

Preliminary Studies Related to Balanced Homodyne Detection of Squeezed Light

M.Tech. Thesis

by

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**Dept. of Astronomy, Astrophysics and Space Engineering
INDIAN INSTITUTE OF TECHNOLOGY INDORE**

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Preliminary Studies Related to Balanced Homodyne Detection of Squeezed Light

A THESIS

*Submitted in partial fulfillment of the
requirements for the award of the degree
of*
Master of Technology

by

Nishant Pawar



**Dept. of Astronomy, Astrophysics and Space Engineering
INDIAN INSTITUTE OF TECHNOLOGY INDORE**

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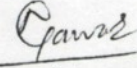


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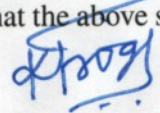
I hereby certify that the work which is being presented in the thesis entitled **Preliminary studies related to Balanced Homodyne Detection of Squeezed Light** in partial fulfillment of the requirements for the award of the degree of **MASTER OF TECHNOLOGY** submitted to the **Department of Astronomy, Astrophysics and Space Engineering (DAASE), Indian Institute of Technology Indore**, is an authentic record of my work carried out during July 2025 – May 2026 under the supervision of **Dr. Jogy George, SO/H, ALOD, RRCAT** and **Prof. Manoneeta Chakraborty, DAASE, IIT Indore**.

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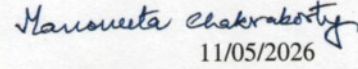
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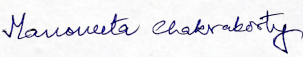
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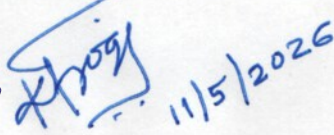
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Abstract

The objective of this project is to investigate experimental requirements for quantum noise limited balanced homodyne detection at 1064 nm, with the long term goal of supporting future squeezed light measurements for precision interferometry and gravitational wave detection. The work focuses on developing a low noise balanced detection platform capable of resolving quantum noise above the electronic background.

The main experimental work consisted of photon shot noise and vacuum noise measurements using balanced photodetectors. Initial measurements with a fiber-coupled balanced photodetector showed the expected increase of noise with optical power, but the results exhibited relatively large fluctuations and incomplete suppression of classical noise. Improved performance was obtained using a free-space balanced photodetector. In the balanced configuration, the measured voltage noise spectral density showed close agreement with the theoretical shot noise prediction and significantly reduced measurement scatter, indicating effective rejection of common mode classical noise. Vacuum noise measurements in a balanced homodyne configuration further showed that the clearance above the electronic dark noise floor improved from about 1.43 dB at 50 μ W local oscillator power to about 5.4 dB at 440 μ W. These results demonstrate that the present detection system provides a practical foundation for future squeezed light measurements at the few-dB level.

Keywords: photon shot noise, vacuum fluctuations, balanced homodyne detection, squeezed light, balanced photodetector.

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Acronyms

LIGO	Laser Interferometer Gravitational-Wave Observatory
NPRO	Non-Planar Ring Oscillator
Nd:YVO₄	Neodymium-doped Yttrium Ortho Vanadate
IR	Infrared
BS	Beam Splitter
HWP	Half Wave Plate
FSR	Free Spectral Range
FWHM	Full Width Half Maximum
KTP	Potassium Titanyl Phosphate
PPKTP	Periodically Poled Potassium Titanyl Phosphate
OPA	Optical Parametric Amplifier
SHG	Second Harmonic Generation
BHD	Balanced Homodyne Detection
PZT	Lead Zirconate Titanate (Piezo)
BPD	Balanced Photo Detector
MZI	Mach-Zehnder Interferometer

Chapter 1

Introduction

1.1 Relevance of the Project

The direct detection of gravitational waves in 2015 marked a milestone in modern astronomy, opening a new observational window into the universe [1]. At the time of this first detection, the Laser Interferometer Gravitational-Wave Observatory (LIGO) detectors were operating near their fundamental sensitivity limits. These limits arise from quantum noise constraints imposed by the Heisenberg Uncertainty Principle. To surpass these quantum limits, advanced techniques such as the injection of squeezed states of light were implemented in the upgraded LIGO detectors starting around 2019. This upgrade significantly enhanced detector sensitivity, leading to a substantial increase in the gravitational wave event detection rate from approximately one event per month to several events per week.

The Indian scientific community is actively engaged in the development of the LIGO-India facility. This upcoming detector will also incorporate squeezed light techniques to achieve improved sensitivity. The Raja Ramanna Centre for Advanced Technology (RRCAT), Indore, as a key participating institution in LIGO-India, is undertaking experimental efforts toward the generation and characterization of squeezed states of light for future deployment.

The generation and detection of squeezed light at 1064 nm follow a four-stage process [2]:

1. **NPRO Laser Source:** A highly stable, single frequency Non-Planar Ring Oscillator (NPRO) Nd:YAG laser serves as the primary coherent light source at 1064 nm.

2. **Second Harmonic Generation (SHG):** A portion of the 1064 nm beam is frequency doubled in a nonlinear crystal (typically KTP) placed within a resonant cavity, producing a 532 nm pump beam for next stage.
3. **Squeezed Light Generation (OPO/OPA):** The 532 nm pump beam drives a sub-threshold Optical Parametric Oscillator (OPO) or Amplifier (OPA), usually incorporating a Periodically Poled Potassium Titanyl Phosphate (PPKTP) crystal. Through the process of Spontaneous Parametric Down-Conversion (SPDC), pump photons at 532 nm are converted into correlated photon pairs at 1064 nm, resulting in the generation of a squeezed vacuum state [3].
4. **Balanced Homodyne Detection (BHD):** Since squeezed vacuum states are highly sensitive to losses, they cannot be directly measured. Instead, they are interfered with a strong 1064 nm local oscillator (LO) field at a 50:50 beam splitter. The resulting outputs are detected using a balanced photodetector, enabling the measurement of quantum noise properties.

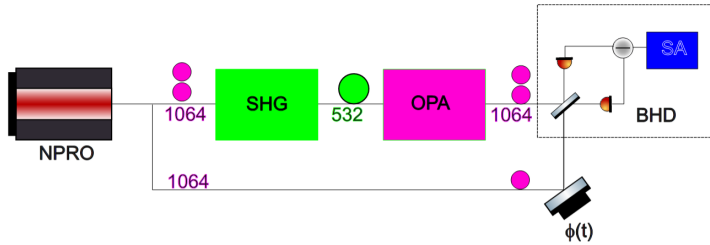


Figure 1.1: Squeezing topology: Schematic overview of the squeezed light generation and detection.

1.2 Aim of the Project

While the overall architecture for squeezed light involves a complex four-stage process, the specific scope of this project is concentrated on the final stage: the precise detection and characterization of quantum noise.

Detection of squeezed light requires an optical system with low loss, stable polarization behaviour, and a detector capable of resolving quantum noise above the electronic dark noise floor (**5 dB** in this particular

case). In line with these requirements, the following experimental studies were performed.

1. **Photon Shot Noise Measurement:** to measure shot noise using balanced photodetector across varying incident laser power, confirming that the measured shot noise increases with optical power.
2. **Vacuum Noise (Fluctuations) Measurement:** to determine the overall noise baseline, consisting of the dark noise of the electronic spectrum analyzer, the dark noise of the balanced photodetector, and the optical shot noise contribution, for different power levels. These measurements were used to estimate the available noise clearance and check whether squeezed light, once generated in the future, could be detected reliably.

Accordingly, this project focuses on establishing an experimentally stable low noise balanced detection setup and evaluating its readiness for future squeezed light measurements.

1.3 Organization of the Thesis

- Chapter 1 provides the introduction and outlines the aim of the project.
- Chapter 2 presents the theoretical background and literature review relevant to the project.
- Chapter 3 describes the preliminary experiments and simulations carried out to support the main quantum noise measurements. These include Mach–Zehnder Interferometer studies, cavity simulations using FINESSE, beam profiling measurements, and polarization studies.
- Chapter 4 presents the main experimental results of the project. It includes photon shot noise measurements using both fiber-coupled and free-space balanced photodetectors, followed by vacuum noise measurements in a balanced homodyne configuration. The chapter also discusses the observed agreement with theoretical expectations and evaluates the readiness of the system for future squeezed light detection.
- Chapter 5 provides summary and conclusions of the project.

Chapter 2

Literature Review

2.1 Nature of Light

The history of our understanding of light has changed from Newton's corpuscular theory and Huygens' wave theory to Maxwell's classical electromagnetic wave theory, which combines electric and magnetic fields. Classical optics views light as a continuous electromagnetic wave that explains diffraction, interference, and coherence. However, Planck's black-body radiation law and Einstein's explanation of the photoelectric effect triggered a major shift. They introduced the idea that light energy is exchanged in distinct packets known as "quanta." While we can often approximate many light-matter interactions using a semi-classical approach, where quantized atoms interact with classical fields, purely quantum phenomena like photon antibunching and sub-Poissonian statistics clearly show that light fundamentally acts as a stream of distinct particles called photons.

2.2 Role of Quantum Optics

In modern experimental contexts like precision interferometry for gravitational wave detection quantum optics is not merely descriptive; it dictates fundamental noise limits and practical strategies (such as squeezed state injection) to enhance sensitivity beyond the standard quantum limit posed by Heisenberg Uncertainty Principle. This framework provides us with the understanding of quantum fluctuations, measurement, and engineered quantum states (squeezed states) that reshape the uncertainty distribution between conjugate observables (quadratures). In particular, shot noise and vacuum fluctuations define the noise floor relevant to the present work.

2.3 Quantization of Electromagnetic Field

To understand light quantum mechanically, the electromagnetic field is modeled as an ensemble of independent simple harmonic oscillators. A classical single-mode field ω in a cavity has an energy or Hamiltonian given by,

$$H = \frac{1}{2}(p^2 + \omega^2 q^2) \quad (2.1)$$

where q and p act as canonical position and momentum variables.

Quantization is achieved by replacing these classical variables with quantum operators $\hat{q}$ and $\hat{p}$, which must satisfy the canonical commutation relation $[\hat{q}, \hat{p}] = i\hbar$. These are then used to construct the non-Hermitian annihilation ($\hat{a}$) and creation ($\hat{a}^\dagger$) operators, which respectively destroy or create a single photon in a given mode. The quantized Hamiltonian becomes [2]

$$\hat{H} = \sum_j \hbar\omega_j \left(\hat{a}_j^\dagger \hat{a}_j + \frac{1}{2} \right) \quad (2.2)$$

where the $\frac{1}{2}\hbar\omega_j$ term represents the zero-point energy, indicating that even in a complete vacuum with no photons present, the electromagnetic field possesses an irreducible, fluctuating energy.

This quantized description is essential for the present work because the measured detector noise cannot be fully explained by classical wave theory alone. The observed shot noise and vacuum noise floors arise directly from field quantization.

2.4 Key Concepts and Mathematics

2.4.1 Quadrature Operators and Uncertainty Principle

Instead of treating light strictly via classical amplitude and phase, quantum optics utilizes dimensionless quadrature operators [2]. The amplitude quadrature $\hat{X}_1$ and phase quadrature $\hat{X}_2$ are defined in terms of creation and annihilation operators:

$$\hat{X}_1 = (\hat{a}^\dagger + \hat{a}) \quad \text{and} \quad \hat{X}_2 = i(\hat{a}^\dagger - \hat{a}) \quad (2.3)$$

Because these operators do not commute $[\hat{X}_1, \hat{X}_2] = 2i$ they are bound by the Heisenberg uncertainty principle:

$$\Delta X_1 \Delta X_2 \geq 1 \quad (2.4)$$

This relation implies that the two conjugate quadratures of the field cannot be simultaneously determined with arbitrary precision. Understanding quadrature fluctuations is central to interpreting the vacuum noise measurements reported later in Chapter 4.

