LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY
- LIGO -
CALIFORNIA INSTITUTE OF TECHNOLOGY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

Technical Note	**LIGO-T2600342–**	2026/11/04

WOPA SURF 2026: Final Report

Abigail Solomon Gebremariam

California Institute of Technology
LIGO Project, MC100-36
Pasadena, CA 91125
Phone (626) 395-2129
Fax (626) 304-9834
E-mail: info@ligo.caltech.edu

Massachusetts Institute of Technology
LIGO Project, Room NW22-295
Cambridge, MA 02139
Phone (617) 253-4824
Fax (617) 253-7014
E-mail: info@ligo.mit.edu

LIGO Hanford Observatory
Route 10, Mile Marker 2
Richland, WA 99352
Phone (509) 372-8106
Fax (509) 372-8137
E-mail: info@ligo.caltech.edu

LIGO Livingston Observatory
19100 LIGO Lane
Livingston, LA 70754
Phone (225) 686-3100
Fax (225) 686-7189
E-mail: info@ligo.caltech.edu

http://www.ligo.caltech.edu/

Contents

1 Introduction **2**

2 Background **2**

2.1 Quantum Noise . . . 3

2.2 Squeezed Light . . . 3

2.3 Coherent Locking Field(CLF) . . . 6

2.4 Waveguide Optical Parametric Amplification (WOPA) . . . 6

3 Objective **7**

4 Approach **7**

4.1 Optical Setup . . . 7

4.2 Electronic setup . . . 8

4.3 Feedback control loop . . . 8

4.4 Mathematical calculation of the error Signal . . . 10

5 Project Progress **11**

5.1 Quantum Noise Lock . . . 11

5.2 Experimental setup optimization . . . 13

6 Results **14**

6.1 Quantum Noise Lock . . . 14

6.1.1 PZT and Piezo controller transfer function . . . 14

6.1.2 Updated loop design results . . . 15

6.2 Experimental setup optimization . . . 16

7 Future Work **17**

8 Acknowledgments **18**

9 Appendix **18**

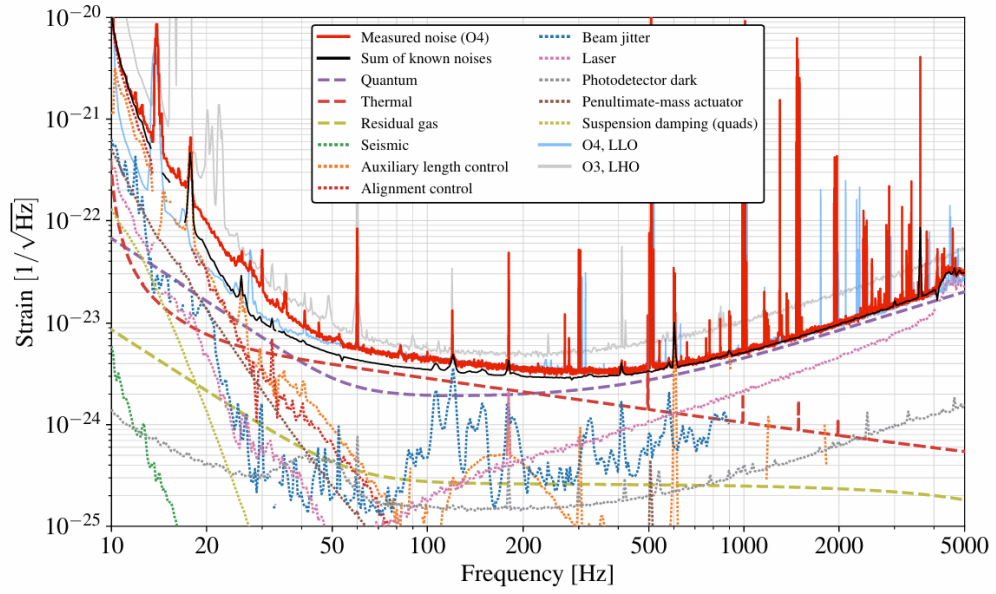
10 References **18**

1 Introduction

The Laser Interferometer Gravitational Observatory (LIGO) detects gravitational waves using highly sensitive and specialized Michelson interferometers with 4 km arms located at the Hanford, Washington, and Livingston, Louisiana observatories. The detection of gravitational waves is essential in the study of astrophysical events such as binary black hole mergers and binary neutron star mergers. As a gravitational wave passes through the interferometer, it produces a slight change in the length of the arms. These changes affect the relative phase of the laser beams in each arm, producing an interference signal in the antisymmetric output port. This results in a measured gravitational wave signal . LIGO made its historic detection in 2015 of gravitational waves from binary black holes merger. Since then, significant effort has been dedicated to improving these detectors by reducing noise sources.

