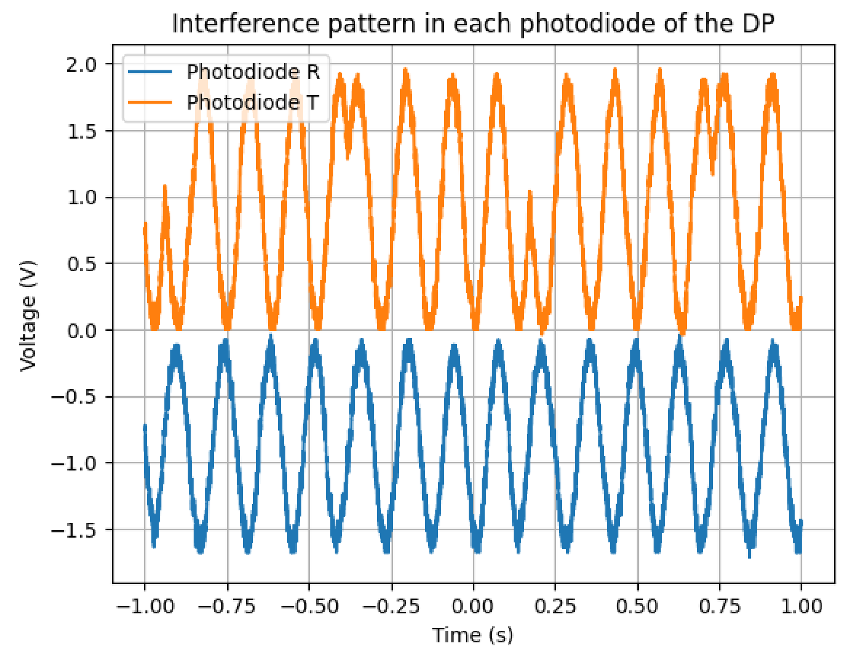

Figure 3. Independent signals from the interferometer outputs, yielding visibilities of 98% and 88%.

4. Detector and Noise Characterization

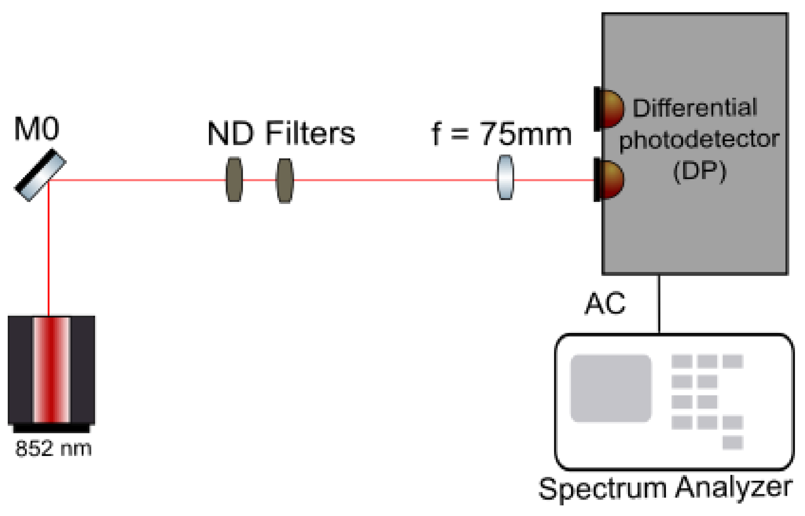

Figure 4. Direct detection setup used for single-photodiode noise characterization.

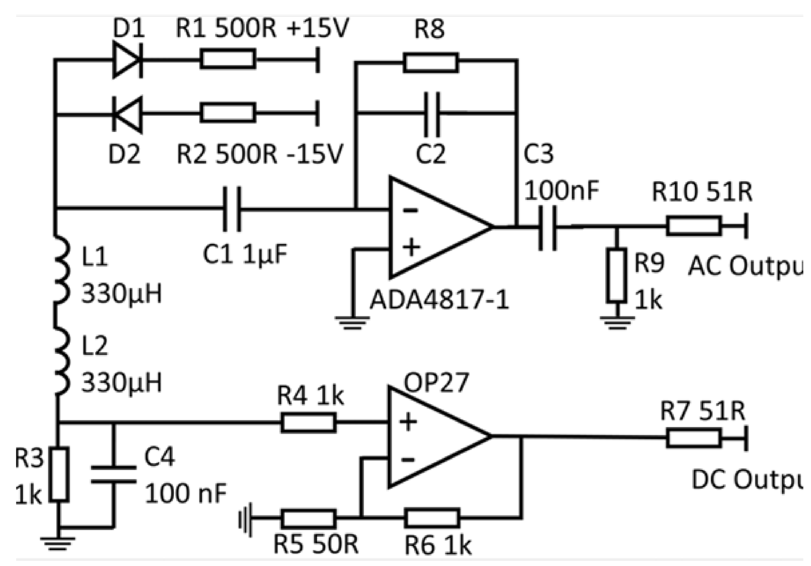

Figure 5. Electronic circuit of the DP. Taken from [1].

The AC branch of the homodyne detector was used to characterize the **noise spectrum** of the system.