2.4.2 States of the Electromagnetic Field

The state of the quantized EM field can be described using various basis states, each with distinct statistical properties:

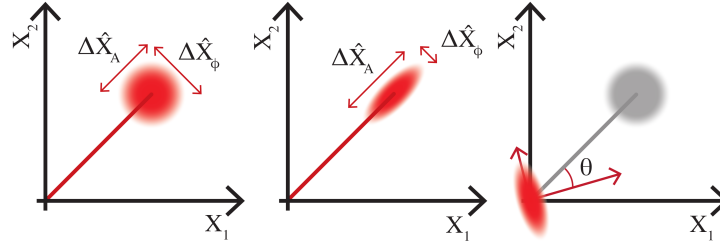


Figure 2.1: left one is a coherent state of light, a squeezed state of light is in the center, and squeezed vacuum is in the right [4].

- **Fock (Number) States** ($|n\rangle$)

These are eigenstates of the photon number operator ($\hat{n} = \hat{a}^\dagger \hat{a}$). In this state, the number of photons is known with absolute certainty ($\Delta n = 0$). However, as a consequence of the uncertainty principle, the phase of the field is completely random and undefined [5, 6].

- **Coherent States** ($|\alpha\rangle$)

These states most closely resemble a classical, stable laser beam (such as the field emitted by an NPRO laser). Coherent states are generated by displacing the vacuum state. They are "minimum uncertainty states," meaning their uncertainty product is at the absolute minimum ($\Delta X_1 \Delta X_2 = 1$), and this noise is symmetrically distributed in both quadratures ($\Delta X_1 = \Delta X_2 = 1$). They exhibit Poissonian photon statistics, meaning the variance in photon number is equal to the mean [2].

- **Squeezed States**

These are tailored non-classical states where the uncertainty in one specific quadrature is "squeezed" below the symmetric vacuum limit (e.g., $\Delta X_1 < 1$) [7]. So according to Heisenberg uncertainty principle, the orthogonal quadrature must be proportionately "anti-squeezed," resulting in increased noise ($\Delta X_2 > 1$).

In the present project, the coherent state is relevant because the laser source approximates a coherent optical field, while squeezed states represent the future target of the detection system under development.

2.5 Quantum Noise

Unlike classical noise sources such as mechanical vibrations or thermal fluctuations which can be theoretically reduced or eliminated, quantum noise is a fundamental unavoidable property of nature. It arises from Heisenberg Uncertainty Principle applied to quantized electromagnetic field. As discussed earlier, when light is modelled as a collection of quantum harmonic oscillators, the minimum energy state possesses an irreducible energy, known as zero-point energy ($\frac{1}{2}\hbar\omega$). Because of this, the field's amplitude and phase can never be perfectly defined simultaneously. Instead, they inherently fluctuate, which is represented mathematically as uncertainties in the field's quadrature operators and this is quantum noise.

2.5.1 Vacuum Noise (Fluctuations)

In classical physics, a vacuum is simply empty space with absolutely no electromagnetic fields present (energy equals zero). However, in quantum optics, the electromagnetic field is modeled mathematically as an infinite collection of simple harmonic oscillators, one for every possible frequency and mode. When we apply quantum mechanics to this model, the Hamiltonian (which represents the total energy of the field) is given by (2.2),

$$\hat{H} = \sum_j \hbar\omega_j \left(\hat{a}_j^\dagger \hat{a}_j + \frac{1}{2} \right)$$

where $\hat{a}_j^\dagger$ and $\hat{a}_j$ are creation and annihilation operators that respectively add or remove a photon from the mode j [7]. The critical part of this equation lies in $\frac{1}{2}$ term. If we consider the absolute ground state of the

field which is vacuum state $|0\rangle$ where the number of photons is zero ($\langle\hat{n}\rangle = 0$), the energy does not go to 0. Instead, it retains a non-reducible minimum energy known as **zero-point energy**:

$$E_{vac} = \frac{1}{2}\hbar\omega \quad (2.5)$$

While the average electric field in this vacuum state is zero ($\langle\hat{E}\rangle = 0$), the variance is always non-zero. The vacuum is a "minimum uncertainty state," meaning its noise is perfectly symmetrical and sits precisely at this fundamental limit. To put it simply, empty space is never truly empty. It is constantly "boiling" with microscopic, transient electromagnetic fields that appear and disappear. This is vacuum noise. It is not just a mathematical concept; it causes highly observable physical effects like the spontaneous emission of photons from excited atoms, the Lamb shift in atomic spectra.

In the experiments presented later, vacuum noise serves as the reference quantum noise baseline against which detector dark noise and future squeezing levels must be compared.

2.5.2 Photon Shot Noise

Shot noise originates from the "graininess", quantized nature of light, manifesting as the variance in the arrival times of individual photons. Even an ideal, perfectly stabilized laser (a coherent state) will exhibit fluctuations in the detected photocurrent because its photon distribution is inherently Poissonian.

A coherent state can be mathematically understood as a vacuum state that has simply been displaced away from the origin in phase space. Because it is just a displaced vacuum, a coherent state carries the exact same fundamental quantum noise as the vacuum itself.

When this coherent laser beam hits a photodetector, the discrete nature of the light becomes obvious. The field is quantized into indivisible packets of energy (photons). Because of the underlying vacuum fluctuations carried by the coherent state, these photons do not arrive at perfectly regular, predictable intervals like cars on a train; rather, they arrive randomly, like raindrops hitting a roof.

Since the arrival of photons obeys a Poisson distribution, the probability $P(n)$ of detecting exactly n photons in a given time interval is:

$$P(n) = \frac{\langle n \rangle^n}{n!} e^{-\langle n \rangle} \quad (2.6)$$

where $\langle n \rangle$ is the average number of photons [5, 7]. As we are aware that, variance of Poisson distribution is always equal to its mean, $(\Delta n)^2 = \langle n \rangle$.

Therefore, the standard deviation (the uncertainty) in the number of photons is simply the square root of the mean:

$$\Delta n = \sqrt{\langle n \rangle} \quad (2.7)$$

When light falls on a photodiode, this randomness in photon arrival translates directly into high-frequency fluctuations in macroscopic photocurrent.

- Current Noise Spectral Density ($A/\sqrt{Hz}$):

$$i_n = \sqrt{2eI} \quad (2.8)$$

where e is the elementary charge and I is the average photocurrent.

- Laser power, P incident on photodiode:

$$I = R \cdot P \quad (2.9)$$

where R is responsivity of the photodiode (A/W)

Then shot noise becomes,

$$i_n = \sqrt{2eRP} \quad (2.10)$$

Thus, shot noise increases with the square root of optical power. In practice, this current noise is converted into a voltage using a transimpedance amplifier, and the resulting voltage spectral density is measured using an electronic spectrum analyzer [8, 6].

In Chapter 4, the shot noise measurements were performed specifically to verify that the balanced detector suppresses classical intensity noise strongly enough to reveal this fundamental quantum noise contribution.

Together, vacuum noise and shot noise establish the absolute floor for measurement sensitivity, known as the Standard Quantum Limit (SQL).

2.6 Squeezed Light Generation and Detection

The generation of a continuous-wave squeezed vacuum state at 1064 nm relies on sequential nonlinear ($\chi^{(2)}$, $\chi^{(3)}$) optical processes hosted in stabilized resonant cavities. The four-stage workflow is the standard approach used in gravitational-wave detector squeezing systems. The polarization $\mathbf{P}$ includes higher order terms:

$$\mathbf{P} = \epsilon_0(\chi^{(1)}\mathbf{E} + \chi^{(2)}\mathbf{E}^2 + \chi^{(3)}\mathbf{E}^3 + \dots) \quad (2.11)$$

where $\chi^{(n)}$ is the n^{th} order nonlinear susceptibility and ϵ_0 , $\mathbf{E}$ are the permittivity of free space and the electric field respectively. Here, $\chi^{(2)}$ nonlinearity governs three-wave mixing interactions, which are responsible for both generating the required pump field via Second Harmonic Generation (SHG) and subsequently generating the squeezed state via Spontaneous Parametric Down-Conversion (SPDC).

Stage 1: The Coherent NPRO Laser Source

The starting element of the architecture is a highly stable, single frequency Non-Planar Ring Oscillator (NPRO) Nd:YAG laser. This laser provides the primary 1064 nm coherent field. The NPRO design is universally favored in precision metrology because its monolithic crystal structure and internal beam path inherently suppress spatial hole burning and provide extraordinary intrinsic frequency and amplitude stability [2]. A fraction of this highly stable 1064 nm light is deviated via a beam splitter to serve as the local oscillator for further stage of homodyne detection, while the majority of the optical power is directed into the nonlinear conversion stages.

Stage 2: Second Harmonic Generation (SHG)

This stage involves generating the high energy pump field required for the subsequent down-conversion process. A portion of the 1064 nm fundamental light is directed into a resonant cavity dedicated to Second Harmonic Generation (SHG). This cavity utilizes a nonlinear crystal, such as Potassium Titanyl Phosphate (KTP), to frequency double the light, producing a bright 532 nm (green) pump field [9]. To achieve the high intensities required for efficient nonlinear conversion, the SHG cavity must be actively locked to the laser frequency. This is achieved

using the Pound-Drever-Hall (PDH) technique, where phase modulation sidebands are added to the input beam via an Electro-Optic Modulator (EOM), generating a steep error signal upon reflection from the cavity.

The thermal expansion of the crystal due to optical absorption must be actively countered with highly precise thermoelectric coolers to maintain optimal phase-matching conditions [10]. The generated second harmonic wave must remain in phase with fundamental driving wave throughout the crystal; therefore, phase matching techniques like Birefringent Phase Matching (Type I, Type II), Quasi-Phase Matching are employed in such cases.

Stage 3: Squeezed Light Generation using OPO

The core of the squeezed light source is the Optical Parametric Oscillator (OPO), strictly operated below its oscillation threshold to prevent the generation of a coherent field, thereby emitting only a squeezed vacuum. The common configuration used in the gw detector research labs around world is a dual-frequency bow-tie resonator.

The bow-tie geometry is a ring cavity design chosen specifically to eliminate standing waves, prevent feedback into the laser source, and provide two distinct focal points; one for the nonlinear crystal and one for optimal input/output coupling. Inside this bow-tie cavity a Periodically Poled KTP (PPKTP) crystal is placed. Periodic poling is a manufacturing technique that permanently flips the orientation of the ferroelectric domains within the crystal at precise, micron-scale spatial intervals. This allows for quasi-phase-matching, which compensates for the refractive index dispersion between the 532 nm pump and the 1064 nm fundamental, yielding extraordinarily high nonlinear conversion efficiencies. The 532 nm pump field enters the OPO and undergoes spontaneous parametric down-conversion (SPDC), an effect where single high energy pump photons probabilistically split into pairs of lower energy, which are correlated photons at 1064 nm. Because these photon pairs are generated simultaneously and maintain phase correlations, the resulting optical state exhibits reduced noise in one quadrature; this state is a squeezed vacuum.

For maximum efficiency, the OPO cavity is engineered to be doubly resonant, meaning it simultaneously satisfies the resonance boundary conditions for both the 532 nm pump and the 1064 nm fundamental

fields, a requirement that provides sub-nanometer active length stabilization [11].

Stage 4: Balanced Homodyne Detection (BHD)

The final stage is the measurement of the squeezed state. The fragile 1064 nm squeezed vacuum comes out of the OPO cavity and must be propagated with minimal optical loss to the detection system. There it is recombined with the bright 1064 nm Local Oscillator (LO) field at a 50/50 beam splitter and directed into a Balanced Photodetector [9].

Balanced Homodyne Detection demands the photodetector should exhibit very low intrinsic electronic noise and also high rejection of classical amplitude noise originating from the laser source. If a single photodiode were used to measure the mixed LO-squeezed signal, the classical Relative Intensity Noise (RIN) of the intense LO would entirely overwhelm the microscopic quantum fluctuations of the squeezed vacuum. By utilizing a 50/50 beam splitter to divide the LO and the signal, the classical intensity fluctuations arrive at the two photodiodes perfectly in phase (common mode). When the balanced detector subtracts the two photocurrents, the common classical noise is canceled, while the quantum fluctuations are added in quadrature because of their random nature and can be observed clearly.