2 Background

The changes in the arm length are so small that noise in the system can greatly impact the detection of these signals. Among the noise sources, quantum noise is the focus of this project.



(a) Noise budget for the LIGO Hanford Observatory, as of December 2023.

Figure 1: LHO LIGO noise budget
[1]

LIGO reduces quantum noise using squeezed light. This project implements a simplified approach to squeezed light generation.

2.1 Quantum Noise

The quantum noises that affect the measurement are the radiation pressure noise and the shot noise. The two sources make the Standard Quantum limit (SQL), which is the best sensitivity that can be achieved with classical light. The formula for the minimum detectable measurement uncertainty achieved with classical light is presented below:

$$h_{SQL} = \sqrt{\frac{4\hbar}{m(\Omega^2)(L^2)}} \tag{1}$$

$\hbar$ is the reduced Planck's constant, Ω represents the angular measurement frequency , m represents mass of the mirror, and L represents the length of the interferometer [2]. To surpass this limit and increase the sensitivity of the detectors, squeezed light is used. The concept of squeezed light is derived from treating each mode of the electromagnetic fields of light as a quantum harmonic oscillator. In order to evaluate the noise properties from the oscillator, quadrature operations are used. These can be described using the $\hat{X}$and $\hat{P}$ quadratures. These quadratures satisfy the Heisenberg uncertainty relation:

$$\Delta\hat{X}^2.\Delta\hat{P}^2 \geq \frac{1}{4}, \tag{2}$$

2.2 Squeezed Light

Two important quantum states are basis for understanding this squeezing in LIGO; vacuum state and coherent state. The vacuum state contains zero average photons. However, the Heisenberg uncertainty principle still presents non-zero fluctuations. In this non-squeezed vacuum, the uncertainty of $\hat{X}$ and $\hat{P}$ is equal given by:

$$\Delta\hat{X} = \Delta\hat{P} = \frac{1}{\sqrt{2}} \tag{3}$$

Unlike the vacuum state, the coherent state has a non zero expectation value of electromagnetic field. Squeezing light is a quantum state in which the uncertainty in one quadrature is reduced at the cost of increasing uncertainty of the other quadrature while still obeying this principle.

A phasor diagram plot is presented below:

