

Characterization of a Balanced Homodyne Detector

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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.

I. Introduction

Continuous-variable quantum systems provide a natural platform for quantum information processing in optical architectures, where quantum states of light are described in terms of continuously valued quadratures. In this framework, information is encoded in so-called qumodes, and their full description is conveniently represented in phase space through the Wigner function. This representation establishes a direct connection between theoretical quantum states and experimentally accessible measurement outcomes.

A key feature of continuous-variable implementations is that quadrature observables can be directly measured using optical interference techniques. In particular, homodyne detection enables access to field quadratures by interfering a signal field with a strong reference beam and measuring the resulting intensity differences. This technique allows the reconstruction of phase-space distributions through tomographic methods, making it a central tool in quantum optical characterization.

The performance of a homodyne-based system depends critically on both the optical interference quality and the electronic stability of the detection stage. On the optical side, high-visibility interference is required to ensure accurate quadrature encoding, while on the electronic side, noise contributions such as electronic noise, shot noise, and relative intensity noise (RIN) determine the ultimate sensitivity of the measurement. A careful characterization of both aspects is therefore necessary to operate in the shot-noise-limited regime required for quantum measurements.

For the purpose of this paper, we seek to characterize the optical and electronic behavior of a balanced homodyne detector (BHD). To do so we will: implement a Mach-Zehnder interferometer, optimize interference visibility, characterize detector noise, identify electronic, shot and RIN noise and prepare the system for future quantum optics measurements.

II. Optical Component

A. Optical Setup

The backbone of the optical setup is a Mach-Zehnder interferometer, which uses the output beam of an 852nm laser, splits it into two paths, and subsequently recombines them to generate interference. Unlike a conventional Mach-Zehnder interferometer, the splitting and recombination stages are accomplished using polarizing beam splitters (PBS) together with half-wave plates, allowing precise control of the optical power and polarization in each arm. Additionally, it is worth mentioning that the paths of this setup are unbalanced in arm length; however, the optical path difference remains well below the coherence length of the laser source, ensuring that interference is preserved. One of the mirrors (M3) is mounted on a piezoelectric actuator, enabling fine control of the relative phase between the two paths and thus active scanning of the interference fringes. Prior to recombination, the optical powers in both arms are carefully adjusted to achieve nearly equal intensities, a condition required for optimal operation of the balanced homodyne detector. The complete optical arrangement is shown in Fig. 1

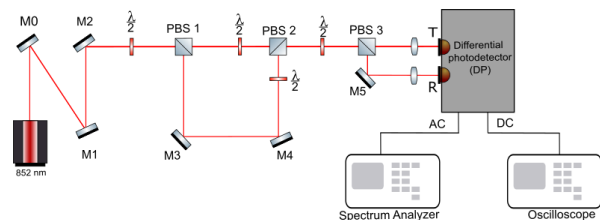


Figure 1. Optical arrangement of the balanced homodyne detector based on a polarization Mach-Zehnder interferometer.

B. Interference & Visibility

The two output ports of the interferometer are monitored simultaneously by the differential photodetector (DP). The intensities measured by the photodiodes are complementary and can be expressed as

$$I_{\pm} = I_1 + I_2 \pm 2\sqrt{I_1 I_2} \cos(\Delta\phi), \quad (1)$$

where I_1 and I_2 are the optical intensities of the interfering fields and $\Delta\phi$ is their relative phase. By subtracting the two signals, the DP removes the common background contribution, yielding an output proportional to the inter-

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ference term, so when the optical powers are balanced, the detector maximizes sensitivity to phase variations.

The quality of the interference was quantified through the visibility of the signals measured on each photo detector individually. Visibility provides a measure of the contrast between constructive and destructive interference and is defined, according to [1], as

$$V = \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}}. \quad (2)$$

A value of 1 corresponds to perfect interference, while lower values indicate imperfect mode overlap, polarization mismatch, or other experimental imperfections. The interference patterns measured at the two output ports of the interferometer are shown in Fig. 2. From these measurements, visibilities of 98% and 88% were obtained for the transmitted and reflected outputs, respectively.