The literature tells us that squeezing is powerful, but only when the full chain works well: low-noise laser, efficient SHG, stable nonlinear cavity, low loss, and clean balanced readout.

Although squeezed light was not generated in the present work, this framework motivates the experimental requirements established in the thesis, particularly low optical loss, polarization control, and sufficient homodyne clearance above the electronics floor.

2.7 Summary

The literature reviewed in this chapter provides the theoretical basics for the experiments presented later in the thesis. The quantization of the electromagnetic field explains the existence of zero-point energy and vacuum fluctuations. Quadrature operators provide description of quantum noise and squeezed states. Coherent states and squeezed states illustrate how the uncertainty of the field may be distributed differently

depending on the quantum state. Shot noise and vacuum noise emerge as the key quantum noise processes relevant to optical measurement.

The concepts stated in this chapter are not merely theoretical background. They define the quantities that the balanced detection system must measure and distinguish from technical and electronic noise. The shot noise and vacuum noise experiments reported in Chapter 4 are therefore direct experimental tests of the concepts developed here. In this sense, the present chapter provides the conceptual bridge between the general theory of quantum optics and the specific balanced detection measurements performed in this work.

Chapter 3

Preliminary Experiments and Simulations

3.1 Mach-Zehnder Interferometer

Theory and Concept

The Mach–Zehnder Interferometer (MZI) is a widely used optical setup for demonstrating and studying the principle of interference. It works by splitting a beam of light into two separate paths and then recombining them to produce an interference pattern. This pattern carries information about the phase difference between the two paths. MZI provides the basic intuition for the Balanced Homodyne Detection experiment, which was carried out in the later stages of the project.

A MZI setup consists of two beam splitters and two mirrors. First, a light beam is incident on the first beam splitter, which divides it into two parts. These two beams then travel along different paths, commonly referred to as the two arms of the interferometer. The mirrors direct the beams so that they meet again at the second beam splitter. At this stage, the beams interfere with each other, and the nature of the interference depends on their relative phase difference. As a result, the output intensity can be either constructive (bright) or destructive (dark).

This interference behavior makes the MZI highly sensitive to changes in optical path length between the two arms. Because of this sensitivity, it is widely used in precision measurements, such as detecting refractive index changes, and also serves as an important tool in quantum mechanics and optics experiments. Any change in the phase of one arm relative to the other, for example due to a variation in path length or the inser-

tion of a material into the beam path, causes a corresponding shift in the interference pattern.

As each beam propagates through the interferometer, it accumulates a phase determined by its optical path length. If the two beams travel different distances or pass through different media, a phase difference, $\Delta\phi$, arises between them upon recombination. This phase difference is given by

$$\Delta\phi = \frac{2\pi}{\lambda}(L_1 - L_2) \quad (3.1)$$

where L_1 and L_2 are lengths of two paths and λ is wavelength of light.

Assuming each arm contributes complex amplitudes $A_1e^{i\phi_1}$ and $A_2e^{i\phi_2}$. At the output, the electric fields from both paths will combine. Therefore, the detected intensity is the modulus squared of the total field::

$$I = |A_1e^{i\phi_1} + A_2e^{i\phi_2}|^2 \quad (3.2)$$

If the amplitudes are equal, the intensity pattern depends only on the phase difference $\Delta\phi$:

$$I = 2A^2[1 + \cos(\Delta\phi)] \quad (3.3)$$

This expression shows that the detected intensity oscillates between bright and dark as the phase difference changes. In other words, constructive and destructive interference occur depending on the relative phase between the two beams. The phase difference can be controlled by changing the path lengths or by altering the optical properties of the material placed in one of the arms.

Experimental Setup

In the lab, we used a in house made pump diode 1064 nm IR Nd:YVO₄ laser, followed by a Faraday isolator to suppress back reflections. A half-wave plate (HWP) and a polarizing beam splitter (PBS) were then used together as a power control stage.

The beam was collimated using the two-pinhole method, ensuring it propagated parallel to the optical table at a height of 90 mm.

As the light enters the Mach–Zehnder interferometer (MZI), the first beam splitter (BS1) divides it into two paths: one directed toward mirror M2 and the other toward mirror M3, which is mounted on a PZT ac-

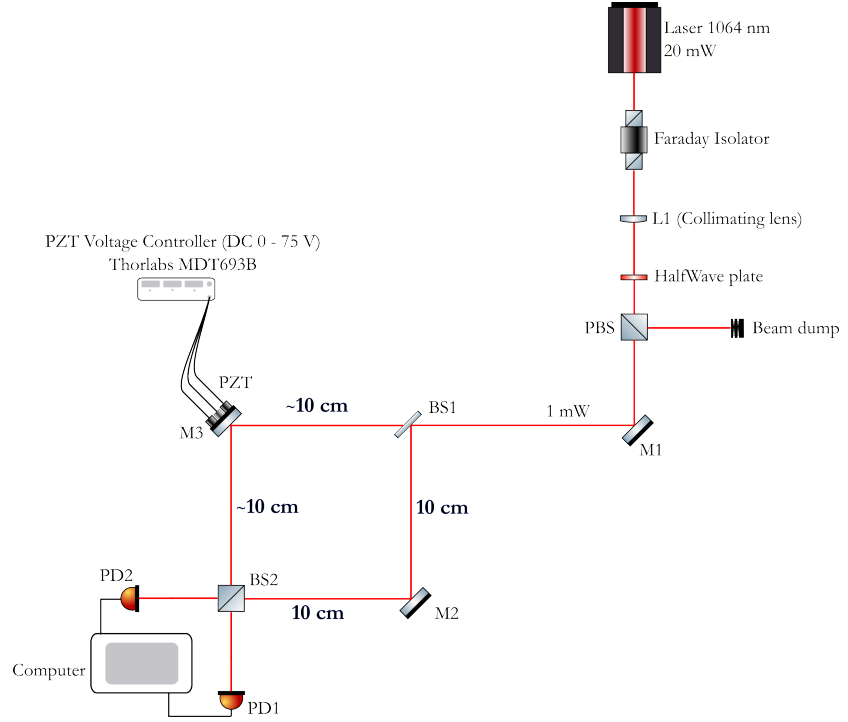


Figure 3.1: Schematic of the Mach-Zehnder Interferometer experiment

tuator. After reflecting from these mirrors, the beams recombine at the second beam splitter (BS2). At the output, observations are made at two ports: the transmitted and reflected outputs of BS2.

Since mirror M3 is attached to a PZT actuator, driving the PZT introduces a path/phase difference between the two arms. This phase difference leads to constructive or destructive interference at BS2.

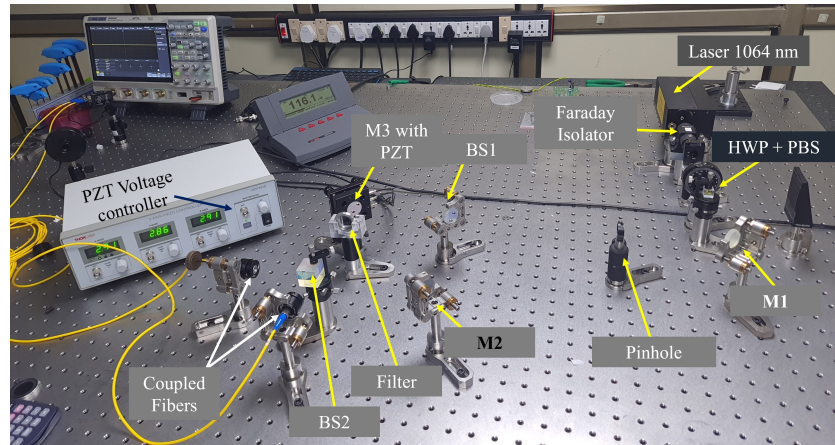


Figure 3.2: Photograph of the tabletop Mach-Zehnder Interferometer

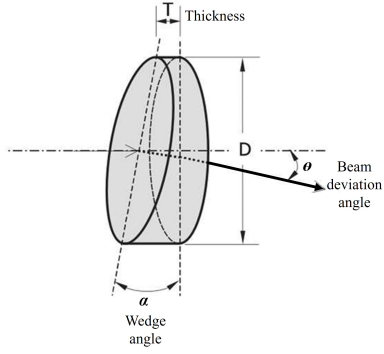
Wedge Measurement

While setting up and aligning the experiment, we observed that the beam underwent a slight vertical shift after passing through the plate beam

splitter (BS1). Initially, we suspected that the issue might have arisen from improper collimation or misalignment. However, upon careful inspection, we found that one surface of the plate beam splitter had a wedge.

This vertical shift is undesirable. However, due to the limited availability of cube beam splitters, we had to use at least one plate beam splitter in the setup. Therefore, we decided to study the effect of the wedge beam splitter through simulation.

Using the Python package LightPipes, we simulated our experimental scenario with two plate beam splitters while keeping the rest of the Mach–Zehnder interferometer (MZI) configuration unchanged. Before performing the simulation, we estimated the approximate wedge angle from the vertical shift of about 3.5 mm observed in the experiment. The calculation is as follows,



θ : angle of beam deviation (measured at 875 mm)

α : wedge angle

n_1 : refractive index of air

n_2 : refractive index of BS (BK7 material)

Figure 3.3: Wedged beam splitter geometry and parameter definitions

$$\sin(\alpha) = \frac{n_1}{n_2} \sin(\theta + \alpha) \quad (3.4)$$

for small angle θ, α

$$\theta = \left(\frac{n_2}{n_1} - 1 \right) \alpha \quad (3.5)$$

$$= (n - 1) \alpha \quad \text{where } \frac{n_2}{n_1} \sim n = 1.5$$

$$\theta = \frac{3.5 \text{ mm}}{875 \text{ mm}}$$

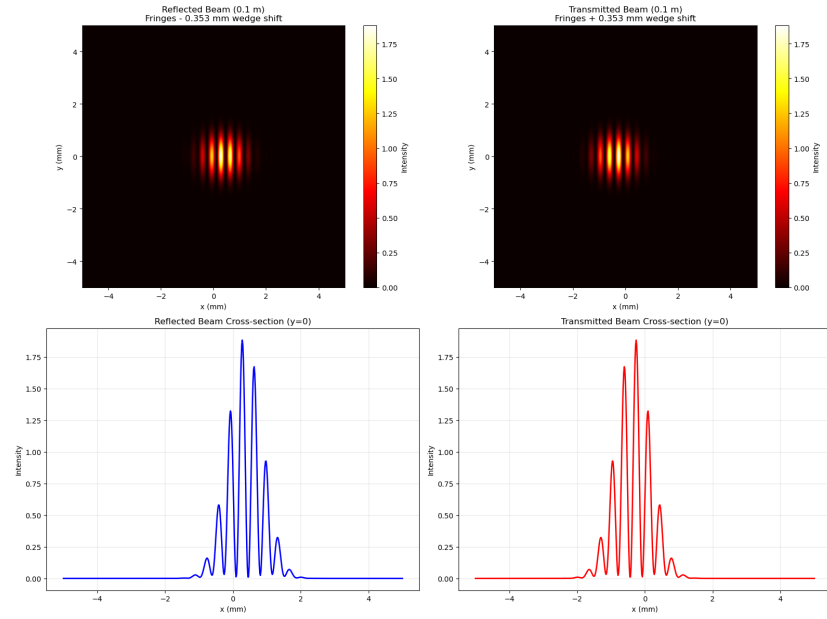
$$= 4.07 \text{ mrad} = 0.233^\circ = 14 \text{ arc minute}$$

$$\alpha = \frac{\theta}{n - 1} = 28 \text{ arc minute} \quad (3.6)$$

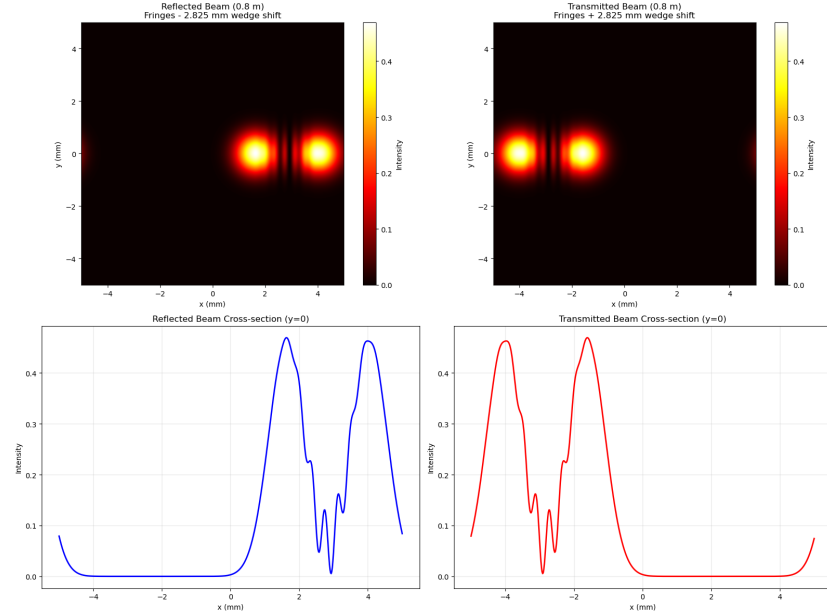
So wedge angle comes out to 28 arc minute.

