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Characterization of a Balanced Homodyne Detection for Optical Explanations

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Abstract

In the realm of quantum optics, the precise characterization of various noise sources such as shot noise, electric noise, and vacuum noise is pivotal for advancing optical measurement technologies and quantum information systems. This study introduces an experimental approach using homodyne detection to convert fluctuations in light intensity into voltage signals. These signals are then analyzed with the aid of an oscilloscope or a spectrum analyzer to dissect the temporal and spectral characteristics of the noise. The integration of these tools allows for a detailed observation and differentiation of quantum noises, providing insights that are critical for refining the accuracy and efficiency of optical systems. The high capability of the Mach-Zehnder interferometer for spatial and spectral analysis of a 633nm HeNe laser beam was demonstrated, yielding satisfactory results for further research and analysis in the area of intrinsic characteristics of quantum noise from the laser itself and the electronic components used (electrical noise). This project was primarily based on two parts: optics and electronics. We successfully completed the optical part, and the electrical component remains for future investigation.

Quantum States of Light

MOTIVATION

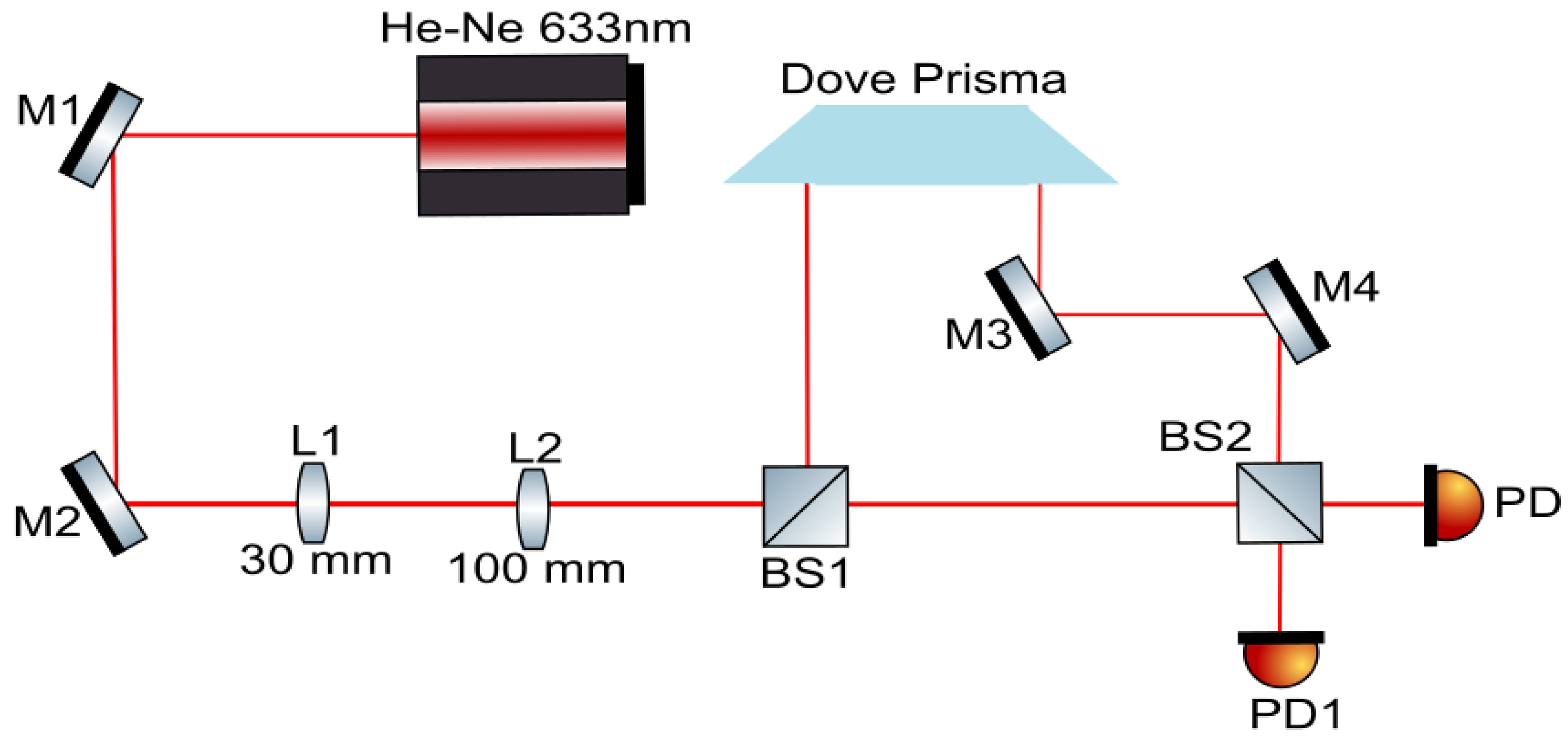
- The interferometer helps measure and manipulate quantum light states.
- Exploiting quantum properties of light can lead to super-precise measurements.
- Using the interferometer to study quantum light offers insights into quantum mechanics, enhancing our understanding of phenomena like superposition and entanglement.
- Mastering quantum light manipulation aids in developing new quantum-based technologies.