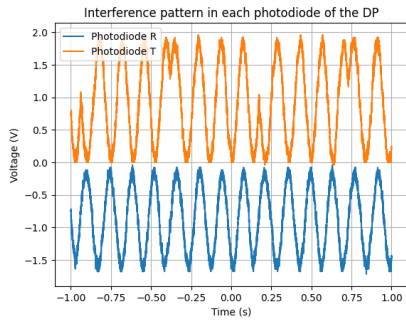


Figure 2. Interference fringes measured at the transmitted and reflected outputs of the interferometer. The measurements were obtained independently by recording one photodetector signal while the other detector was blocked.

C. Optical Results

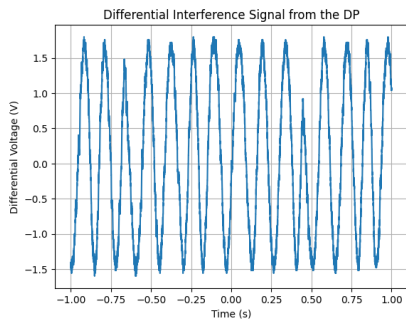


Figure 3. Differential DC output showing the π phase shift between both interferometer outputs.

The differential DC measurements exhibited a clear increase in the interference term when subtracting both interferometer outputs. Additionally, the expected π phase difference between the two signals was successfully verified, confirming the interferometric origin of the response and indicating stable optical alignment throughout the experiment. This is shown in 3

III. Electronic Component

A. Detector and Circuit

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

homodyne detector (BHD) circuit implements a differential photodetection scheme in which the photocurrents from two photodiodes are subtracted, suppressing common-mode classical noise while preserving the quantum signal. The electronic design follows the low-noise transimpedance amplifier described in [2, 3].

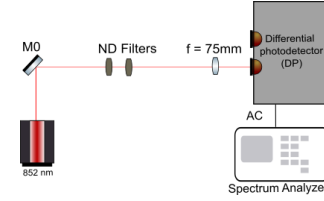


Figure 4. Direct detection setup used for single-photodiode noise characterization.

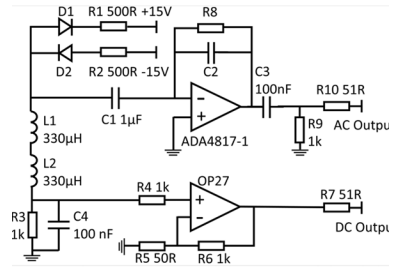


Figure 5. Electronic circuit of the balanced detector. Taken from [2].

B. Noise Characterization

Three distinct noise contributions were identified and characterized across different optical power regimes:

1. **Electronic noise floor** — detector and amplifier noise present with no optical input. This contribution is constant and independent of optical power.
2. **Shot noise** — quantum noise arising from the discrete nature of photon detection, scaling linearly with optical power ($\propto P$). This is the fundamental quantum limit of the measurement.
3. **Laser intensity noise (RIN)** — classical excess noise originating from fluctuations in the laser output power, scaling quadratically with optical power ($\propto P^2$).

The scaling behavior of each noise type determines its dominance in a given power regime. Electronic noise is always present and sets a lower bound. Shot noise grows linearly and eventually dominates over electronic noise. At higher powers, RIN grows faster than shot noise and becomes the limiting factor, reducing the signal-to-noise ratio. Identifying the shot-noise-dominated regime is therefore essential for quantum measurements.

C. Finding the Shot-Noise-Dominated Region

To identify the power range in which shot noise dominates, the following procedure was applied to the acquired spectra:

1. **Convert units:** Power spectral density values were converted from dBm to mW to allow linear integration.
2. **Frequency integration:** The noise power was integrated over a defined frequency band, yielding a single

integrated noise value per spectrum.

3. **Power scaling analysis:** The integrated noise values were plotted as a function of optical input power, and curve fits were applied to identify the dominant scaling law ($\propto P$, $\propto P^2$, or constant).

4. **Regime identification:** The fit results were used to determine the power range where shot noise scaling dominates over both electronic noise and RIN.