Using this estimated wedge angle in the simulation, we examined the interference pattern at different observation positions, such as near BS2

and at a certain distance away from BS2. The Python code used for the simulation is provided in the Appendix on page 49.



(a) Simulated interference at 0.1 m



(b) Simulated interference at 0.8 m

Figure 3.4: LightPipes simulation of interference in the Mach–Zehnder Interferometer with wedged plate beam splitters

From the simulation results, it became clear that if plate beam splitters with wedge are used at both required positions, it is not possible to keep the two beams well overlapped. As seen in the results, at a distance of 0.1 m from BS2 the beams still interfere to a reasonable extent. How-

ever, as the observation screen is moved farther away, for example to 0.8 m, the beams no longer merge properly.

Adjustment to MZI Setup

To overcome the beam shift caused by the wedged beam splitter, ideally both beam splitters should have been replaced with cube beam splitters. However, we were able to arrange only one. Since proper overlap of the beams at the output was essential, it was clear that the single cube beam splitter had to be used at the BS2 position.

We therefore continued using the wedged plate beam splitter at BS1. By carefully rotating BS1, we adjusted its orientation so that the beam shift introduced by the wedge became completely horizontal, that is, parallel to the optical bench. This horizontal displacement could then be compensated by slightly shifting mirror M3. Although this adjustment increased the corresponding arm length, it did not pose a problem, since the PZT drive also changes the arm length during operation. Hence, this approach was adopted in the setup.

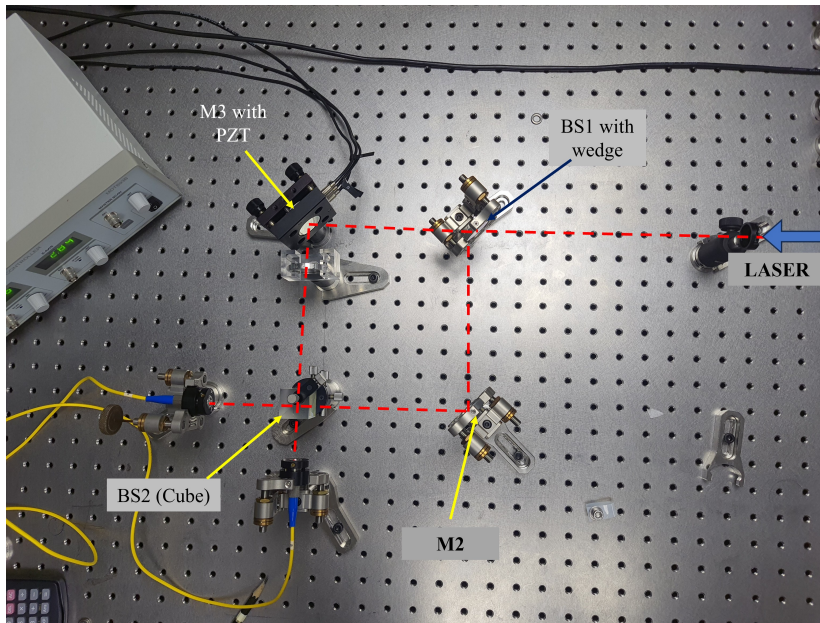


Figure 3.5: Modified Mach–Zehnder Interferometer layout used to compensate the wedge induced beam shift

PZT Expansion Measurement

We automated the operation of the MZI setup by driving the PZT through a Python script while simultaneously recording the outputs of both pho-

todiodes, PD1 and PD2. A 50 V triangular ramp with a period of 720 seconds was applied to the PZT. When fitting a cosine function to the obtained data points,

$$PD_1 = y_0 + \frac{K}{2} (1 + \cos[\frac{2\pi}{V_h}(x - x_0)]) \quad (3.7)$$

where, y_0 is the offset or minimum intensity,

$\frac{K}{2}$ is amplitude of the interference signal,

V_h is voltage period corresponding to 2π phase shift (one λ).

Through numerical fitting V_h comes out to be 14.03 ± 0.02 V

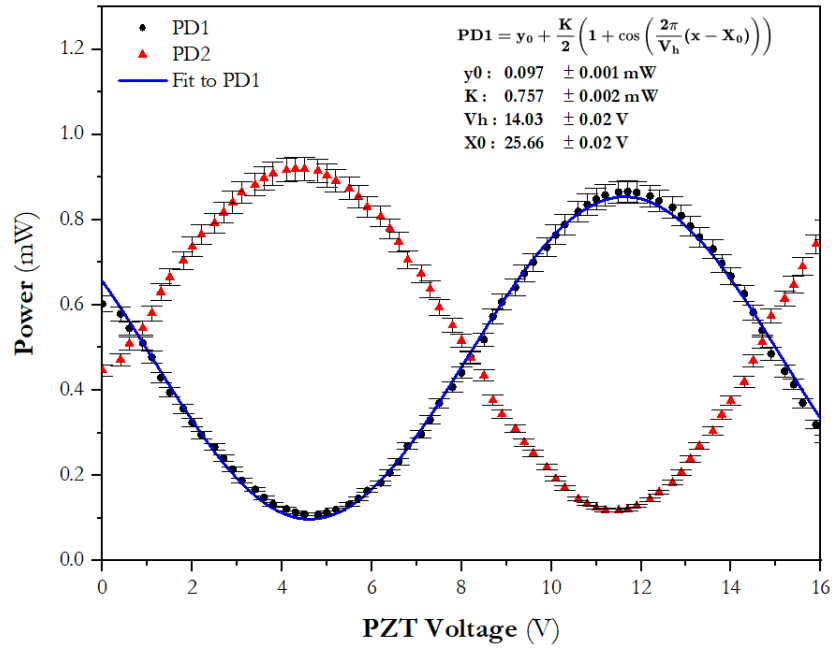


Figure 3.6: Measured output powers at PD₁ and PD₂ as a function of PZT drive voltage, together with cosine fits

The PZT displacement is expressed as following,

$$\begin{aligned} d &= \frac{1064 \text{ nm}}{2\cos(45^\circ)} \cdot \frac{150 \text{ V}}{V_h} \\ &= \frac{1064 \text{ nm}}{2\cos(45^\circ)} \cdot \frac{150 \text{ V}}{14.03 \pm 0.02 \text{ V}} \\ &= 8.04 \pm 0.01 \mu\text{m} \end{aligned} \quad (3.8)$$

Earlier, these measurements were carried out manually by varying the voltage step by step and recording the corresponding power observed at

PD1 and PD2. From those measurements, we obtained a PZT displacement of $7.8 \pm 0.2 \mu\text{m}$.

After automating the process, we obtained a more precise value of $8.04 \pm 0.01 \mu\text{m}$, which is very close to the nominal displacement of $8 \mu\text{m}$ specified in the product datasheet for the PZT model KC1-PZ/M provided by Thorlabs [12].

3.2 Cavity Simulations in FINESSE

Introduction

Finesse (Frequency-domain INterferomEter Simulation SoftwarE) is a tool used to simulate optical systems such as cavities and interferometers. Performing simulations beforehand is a good practice, as it helps in developing a better understanding of the optical system before working on the optical bench.

Using Finesse 2, a Fabry–Perot cavity was simulated in three different configurations based on the reflectivities of the mirrors: an under-coupled cavity, an over-coupled cavity, and an impedance-matched cavity.

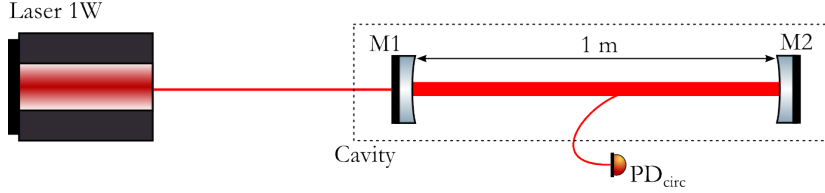


Figure 3.7: Schematic of the Fabry–Perot cavity model used in FINESSE simulations

Cavity Parameters

While designing a cavity, it is important to consider parameters such as the Free Spectral Range ($\Delta\nu_{\text{FSR}}$), Finesse $\mathcal{F}$, Full Width at Half Maximum (FWHM), and P_{max} (power buildup), as these determine the cavity performance for the desired application.

Free Spectral Range ($\Delta\nu_{\text{FSR}}$):

The free spectral range represents the separation between two consecutive resonance peaks of the cavity. It depends on the cavity length, L , and is given by,

$$\Delta\nu_{\text{FSR}} = \frac{c}{2L} \quad (3.9)$$

where, c is speed of light.

Finesse ($\mathcal{F}$):

The finesse of a cavity depends on the reflectivities of its mirrors and indicates how many times, approximately, the light bounces back and forth inside the cavity before leaking out. In general, a higher finesse corresponds to a sharper resonance and stronger confinement of light within the cavity, which is often desirable for many applications.

$$\mathcal{F} = \frac{\pi(R_1 R_2)^{\frac{1}{4}}}{1 - \sqrt{R_1 R_2}} = \frac{\text{FSR}}{\text{FWHM}} \quad (3.10)$$

where, R_1 and R_2 are intensity reflectivities of input and output mirrors respectively.

Power circulating in the cavity ($P_{\text{circ(max)}}$):

As the light undergoes multiple reflections inside the cavity, constructive interference occurs at resonance, leading to a buildup of power within the cavity. This circulating power can become significantly larger than the input power, depending on the cavity parameters.

$$P_{\text{circ(max)}} = P_{\text{in}} \frac{T_1}{(1 - \sqrt{R_1 R_2})^2} \quad (3.11)$$

where P_{in} is input power, T_1 is transmission of input mirror.

Here, the simulated cavity is of 1 m in length for input of 1064 nm laser of 1 W and varying reflectivities according to 3 cases under study. T_1 and T_2 are transmission of input and output mirrors respectively [13, 14, 3].

Simulated Cases

Impedance Matched Cavity

In an impedance-matched cavity, the transmissivity of the input and output mirrors are equal ($T_1 = T_2$), implying equal reflectivities ($R_1 = R_2$). Based on the calculated reflectivity and transmissivity values, the theoretical Finesse is 29.80 with a maximum circulating power ($P_{\text{circ(max)}}$) of 10 W. Simulation results are close to theoretical values, with a measured Finesse of 29.76 and $P_{\text{circ(max)}} \approx 10$ W, as in Figure 3.8.