Characterization of Quantum Noises

MOTIVATION

- Understanding quantum noises through HBD helps in refining the accuracy and sensitivity of quantum measurement systems, essential for experiments involving quantum states.
- By better characterizing the different types of quantum noises such as shot noise, electric noise, and vacuum noise, these systems enable more effective noise reduction strategies.
- Understanding and mitigating quantum noises can lead to more reliable qubits and quantum gates, directly impacting the efficiency and error rates in quantum systems.

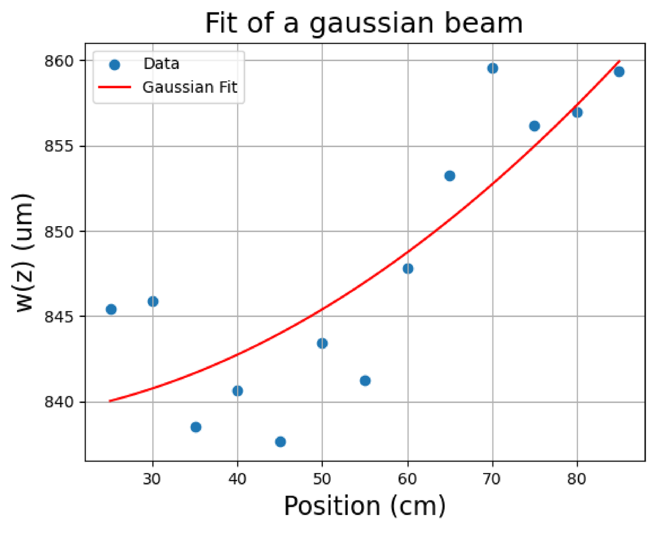
Mach-Zehnder Interferometer



$$\omega_z = \omega_0\sqrt{1+\left(\frac{z-z_0}{z_R}\right)^2} \quad con\ z_R = \frac{\pi\omega_0^2}{\lambda}$$