1. **Electronic noise floor** – detector and amplifier noise with no optical input.
2. **Shot noise** – quantum noise scaling linearly with optical power ($\propto P$).
3. **Laser intensity noise** – classical excess noise scaling as ($\propto P^2$).

Noise types:

1. **Electronic Noise:** Constant and always present.
2. **Shot Noise:** Scales linearly, good noise to signal ratio.
3. **Rin Noise:** Scales non-linearly, bad noise to signal ratio.

Finding Shot noise dominated regions:

1. Convert **dBm to mW**.
2. **Integrate** values within a set frequency range.
3. **Plot the integral values vs power** and fit curves.
4. **Determine the noise type** that dominates each region.

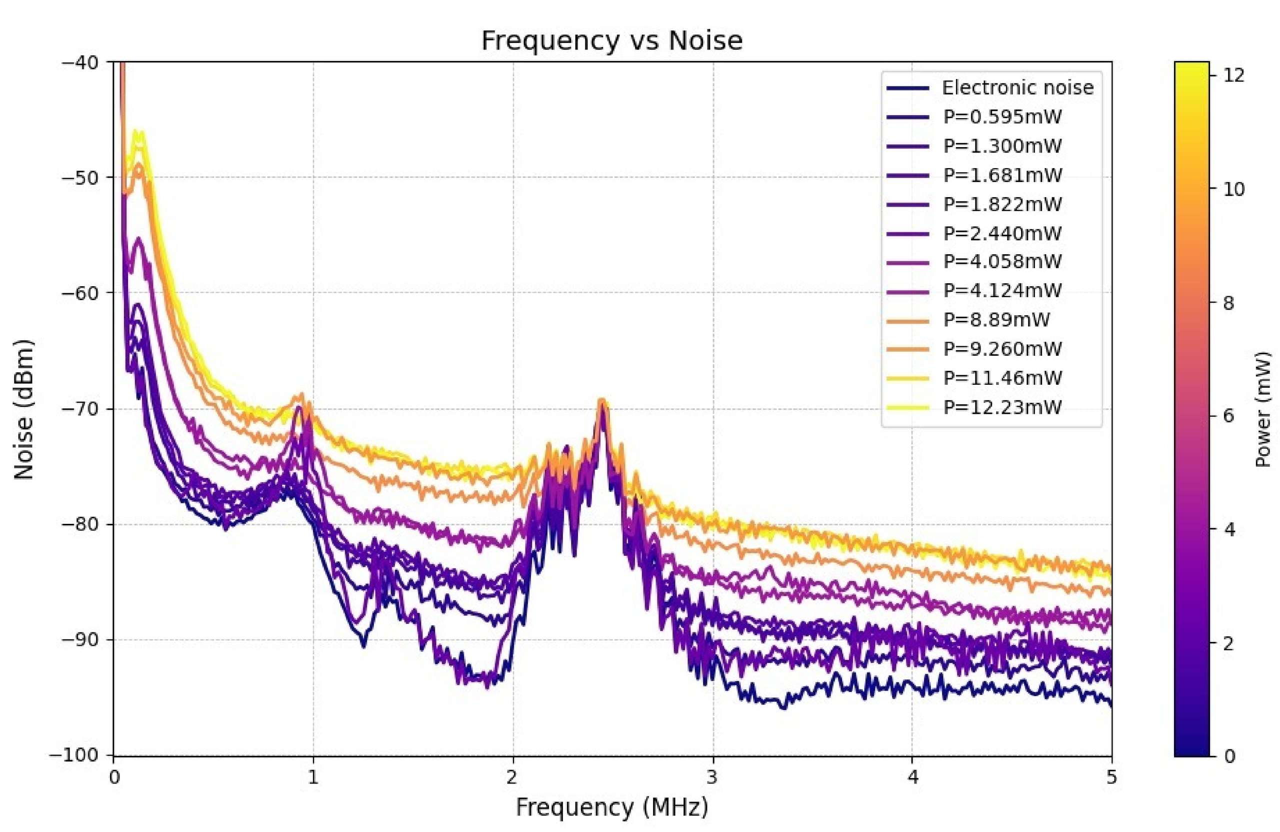

Figure 6. Noise dependency on frequency for different input powers.