Over-coupled Cavity

In an over-coupled configuration, the transmissivity of the input mirror exceeds that of the output mirror ($T_1 > T_2$, or $R_1 < R_2$). For this simulation, we assumed values of $T_1 = 10\%$ and $T_2 = 1\%$. The re-

sulting theoretical parameters are $\text{Finesse}_{\text{theoretical}} = 54.5$ and $P_{\text{circ(max)}} = 31.8$ W. The simulated values match the theoretical predictions, yielding $\text{Finesse}_{\text{measured}} = 54.5$ and $P_{\text{circ(max)}} \approx 31.8$ W, as in Figure 3.9.

Under-coupled Cavity

The under-coupled cavity is the inverse of the over-coupled case, where the input mirror transmissivity is lower than the output mirror transmissivity ($T_1 < T_2$, or $R_1 > R_2$). By assuming $T_1 = 1\%$ and $T_2 = 10\%$, the calculated cavity parameters are $\text{Finesse}_{\text{theoretical}} = 54.5$ and $P_{\text{circ(max)}} = 3.1$ W. The simulation confirms these values, with $\text{Finesse}_{\text{measured}}$ of 54.5 and $P_{\text{circ(max)}} \approx 3.1$ W, as in Figure 3.10.

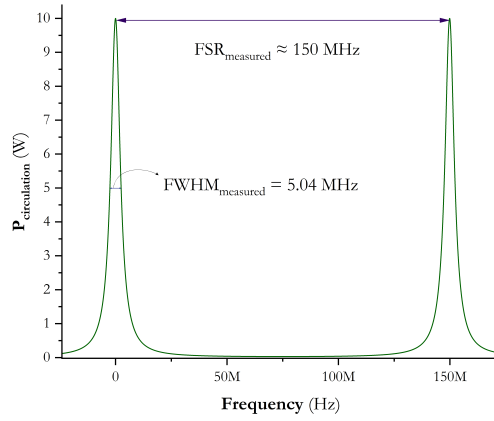


Figure 3.8: Simulation measurement of $\Delta\nu_{\text{FSR}}$ and FWHM for Impedance-matched cavity

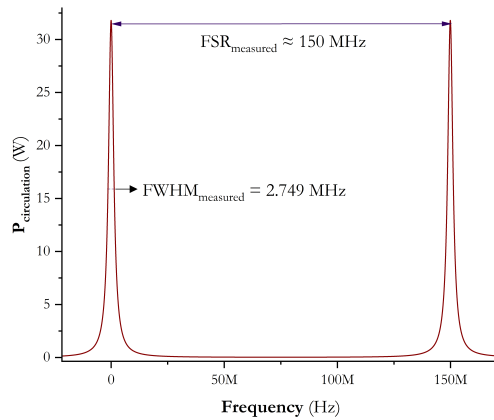


Figure 3.9: Simulation measurement of $\Delta\nu_{\text{FSR}}$ and FWHM for Over-coupled cavity

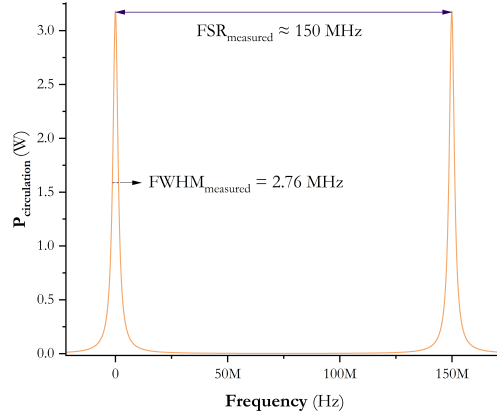


Figure 3.10: Simulation measurement of $\Delta\nu_{\text{FSR}}$ and FWHM for Under-coupled cavity

Parameter	Impedance-Matched	Over-Coupled	Under-Coupled
$F_{\text{theoretical}}$	29.80	54.5	54.5
F_{measured}	29.76	54.5	54.26
$P_{\text{circ(max)}} \text{ (W)}$	10	31.8	3.1

Table 3.1: Comparison of the simulated impedance-matched, over-coupled, and under-coupled Fabry–Perot cavity configurations in terms of finesse and circulating power.

From this comparison in Table 3.1, it can be seen that the over-coupled cavity has the highest buildup (circulating power) among the simulated cases. For an Optical Parametric Amplifier (OPA), a higher buildup is desirable because it increases the interaction between the input pump light and the nonlinear crystal, which in turn can lead to the generation of a larger number of correlated photons.

3.3 Beam Profiling

Gaussian Nature of Laser Beam and Beam Parameters

Most laser beams, particularly those from well-designed laser cavities, exhibit a Gaussian intensity profile. It means that the irradiance (power per unit area) follows a Gaussian distribution in the transverse plane, with the intensity highest at the beam center and decreasing exponentially with radial distance. The mathematical description of a Gaussian beam's irradiance at any point is given by:

$$I(r, z) = I_0 \left(\frac{w_0}{w(z)} \right)^2 \exp \left(-\frac{2r^2}{w(z)^2} \right) \quad (3.12)$$

where I_0 is the peak irradiance, r is the radial distance from the beam axis, $w(z)$ is the beam radius at position z along the propagation axis, and w_0 is the beam waist (minimum beam radius). The beam radius $w(z)$ goes according to:

$$w(z) = w_0 \sqrt{1 + \frac{(z - z_0)^2}{z_R^2}} \quad (3.13)$$

where z_0 is the location of the beam waist and $z_R = \pi w_0^2 / \lambda$ is the Rayleigh range, with λ the wavelength of the laser [15, 16].

Beam profiling is the measurement and characterization of the spatial intensity distribution of a laser beam at various positions along its propagation axis. Understanding this beam propagation behavior is essential for designing optical systems, focusing laser beams to desired spot sizes, and optimizing beam delivery in applications.

In this experiment, beam profiling was performed using two methods at distances of 200 mm, 300 mm, 400 mm, and 500 mm from the laser head:

1. Knife Edge method
2. Thorlabs BP209 Beam Profiler-based measurements.

Knife Edge Method

The knife edge method is a common and widely used technique for measuring laser beam radius that relies on the principle of partial beam obstruction. In this approach, an opaque edge (such as a razor blade or precision knife edge) is translated perpendicular to the beam propagation direction, progressively blocking more of the beam cross-section.



Figure 3.11: Knife Edge translation stage used for beam profiling

As the knife edge moves through the beam profile, a photodetector positioned in line with beam propagation measures the transmitted power. Power versus knife edge lateral position is recorded for different

locations along the beam path. A Gaussian beam waist fit based on Eq (3.13) is applied to this data. The beam radius w can be extracted from the fit parameter.

In the experiment, beam radius measurements were conducted at four discrete positions along the laser propagation axis: 200 mm, 300 mm, 400 mm, and 500 mm from the laser head. At each position, the knife edge was scanned through the beam profile while recording the transmitted power, and the data was fitted to the Gaussian function to obtain the beam radius. Through fitting procedure shown in Figure 3.12, the values obtained were: beam waist w_0 of $232.3 \mu\text{m}$ located at a position -82.46 mm from the laser head. The negative position indicates that the beam waist occurs behind the laser head, within the laser cavity.

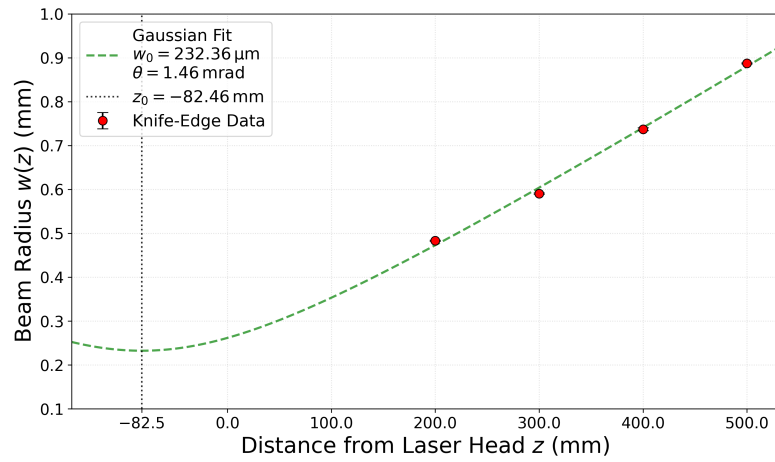


Figure 3.12: Beam radius measurements obtained using the Knife Edge method, together with the fitted Gaussian beam propagation model

Thorlabs BP209 Beam Profiler-based Measurements

The Thorlabs BP209 beam profiler represents a compact, sophisticated, camera-based approach to beam characterization that offers significant advantages over other methods. The primary advantages of camera-based beam profilers include their ability to capture the complete beam profile instantaneously (eliminating issues with temporal beam fluctuations that can affect scanning methods) [17].



Figure 3.13: BP209 Beam Profiler [17]

Using this beam profiler, beam radius measurements were obtained at the same four positions used in the knife edge method: 200 mm, 300 mm, 400 mm, and 500 mm from the laser head. At each location, the profiler captured the beam's two-dimensional intensity distribution. The beam profiler data were subjected to the same curve fitting procedure used for the knife edge results.

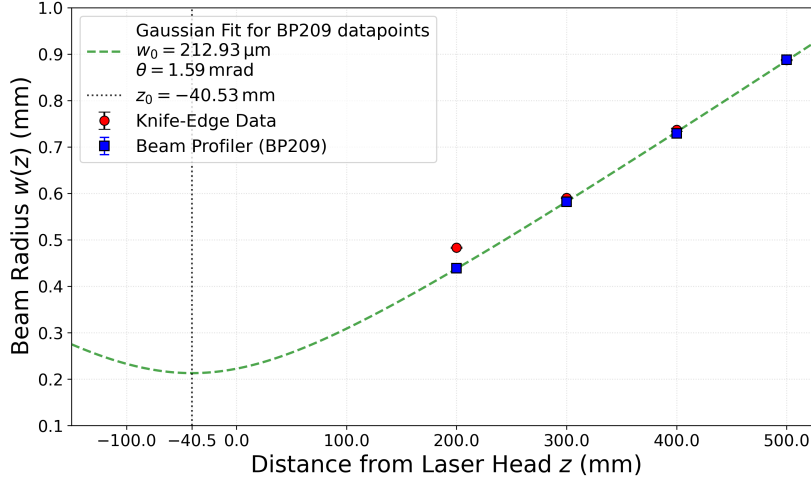


Figure 3.14: Comparison of beam profiling results obtained using the Knife Edge method and the BP209 beam profiler

This analysis tells us that, a beam waist of $212.9 \mu\text{m}$ located at -40.5 mm from the laser head. Compared to the knife edge results, the beam profiler measurement indicates a slightly smaller beam waist (by approximately 8%) positioned further forward along the beam propagation path (by about 42 mm) as shown in Figure 3.14

Parameter	Knife Edge method	BP209 beam profiler
Waist radius, w_0	$232.3 \mu\text{m}$	$212.9 \mu\text{m}$
Waist position, z_0	-82.5 mm	-40.5 mm
Divergence, θ	1.46 mrad	1.59 mrad

Table 3.2: Comparison of beam parameters obtained from Knife Edge and BP209 beam profiler measurements.

The small difference between the two fitted waist values and positions is reasonable and can arise from experimental uncertainties, limited number of measurement points, and differences in how the beam radius is determined by each method. Moreover, the agreement between the two methods supports that the laser output beam is close to Gaussian and physically consistent. Going forward, all further experiments assume $w_0 \approx 213 \mu\text{m}$.

3.4 Polarization Studies

To understand the evolution of polarization as light propagates through the optical setup required for BHD, a polarization measurement experiment was carried out using the Thorlabs PAX1000 series polarimeter [18]. The specific aim was to evaluate and understand the impact of different reflective surfaces, specifically comparing metallic mirrors versus dielectric mirrors for a linearly polarized 1064 nm beam.



Figure 3.15:
PAX1000 Series
Polarimeter [18]

Thorlabs PAX1000 is a highly precise, wave-plate-based metrology module designed specifically to map the State of Polarization (SOP) of collimated, monochromatic coherent light.