D. Noise vs. Frequency

Figure 6 shows the measured noise power spectral density as a function of frequency for several input optical powers. The spectra reveal the frequency-dependent structure of each noise contribution, including low-frequency RIN excess and a flatter shot-noise floor at higher frequencies.

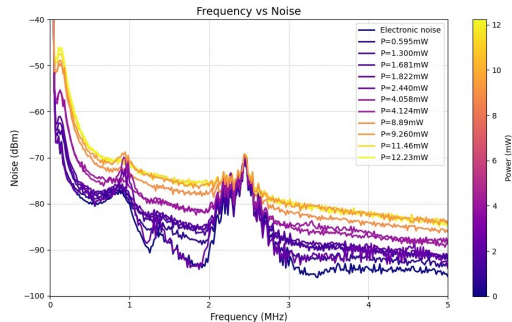


Figure 6. Noise power spectral density as a function of frequency for different input optical powers. Each trace corresponds to a distinct power level, illustrating the transition from electronic noise to shot noise and RIN dominated regimes.

Figures 7 and 8 show the integrated noise power plotted against optical input power for two frequency bands. The fitted curves allow identification of the dominant noise scaling in each region.

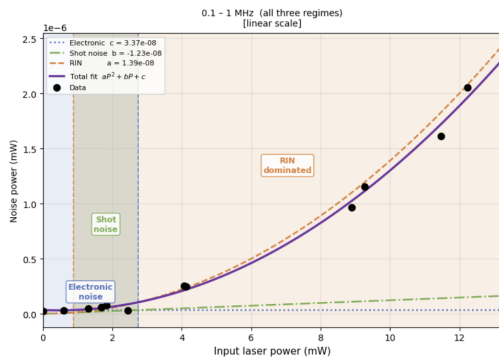


Figure 7. Integrated noise scaling in a low-frequency region, where shot-noise-dominated behavior is limited due to stronger RIN contributions.

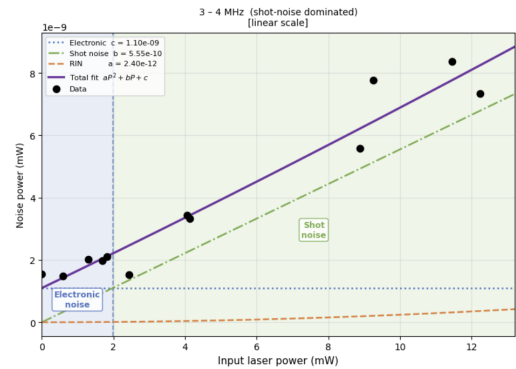


Figure 8. Integrated noise scaling in a higher-frequency region showing a significant shot-noise-dominated regime, suitable for quantum quadrature measurements.

IV. Conclusions

The implementation and characterization of a balanced homodyne detector (BHD) based on a Mach–Zehnder interferometer has been successfully carried out. High interference visibilities of 98% and 88% were obtained at the transmitted and reflected outputs respectively, confirming proper optical alignment and balanced detection conditions. On the electronic side, the noise spectrum of the system was characterized by identifying three distinct noise contributions: electronic noise floor, shot noise, and laser intensity noise (RIN). By integrating the power spectral density over defined frequency bands and analyzing the scaling with optical power, a shot-noise-dominated regime was identified in the 3–4 MHz frequency range. In contrast, lower frequency bands (0.1–1.0 MHz) were found to be dominated by RIN, limiting their usefulness for quantum measurements. These results establish a calibrated operating point for the detector and confirm that the system is capable of performing measurements in the shot-noise-dominated regime, which is a prerequisite for quantum quadrature measurements. Future work will focus on extending this characterization to the full differential BHD signal, acquiring quadrature distributions using the spectrum analyzer, and reconstructing the Wigner function for both vacuum and coherent states through optical homodyne tomography.

- [1] Grant R. Fowles. *Introduction to Modern Optics*. Dover Publications, 2 edition, 1975.
- [2] 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.

- [3] Samuel Esteban Sánchez Rodríguez. Noise measurements in a balanced homodyne detector for the reconstruction of the wigner function of coherent and vacuum states. 2026.