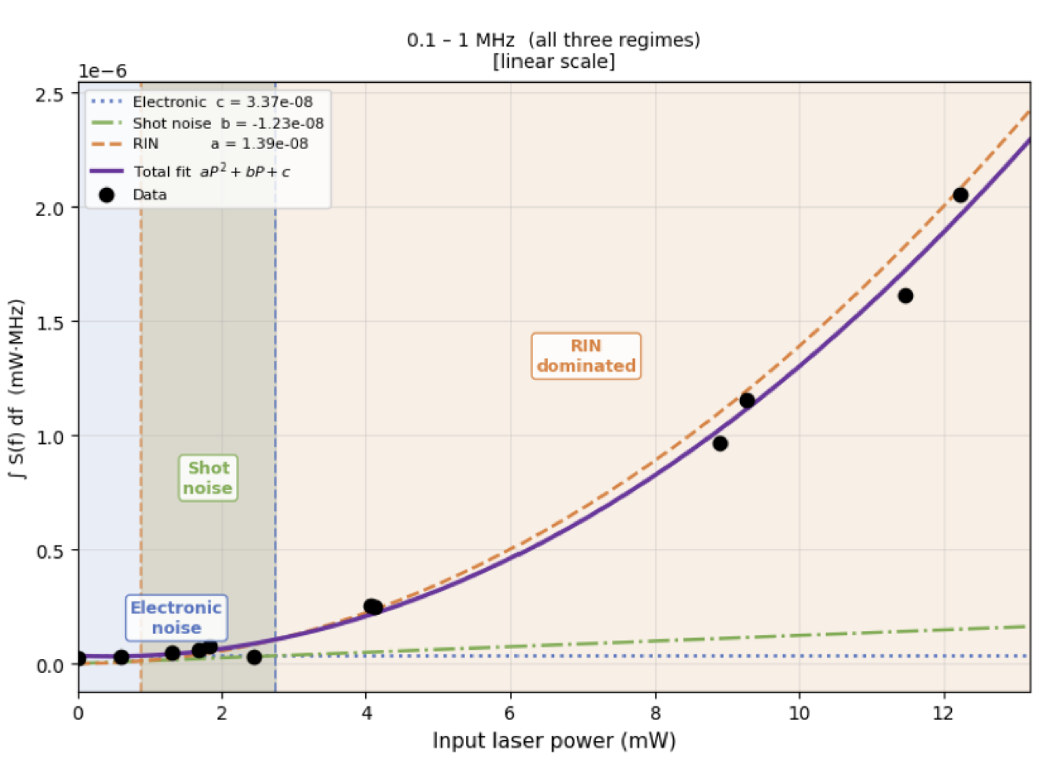

Figure 8. Integrated noise scaling in a low-frequency region, where shot-noise-dominated behavior is limited.

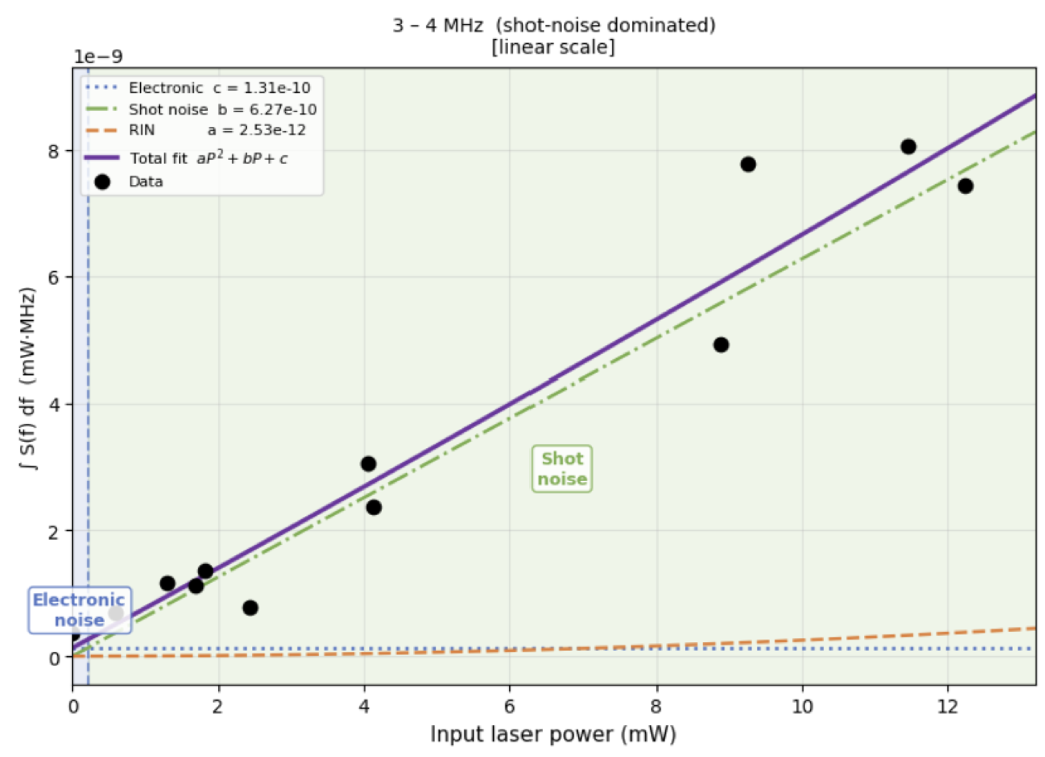

Figure 7. Integrated noise scaling in a higher-frequency region showing a significant shot-noise-dominated regime.

7. References

[1] Shubo Lang, Shicheng Zhang, Xiaolin Li, Yueping Niu, and Shangqing Gong. Low noise balanced homodyne detector for quantum noise measurement. *IEEE Access*, 10:27912–27916, 2022.

6. Conclusions and Future Work

1. High interference visibility confirmed proper optical alignment and balanced detection.
2. A shot-noise-dominated region was identified around 3–4 MHz through direct detection.
3. Future work includes noise characterization of the BHD differential signal.