Mirrors are ubiquitous in optical setups for beam routing and steering, but their reflection physics differ fundamentally based on their composition, generating highly divergent effects on s-polarized light (where the electric field is perpendicular to the plane of incidence) and p-polarized light (where the electric field is parallel to the plane of incidence) [19].

When linearly polarized light, oriented such that it contains both s- and p-components (for instance, polarized at 45° relative to the optical table), strikes a standard dielectric mirror, the reflection is governed by macroscopic thin-film interference. Dielectric mirrors are composed of multiple alternating microscopic layers of high and low refractive index materials (such as fused silica). If the dielectric mirror is specifically optimized for the 1064 nm wavelength and the correct angle of incidence (most common either 0° or 45°), it generally preserves the relative phase between the s- and p-components. Therefore, linearly polarized light remains linearly polarized upon reflection [20].

On the other hand, metallic mirrors (such as protected silver) operate on different physical principles. The reflection from a metallic boundary is described by the Fresnel equations using a complex permittivity. This complex nature inherently causes a differential phase shift between the s- and p-polarization components upon reflection. Furthermore, s-polarized light generally exhibits a slightly higher reflectivity magnitude than p-polarized light at large angles of incidence on metallic surfaces [20].

In the experiment, measurements confirmed these theoretical predictions. When a pure linearly polarized 1064 nm beam was reflected off a protected metallic mirror at a 45° angle of incidence, the PAX1000 mapped a distinct changes in the polarization state whereas in case of dielectric mirror state of polarization was nearly unchanged.

Mirror Coating Type	Polarization Preservation (Mixed states)	Preservation (Mixed s/p)	Differential Shift (s vs p)	Phase
Dielectric	High (if aligned to design axis)		Nearly zero	
Metallic (Silver)	Poor (at non-normal incidence)		Significant, angle-dependent	

Table 3.3: Qualitative comparison of polarization preservation for dielectric and metallic mirrors.

A conclusion drawn from this study and comparison in Table 3.3 is that for the OPO and BHD setups, high-quality, polarization-preserving dielectric mirrors must be used to maintain the linear polarization purity of the 1064 nm fields.

3.5 Summary

The experiments and simulations presented in this chapter established the practical optical foundation required for the later quantum noise measurements. Taken together, these studies were not isolated side experiments, but directly supported the main objective of the thesis. They reduced uncertainty in beam handling, alignment, interference control, and optical component choice, thereby enabling the more reliable shot noise and vacuum noise measurements described in Chapter 4.

Chapter 4

Quantum Noise Experiments

This chapter presents the quantum noise experiments carried out using balanced photodetection and balanced homodyne detection. The main goal of this work was to verify whether the experimental system can reliably observe quantum noise and can later be used for squeezed light measurements. Two major experiments were performed: photon shot noise measurement and vacuum noise measurement.

4.1 Photon Shot Noise Measurement

As discussed earlier in section 2.5.2, shot noise arises due to the discrete nature of light. Since each photon arrives at the detector independently of others, the number of detections in a given time interval fluctuates around a mean value. In an ideal measurement, these fluctuations follow Poissonian statistics, and the associated shot noise spectral density increases as the square root of optical power. Therefore, observing the expected $\sqrt{P}$ scaling of the noise provides a direct experimental signature of quantum noise limited detection.

In practice, however, the measured detector output often contains both quantum noise and classical technical noise. These classical contributions include residual laser intensity noise, polarization fluctuations, imperfect balancing, and detector-related instabilities. For this reason, shot noise measurements were performed in balanced configuration. In this detection setup, the goal is to eliminate common-mode classical noise to reach this fundamental quantum noise floor. When two identical detectors receive exactly equal power from the same source, their subtracted output cancels the correlated classical noises like Relative In-

tensity Noise (RIN), leaving only the uncorrelated shot noise of the two beams, and these add in quadrature.

Recalling the eq. 2.8 and eq. 2.10 for conceptual reference.

$$i_n = \sqrt{2eI}$$

$$i_n = \sqrt{2eRP}$$

In practical measurements, this current is converted into a voltage signal via a transimpedance amplifier (TIA) so we need to accordingly take this into consideration while estimating corresponding voltage spectral density V_{psd} of shot noise. The spectral density of shot noise is "white," which means it is distributed uniformly across the frequency spectrum. Characterizing this noise requires an electronic spectrum analyzer (ESA) capable of resolving signals in the MHz regime (e.g., 20 MHz) where classical noises are not dominant.

The accuracy of quantum noise measurements is dependent on the configuration of the measurement instruments being used. The Rigol RSA3000 series ESA [21] served as the primary tool for frequency domain analysis in these experiments. The following ESA settings were maintained across all experiments to ensure data consistency and to allow for direct comparisons between different detectors.

Parameter	Value
Centre frequency	20 MHz
Span	40 MHz
RBW	100 kHz
VBW	10 kHz
Pre-amp	OFF
Average number of points	50
Average mode	Log
Trace type	Average
Trace detector type	Average (RMS)

Table 4.1: ESA settings used for quantum noise experiments

The Resolution Bandwidth (RBW) is a critical factor in normalizing measured voltages to spectral density units ($V/\sqrt{Hz}$). The power measured by the ESA is integrated over the RBW. Therefore, a measurement in Volts must be divided by the square root of the RBW to obtain the spectral density.

4.2 Fiber-coupled TIA-527 BPD-based Shot Noise Measurement

The first shot noise experiment was carried out using TTI TIA-527 Balanced photodetector [22]. It is matched InGaAs detector with one output port and provides selectable (1X and 10X) transimpedance gain. Before performing the noise measurements, its optical to electrical conversion gain was measured at the 1X gain setting with a $14\text{ k}\Omega$ transimpedance and DC coupling. For a digital storage oscilloscope input impedance of $1\text{ M}\Omega$, the conversion gain was found to be approximately 10.3 kV/W , whereas for a $50\text{ }\Omega$ termination the measured value was approximately 5 kV/W . The reduction by nearly a factor of two is consistent with the expected loading caused by the lower termination impedance.

In the experiment, the optical power was balanced between the two ports of the BPD, and the RF output was measured on the ESA at 20 MHz . For each optical power, the expected shot noise value was calculated theoretically, including the detector responsivity, transimpedance gain and the effect of the observation bandwidth. The measured values were then compared with the theoretical prediction in Table 4.2.

Power (μW)	Expected V_{psd} ($\text{nV}/\sqrt{\text{Hz}}$)	Measured V_{psd} ($\text{nV}/\sqrt{\text{Hz}}$)	Std. Deviation ($\text{nV}/\sqrt{\text{Hz}}$)
100	34.1	36.1	3.0
150	41.8	46.8	5.0
200	48.2	55.1	6.3
250	53.9	60.4	7.5
300	59.0	66.5	6.9

Table 4.2: Comparison of expected and measured V_{psd} for the fiber-coupled TIA-527 balanced photodetector.

As per the expected shot noise behaviour, this result shows the increase in noise with increment in power. For incident powers of 100, 150, 200, 250, and $300\text{ }\mu\text{W}$, the theoretical voltage spectral density increased from 34.1 to $59.0\text{ nV}/\sqrt{\text{Hz}}$, while the measured values increased from 36.1 to $66.5\text{ nV}/\sqrt{\text{Hz}}$. However, the agreement between theory and experiment was not very good, and the standard deviation of the measured values remained relatively large, ranging from 3.0 to $7.5\text{ nV}/\sqrt{\text{Hz}}$.

These results indicate that detector output still contained the classical noises. The primary cause was identified as the use of non-polarization maintaining fiber. Polarization state fluctuations in the fiber arms lead to variations in the interference conditions at the BPD's internal coupler, resulting in unstable power balancing. This prevents the detector

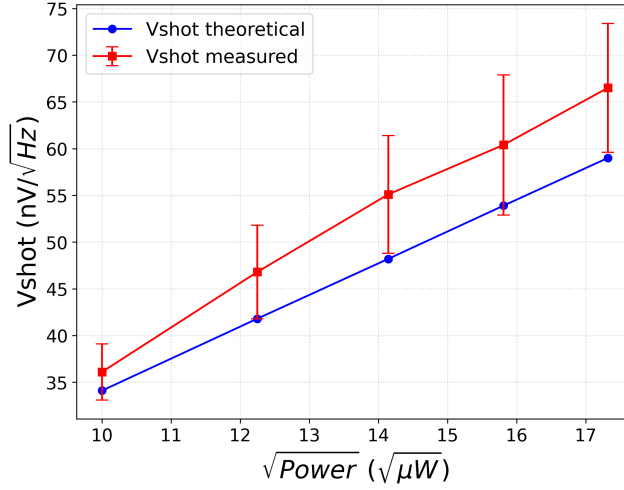


Figure 4.1: Shot noise measurements obtained using the fiber-coupled TIA-527 balanced photodetector

from achieving its maximum Common Mode Rejection Ratio (CMRR), causing residual classical noise to sit on top of the quantum shot noise. Although this detector showed the expected shot noise trend, its stability and noise rejection were insufficient for precision measurements.

To achieve more stability and improve the shot noise measurement, experiment was shifted to free-space balanced photodetector, where beam alignment and polarization control could be handled more directly.

4.3 Free-Space BPD-based Shot Noise Measurement

Similar to TIA-527, this PDB230C is also a matched InGaAs detector. It has 3 output channels, MON +, MON -, RF. Monitor channels are mainly used for alignment purposes [23]. This detector has very small active aperture area of 0.3 mm diameter which imposes a strict requirement of optical alignment and beam transfer.



Figure 4.2: PDB230C Balanced Photodetector

Beam Transfer and Alignment Geometry

Given the restriction due to smaller active aperture diameter, the goal of the beam transfer system was to focus two parallel laser beams onto the BPD apertures such that the beam diameter at the detector plane should

be approximately $200\text{ }\mu\text{m}$. This size is large enough to avoid local saturation of the InGaAs photodiodes while remaining safely within the $300\text{ }\mu\text{m}$ physical aperture to prevent clipping loss. A simple yet precise setup was required to meet the demands of experiment. The design employed a configuration with two lenses as follows:

- L_1 ($f = 200\text{ mm}$): to collimate the incoming diverging beam.
- L_2 ($f = 150\text{ mm}$): to focus the collimated beam onto the BPD.
- Spot radius of $93.1\text{ }\mu\text{m}$ at detector plane (1289 mm from laser head)

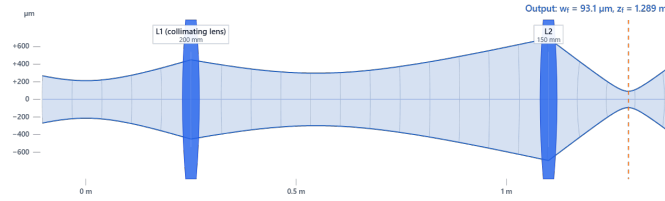


Figure 4.3: Optical beam transfer design used to deliver the laser beam onto the free-space balanced photodetector

Apertures of PDB230C are separated by exactly 50.8 mm (2 inches). To ensure both beams hit the centers of these apertures with near-identical spot sizes, a "beam walking" procedure was implemented. This involved using two kinematic mirrors for one of the paths to independently control the position (transverse shift) and the angle (tilt) of the beam as shown in Figure 4.4

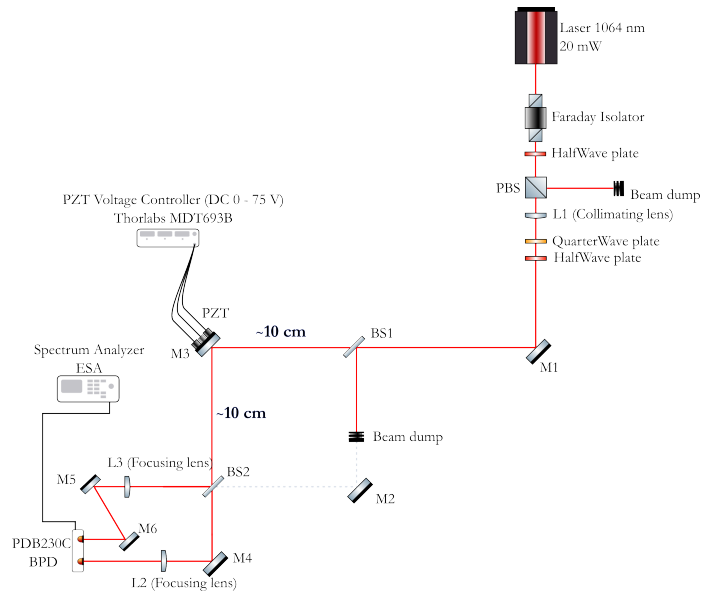


Figure 4.4: Schematic of Free-space BPD based Shot Noise and Vacuum Noise measurement setup

Free-Space BPD Basic Characterization

After successful alignment and beam transfer onto the detector, conversion gain measurements were carried out for each output channel. For Monitor channels, conversion gain was measured 7.0 kV/W and 7.3 kV/W for MON - and MON + channels respectively. Conversion gain of the RF channel is 17.56 kV/W; as calculated through linear fit in Figure 4.5. For single channel operation, it was observed that at very low values of incident power ($< 15 \mu\text{W}$), the BPD response is not consistent. These values established the calibration required for subsequent shot noise study.