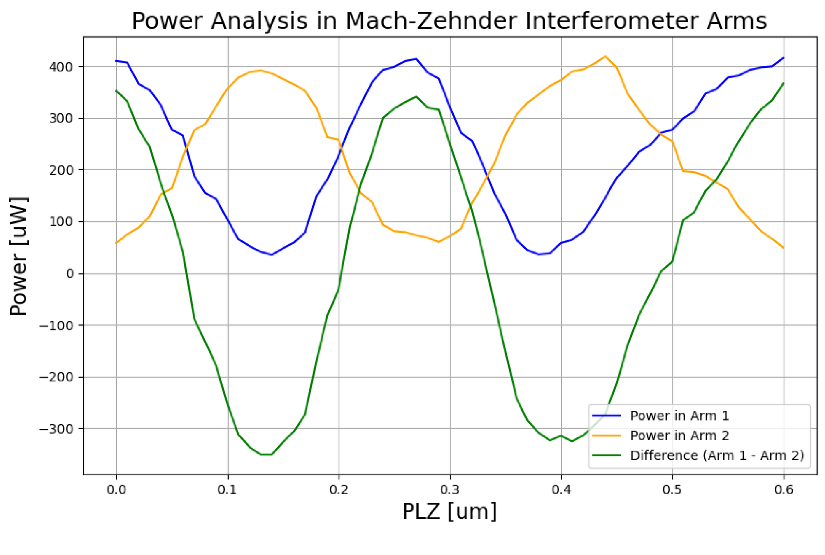
$$V = \frac{P_{max}-P_{min}}{P_{max}+P_{min}}$$

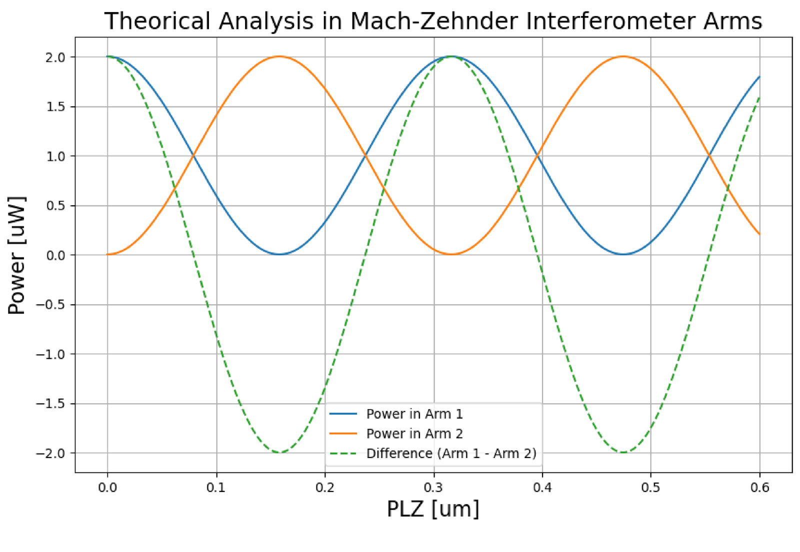
- The Rayleigh distance z_R allows us to determine the distance over which our beam does not vary during the experiment.
- Thus, through ω_z, a fit of the experimental data for the waist can be performed, thereby obtaining both z_0 and ω_0.
- In a Mach-Zehnder interferometer, visibility refers to the system's ability to distinguish between the highest and lowest intensity levels observed.