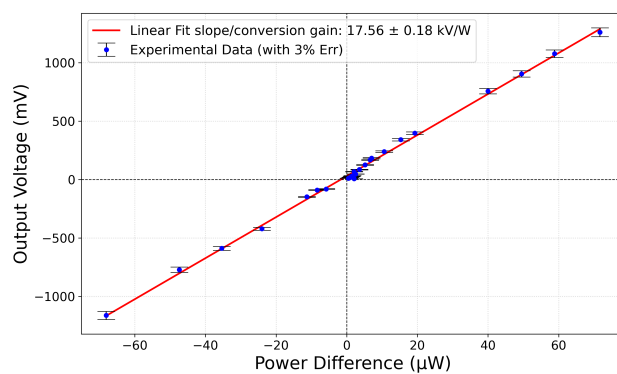


Figure 4.5: Measured RF output conversion gain of the PDB230C balanced photodetector

4.3.1 Shot Noise Measurements

Two experiments were carried out with PDB230C for shot noise measurement,

- Single channel shot noise measurement
- Balanced power shot noise measurement

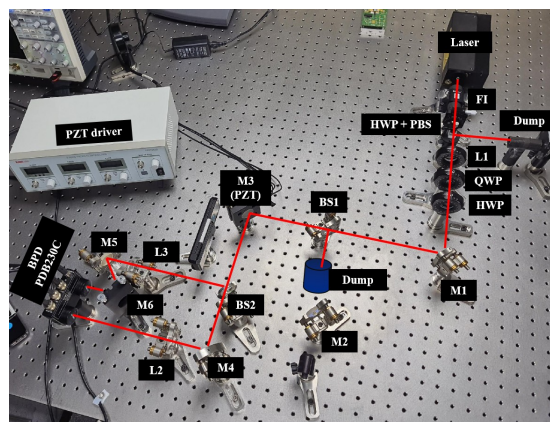


Figure 4.6: Photograph of the tabletop arrangement used for the quantum noise experiments

Single Channel Shot Noise Measurement

The PDB230C has the capability to bear up to $115 \mu W$ per single channel before CW saturation. Before operating the detector in a balanced mode, a single channel shot noise study was carried out. Since the configuration does not reject common-mode laser intensity fluctuations, the resulting measurement contains both quantum shot noise and classical technical noise.

In this case, optical power (up to $\approx 100 \mu W$) was incident only on MON - channel and RF output was fed to ESA with same settings as mentioned earlier in the Table 4.1.

Power (μW)	Expected V_{psd} ($\mu V/\sqrt{Hz}$)	Measured V_{psd} ($\mu V/\sqrt{Hz}$)	Std. Deviation ($\mu V/\sqrt{Hz}$)
100.7	0.1164	0.1270	0.0646
79.7	0.1035	0.1184	0.0681
66.5	0.0946	0.0908	0.0819
49.4	0.0815	0.0901	0.0820
35.2	0.0688	0.0615	0.1035
20.4	0.0523	0.0656	0.0979

Table 4.3: Comparison of expected and measured V_{psd} for single channel operation of the PDB230C.

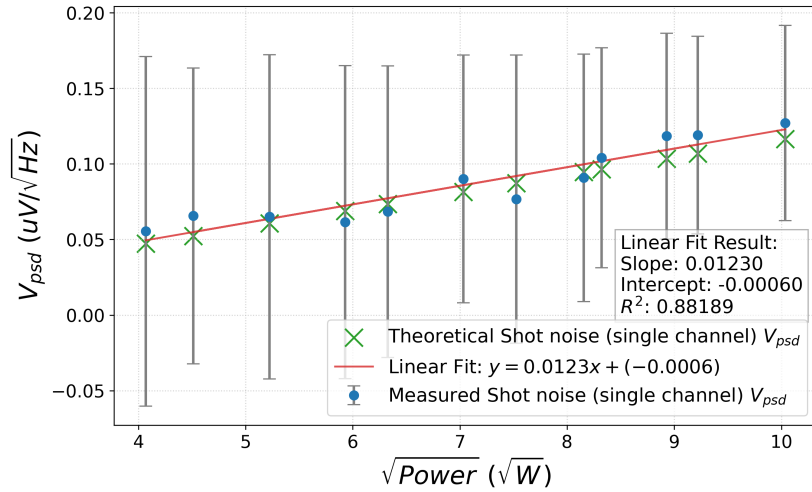


Figure 4.7: Results of single channel-based shot noise study

The measured data showed that the noise level still increased approximately with $\sqrt{P}$, as expected for shot noise. However matching between theoretical and measured values remained poor. For example, across the measured power range from about 20.36 to $100.70 \mu W$, the measured values fluctuated significantly and the standard deviation was high as clearly seen in Figure 4.7, reaching values comparable to or larger than the theoretical signal at low powers. Since the optical powers were not

balanced, common mode classical intensity noise was not effectively rejected.

Thus, although the single channel measurement was useful as a reference, it clearly demonstrated that balanced operation is essential if the detector is to approach the quantum noise limit.

Balanced Power Shot Noise Measurement

In the balanced configuration, nearly equal power was maintained on both ports. The high common mode rejection ratio (CMRR) of the PDB230C helps suppress classical noise. Incident power on each channel was varied from 20 μW to 220 μW . Under ideal balancing, the difference output contains primarily the uncorrelated shot noise contributions of the two beams but in the actual table-top setup, there was a slight imbalance in power due to an additional mirror used for alignment and beam walking purposes in one of the paths.

Power (μW)	Expected V_{psd} ($\mu\text{V}/\sqrt{\text{Hz}}$)	Measured V_{psd} ($\mu\text{V}/\sqrt{\text{Hz}}$)	Std. Deviation ($\mu\text{V}/\sqrt{\text{Hz}}$)
220.0	0.1720	0.1809	0.0052
200.0	0.1640	0.1697	0.0024
179.5	0.1554	0.1609	0.0063
160.1	0.1467	0.1476	0.0033
139.7	0.1371	0.1415	0.0038
120.5	0.1273	0.1303	0.0029
100.1	0.1160	0.1195	0.0023
79.9	0.1036	0.109	0.0032
66.7	0.0947	0.0974	0.0031
49.6	0.0817	0.0856	0.0042
35.3	0.0689	0.0698	0.0038
20.0	0.0519	0.0527	0.0047

Table 4.4: Comparison of expected and measured V_{psd} for balanced power operation of the PDB230C.

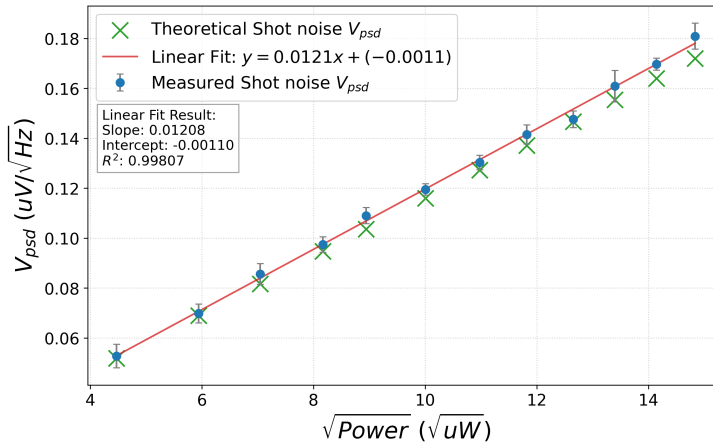


Figure 4.8: Results of shot noise study for balanced configuration

The transition to a balanced power configuration showed a significant improvement in results over both the fiber-coupled case and the single channel case. The measured voltage spectral density followed the theoretical shot noise prediction closely over the full power range studied. The theoretical values ranged from 0.0519 to 0.1720 $\mu\text{V}/\sqrt{\text{Hz}}$, while the measured values ranged from approximately 0.0527 to 0.1809 $\mu\text{V}/\sqrt{\text{Hz}}$, with very small deviations. In addition, the standard deviation dropped substantially, remaining in the range of about 0.0023 to 0.0063 $\mu\text{V}/\sqrt{\text{Hz}}$.

This result confirms proper balanced detector operation and indicates that the free-space system approached a stable quantum noise limited level over the measured power range, where classical noises were successfully suppressed to a large extent.

4.4 Comparison of the Shot Noise Measurements

Configuration	Agreement with theory	Main limitation / observation
Fiber-coupled balanced power BPD	Moderate	Large fluctuations; imperfect balancing due to fiber instability
Free-space single channel	Poor	Classical noise remains because subtraction is absent
Free-space balanced power BPD	Very good	Classical noise largely suppressed; reliable shot noise calibration

Table 4.5: Qualitative comparison of shot noise measurements.

Together, the three shot noise studies provide a clear progression in detector performance. The fiber-coupled balanced detector showed the expected increase in noise with optical power, but suffered from instability and poor agreement with theoretical values, primarily due to polarization fluctuations and incomplete balancing. The free-space detector in

single channel mode also showed the expected power scaling, but without balanced subtraction the measurements remained strongly affected by classical noise. Only in the balanced free-space configuration was close agreement with theory obtained together with low measurement deviation.

This comparison demonstrates that common mode noise rejection is not merely a refinement but an essential requirement for observing shot noise limited behavior in the present system. It also confirms that the transition to a free-space BPD was justified and technically effective. Therefore, it serves as experimentally reliable shot noise calibration needed for the next stage of Balanced Homodyne Setup.

4.5 Vacuum Noise Measurement

With a stable shot noise limited baseline established, the experiments progressed further toward vacuum noise measurement in a Balanced Homodyne Detection (BHD) setup. In this experiment goal is to observe the quantum noise baseline associated with vacuum noise and verify whether the complete balanced homodyne detection (BHD) setup has enough clearance above the electronic dark noise to measure squeezed light. This is an important readiness test. When a squeezed state is produced, it cannot be observed properly if the electronic noise floor is too close to the quantum-noise baseline.

In BHD configuration used here, one arm of the Mach–Zehnder interferometer was blocked so that no coherent signal field entered that port. The other arm acted as the local oscillator (LO), and its phase was scanned using a PZT mirror. For different optical power levels, LO beam interferes with a signal port that is intentionally blocked to allow only vacuum fluctuations to enter. This is equivalent to measuring effect of the ground-state fluctuations (zero-point energy) of the electromagnetic field as discussed earlier in the section 2.5.1, governed by the Heisenberg uncertainty principle as per the eq 2.5.

$$E_{vac} = \frac{1}{2} \hbar \omega$$

Interference Scenarios in Homodyne Detection

To understand the vacuum noise baseline, it is helpful to compare the expected outcomes for different states entering the signal port of the 50:50

beam splitter in a BHD setup when local oscillator phase is scanned using the PZT.

Signal Port State	Interference Effect	Noise Output Behavior
Vacuum State	No interference	Flat noise line at the shot noise level
Coherent State	Coherent interference	Sinusoidal oscillation with LO–signal phase
Squeezed State	Quantum noise interference	Phase-dependent noise suppression/enhancement

Table 4.6: Expected balanced homodyne noise behavior for different signal-port states.

When the signal port contains vacuum, no classical interference occurs and the noise trace remains flat as vacuum noise is phase independent. If a coherent signal were present, the output would show phase dependent sinusoidal oscillation. If a squeezed state were present, the output would show phase dependent suppression and enhancement of the noise relative to the vacuum baseline.

An important metric for any balanced homodyne detection system is the clearance between the quantum noise baseline (V_{RF}) and the electronic dark noise floor (V_{dark}). The electronic dark noise is the sum of the BPD internal noise and the ESA’s own noise floor.

$$\text{Clearance (dB)} = 20 \log_{10} \left(\frac{V_{\text{RF}}}{V_{\text{dark}}} \right). \quad (4.1)$$

For example, to detect a squeezed state that is 2 dB below the shot noise limit, the clearance must be significantly greater than 2 dB [3]. Particularly for this project goal was to achieve clearance of 5 dB, which will in future serve the detection needs of initial phases of squeezed light generation setup at RRCAT.

Measurements were conducted for two LO power levels: 50 μW and 440 μW . The PZT was driven with a 16 V ramp to scan through more than one wavelength of phase. RF output was fed to ESA with same settings as mentioned in Table 4.1 at 20 MHz. Simultaneously, monitor

output channels of BPD were observed on digital storage oscilloscope as check for incident power levels.

4.5.1 Case 1: 50 μW Local Oscillator Power

To begin with first measurement was carried out with local oscillator power of 50 μW . Results obtained are as follows,

- Average ESA Output: 63.24 μV
- Electronic Dark Noise: 53.6 μV ($\sigma = 0.55\mu\text{V}$)
- ESA Dark Noise: 14 μV ($\sigma = 0.1\mu\text{V}$)
- Calculated Clearance: 1.43 dB

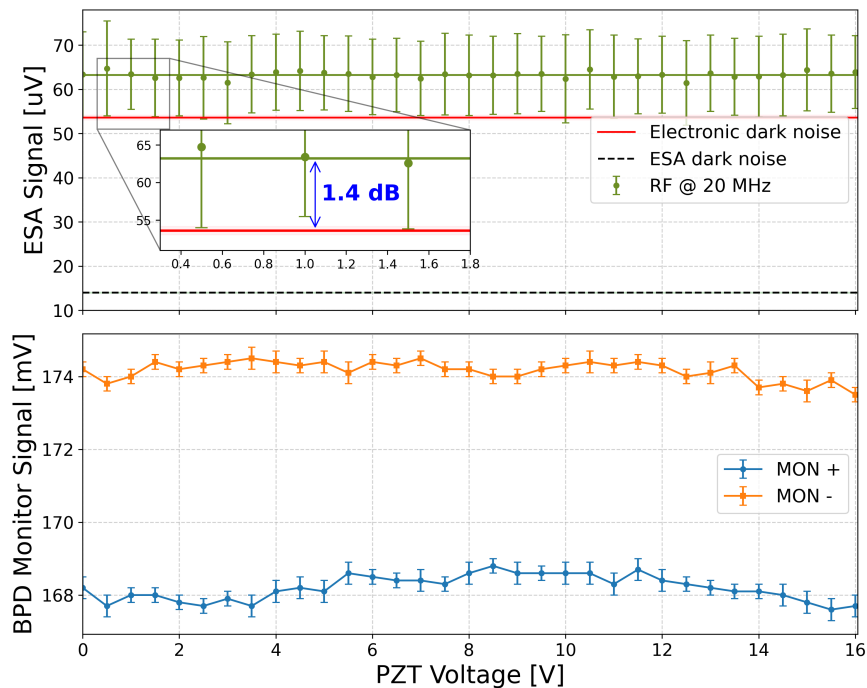


Figure 4.9: Clearance of 1.4 dB for LO power of 50 μW

At this LO power level of 50 μW , observed clearance of 1.4 dB indicates that the vacuum noise baseline is only slightly above the electronic noise floor. This limited clearance means that any quantum squeezing would be "buried" under the detector's electronic noise, making it undetectable. Figure 4.9 shows that the standard deviation of the quantum noise level brings it close to the electronic dark noise floor at several points, further emphasizing the limited detectability in this configuration.

4.5.2 Case 2: 440 μW Local Oscillator Power

To check for a better clearance value than that obtained with a 50 μW local oscillator, measurement was repeated with higher local oscillator power of 440 μW . In this case, the average ESA output increased significantly. Results obtained are as follows,

- Average ESA Output: 100.5 μV
- Electronic Dark Noise: 53.6 μV ($\sigma = 0.55\mu\text{V}$)
- ESA Dark Noise: 14 μV ($\sigma = 0.1\mu\text{V}$)
- Calculated Clearance: 5.46 dB

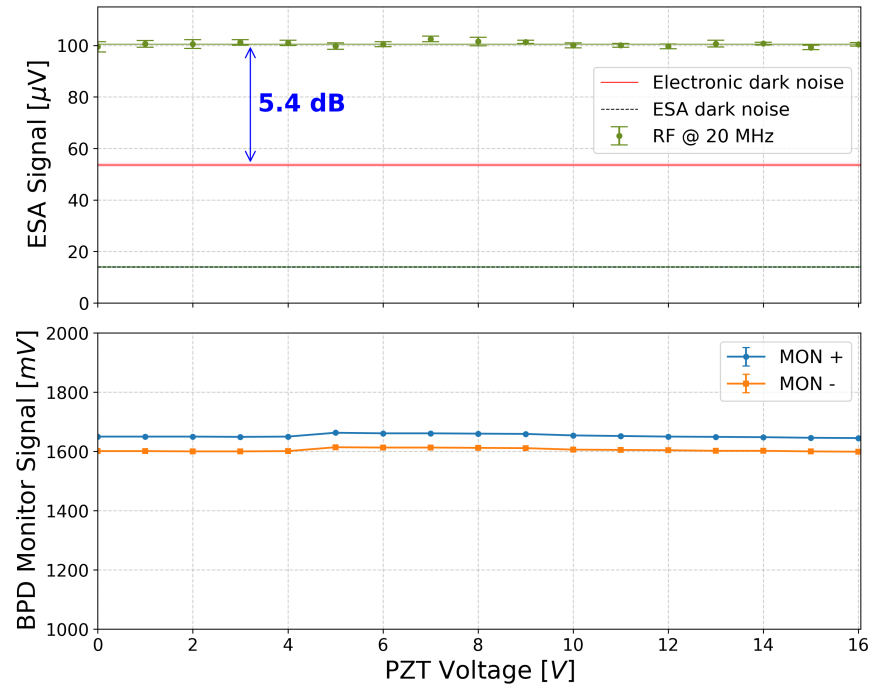


Figure 4.10: Clearance of 5.4 dB for LO power of 440 μW

Increasing the LO power to 440 μW improves the clearance to 5.46 dB. As a result, the system becomes capable, at least in principle, of detecting a squeezed light of few-decibel level. The increase in LO power effectively raises the quantum noise signal while leaving the electronics floor unchanged, thereby improving observability. This is a clear indication from the present work that the balanced homodyne system is approaching practical readiness for future squeezed light experiments.

4.6 Interpretation of Vacuum Noise Measurements

A key experimental observation is that the RF signal remains nearly flat during the PZT scan in both local oscillator cases. This is exactly what is expected when vacuum fluctuations enter the signal port. Vacuum has zero mean field and therefore does not produce a classical interference. The homodyne phase changes when the PZT is scanned, but since ordinary vacuum noise is phase independent, the measured RF baseline remains essentially constant. Another important observation is that the clearance depends strongly on LO power, and in this experiment, the available clearance improves substantially when the LO is increased from $50 \mu\text{W}$ to $440 \mu\text{W}$.

A squeezed state has phase dependent quadrature fluctuations, so in that case scanning the PZT would rotate the measured quadrature and produce a phase-dependent noise curve, with noise suppression below shot noise at one phase and enhancement at the orthogonal phase. Thus, the vacuum noise measurement serves following purposes:

- it verifies that the homodyne system is responding in a physically correct way when vacuum enters the signal port, and
- it quantifies the clearance between the quantum noise baseline and the electronics floor.

Chapter 5

Conclusion

This project investigated the experimental requirements for quantum noise limited homodyne detection at 1064 nm, with the long term objective of supporting future squeezed light measurements. It was motivated by the role of quantum noise in precision interferometry and by the need to develop a stable balanced detection platform before attempting full squeezed light generation and characterization. In this context, the thesis combined theoretical study, supporting preliminary experiments, and quantum noise measurements to evaluate the readiness of the present system.

A broad theoretical background was first established through the study of field quantization, quadrature fluctuations, coherent and squeezed states, vacuum noise, photon shot noise, and balanced homodyne detection. Followed by preliminary experiments and simulations which played an important supporting role in the development of the final measurement system. The Mach–Zehnder interferometer study provided practical understanding of interference, optical path imbalance, and PZT-based phase control. The cavity simulations in FINESSE showed how different coupling conditions influence finesse and circulating power. Beam profiling confirmed that the laser output was close to Gaussian and provided the beam parameters required for beam transfer design. Polarization studies showed that dielectric mirrors preserve the linear polarization state more reliably than metallic mirrors, which is highly relevant for future balanced homodyne and squeezed light experiments.

Quantum noise experiments, Shot Noise Measurement and Vacuum Noise Measurement provided the central results of the thesis. The first shot noise measurements were performed using a fiber-coupled TIA-527 balanced photodetector. These measurements showed the expected increase of noise with increasing optical power, confirming the basic shot

noise trend. However, the agreement with theoretical values was moderate and the standard deviation of the measurements remained relatively large. The primary reason identified was the use of non polarization maintaining fiber, which led to polarization fluctuations, unstable balancing, and incomplete suppression of classical noise. This configuration therefore did not provide sufficiently stable performance for precision quantum noise measurement.

To overcome these limitations, the experiment was shifted to a free-space balanced photodetector, the PDB230C. A beam transfer system was designed and aligned to ensure proper beam size and positioning on the two detector apertures. The free-space detector was then studied in both single channel and balanced modes. In the single channel configuration, the measured noise still showed significant fluctuations and poor agreement with theoretical shot noise predictions, demonstrating that classical noise remained present when balanced subtraction was absent. This made it clear that balanced operation was essential for reaching the quantum noise limited regime.

The most important shot noise result was obtained in the balanced free-space configuration. Under balanced incident power, the measured voltage spectral density matched the theoretical shot noise prediction very well over the full power range studied. At the same time, the standard deviation of the measurements reduced significantly. This clear improvement demonstrates that common mode classical noise was successfully suppressed and that the detector was operating close to the expected quantum noise limit. Thus, the free-space balanced PDB230C provided the reliable shot noise calibration required for the next stage of balanced homodyne measurements.

After establishing this stable shot noise baseline, measurements of effect of vacuum noise were performed in a balanced homodyne detection setup. The purpose of this experiment was to determine whether the vacuum noise baseline could be resolved sufficiently above the electronic dark noise floor. This was quantified through the clearance. At a local oscillator power of $50 \mu\text{W}$, the measured clearance was only 1.43 dB, indicating that the quantum noise baseline is too close to the electronics floor for reliable squeezed light detection. However, when the local oscillator power was increased to about $440 \mu\text{W}$, the clearance improved to 5.46 dB. This result is significant because it shows that the present system is capable, in principle, of resolving squeezing at approximately the 5 dB level, in controlled conditions.

The present work has completed an important preparatory stage by demonstrating quantum noise limited balanced detection in a free-space configuration and by establishing measurable vacuum noise clearance above the electronics floor. The future work is to combine this detection platform with a squeezed light source and proceed toward direct observation of phase-dependent squeezing at 1064 nm.

Appendix

- Google Colab-based Python code, simulation and analysis plots for the experiments carried out can be found [here](#)

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