$$P_{media} = \frac{P_{max}+P_{min}}{2}$$

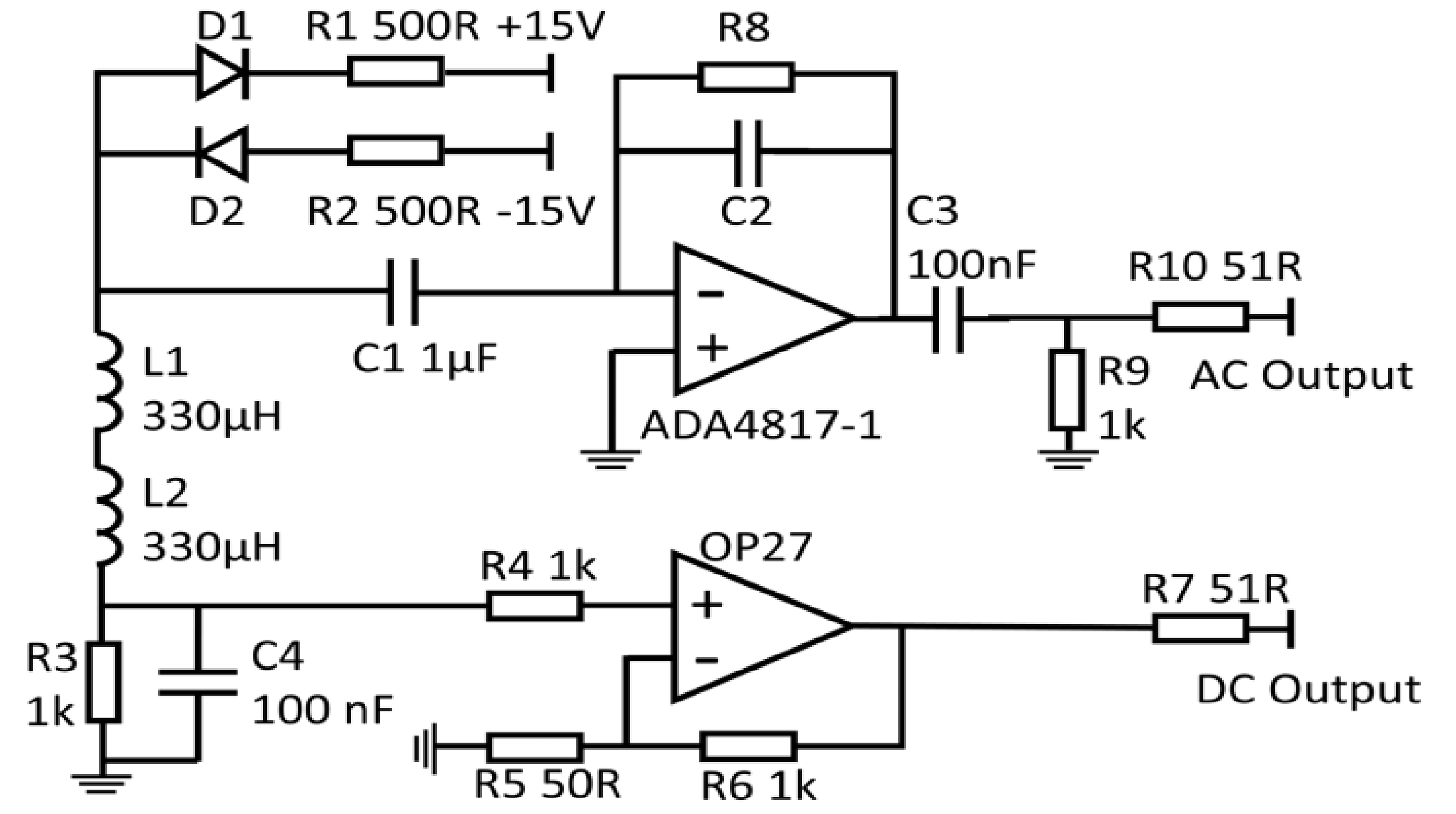
$$P = P_{media}\left(1 \pm V\cos\left(\frac{2\pi\Delta x}{\lambda}\right)\right)$$





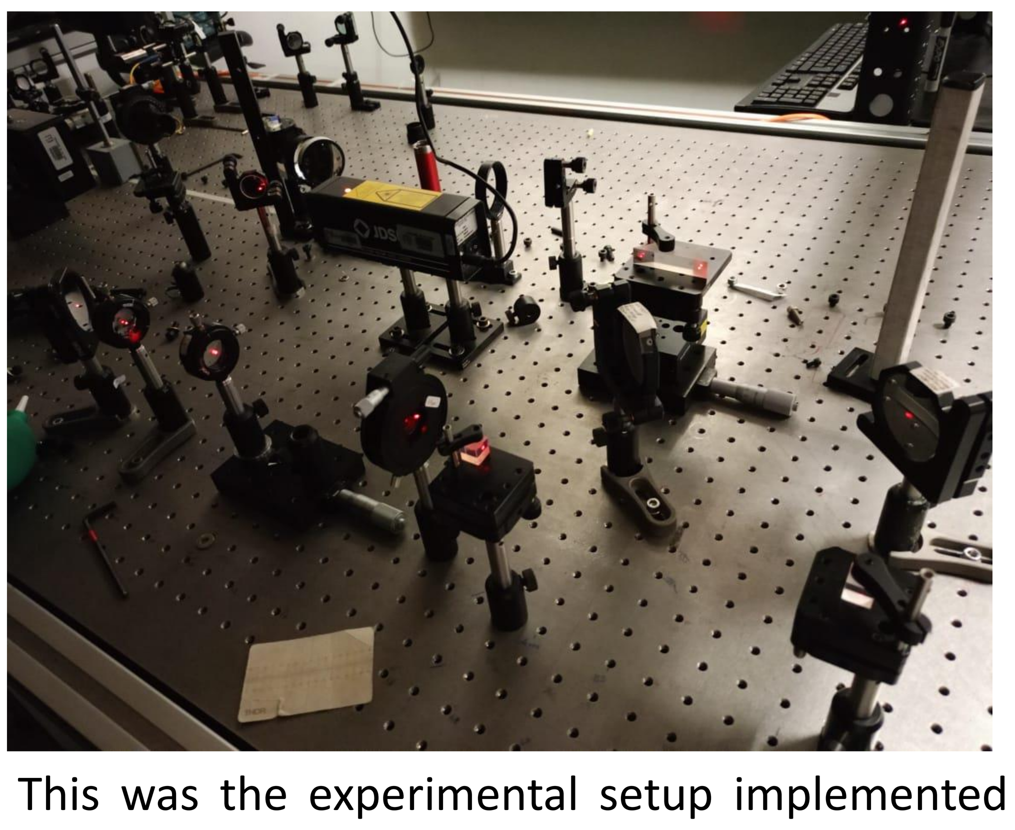
We see a contrast between the theoretical (right) and what was obtained experimentally (left). This may be due to errors in data collection, such that although they may appear similar, the results were not completely accurate.

Homodyne Detection



Transimpedance circuit is essential for converting photodetector currents into voltage signals, allowing for accurate signal amplification. This circuit minimizes noise, maintaining a high signal-to-noise ratio crucial for observing subtle quantum phenomena [2], where its high bandwidth supports rapid signal fluctuations. Ultimately, the electrical circuit could not be finalized; however, the model that best fits the characteristics of the optical components used and the specific needs of this research was chosen.

Experimental implementation



Experimental values

$$z_R = 3.48 \pm 0.04m$$
$$z_0 = 0.613 \pm 0.002\ cm$$
$$\omega_0 = 1677.62 \pm 16.79\ \mu m$$
$$V = 0.876 \pm 0.005$$

This was the experimental setup implemented on the optical table, using a Mach-Zehnder interferometer to perform precise measurements and analyze the interference of the split light beams. In the end, FDS010 reference photodiodes were implemented, which are planned to be used to observe the signals on the oscilloscope. Additionally, all optical components are sourced from ThorLabs, with specifications for the employed wavelength and their characteristics in the previously shown model.

Conclusions and Future Work

- A functional interferometer with the best possible statistics was established during its development in the laboratory.
- It has theoretically become a possibility to characterize and identify quantum noise or shot noise by analyzing other types of noise, thereby gaining a better understanding of this kind of noise.
- It is expected that in the future, the construction of the transimpedance circuit will allow for better optical characterizations.
- It is anticipated that using the transimpedance circuit will lead to a understanding of quantum states and noises.
- Methods will be sought that allow us to understand vacuum noise and its relevance in an HBD.

References

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- [3] Lang, S., Zhang, S., Li, X., Niu, Y., & Gong, S. (2022). Low Noise Balanced Homodyne Detector for Quantum Noise Measurement. IEEE Access, 10, 27912–27916.