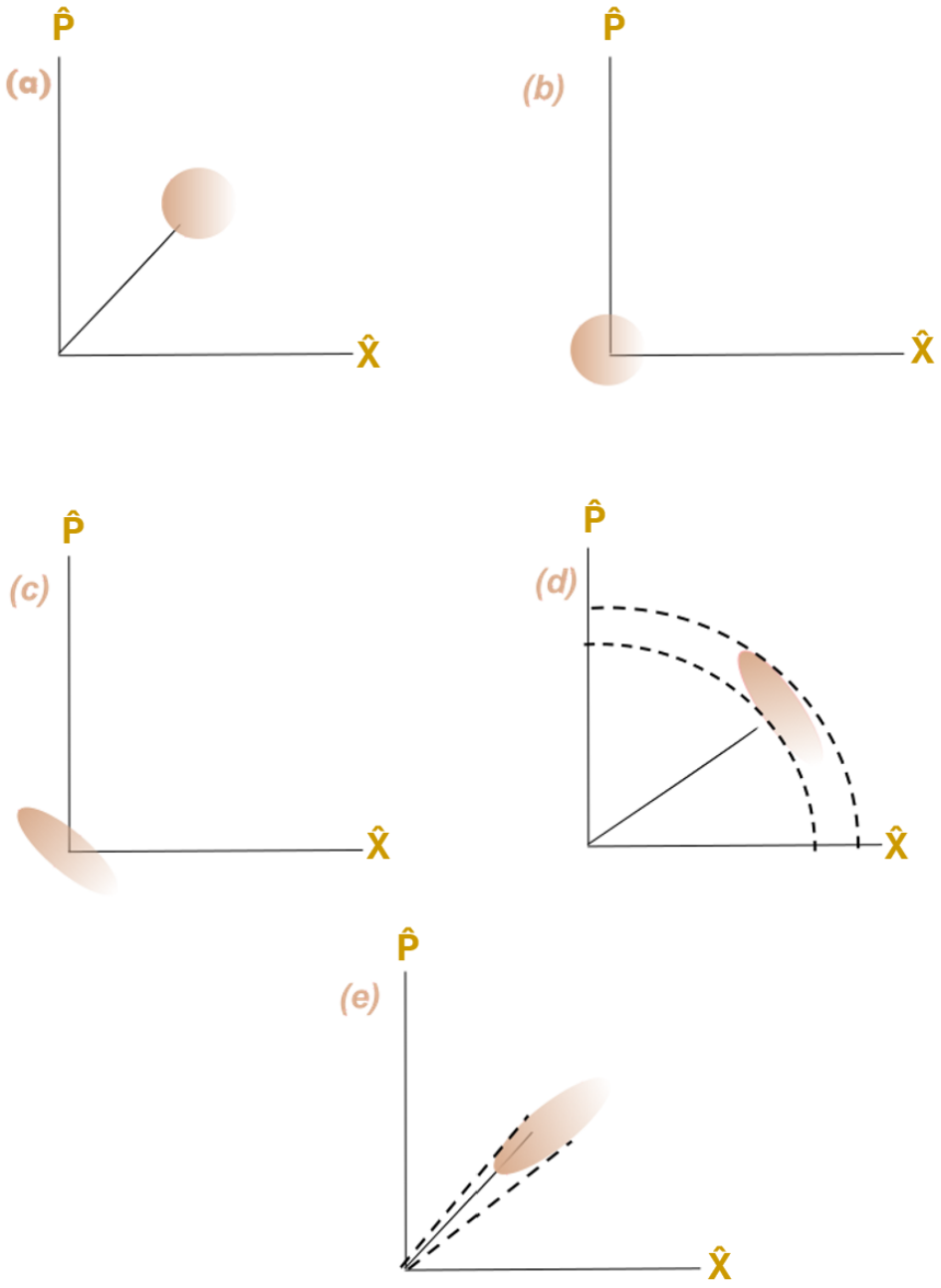


Figure 2: Quantum States

(a) Coherent state in the absence of squeezing (b) Vacuum state without squeezing (c) Squeezed vacuum (d)Squeezed Amplitude (e) Squeezed Phase. The lines from the origin represents the amplitude while the angle between the line and the $\hat{X}$ represents the phase [3].

LIGO uses these two states together. The squeezed vacuum reduces the detector's quantum noise. Hence, gravitational signals can be detected with much higher precision.

The practical method used to achieve this is via non-linear optics. The two primary non-linear processes used for achieving squeezing in this project are the following:

- **Second Harmonic Generation (SHG)**: This non-linear dynamics occurs by sending photons of frequency ω into the optics generating photons with twice the frequency (2ω). This is a useful part in the process since the high energy photons are used as pump fields as input to generate squeezing. Due to limitations of the non-linear crystal, a complete conversion can not be achieved hence there are still photons of similar frequency as the incoming photons.

- **Spontaneous Parametric Down Conversion (SPDC)** This is achieved by sending in a high energy photon with frequency of 2ω into a non-linear crystal where each pump photon may be converted into a pair of lower energy photons each with frequency of ω. As with SHG, complete conversion can not be achieved. SPDC can be achieved by using non-linear crystals such as Periodically Poled Lithium Niobate (PPLN).

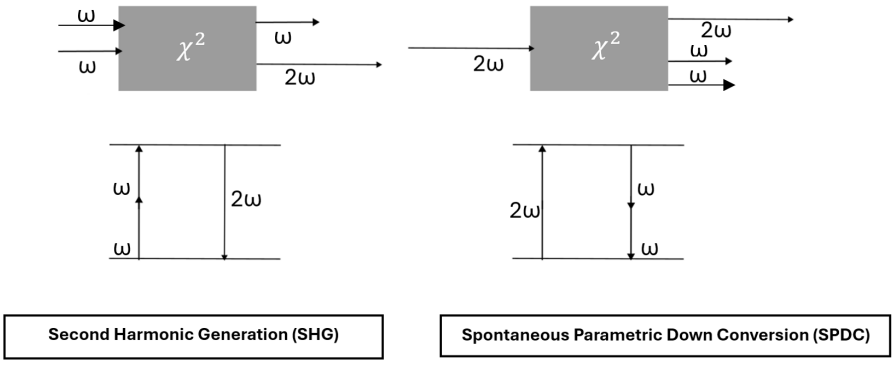


Figure 3: Non-linear Processes: Pairs of photons are sent and generated by the crystal

The implementation of these processes in Waveguide Optical Parametric Amplification (WOPA) is discussed in later sections. Advanced LIGO implements frequency dependent squeezing. An Optical Parametric Oscillator (OPO) is used to generate squeezing. This includes using the non-linear crystals described in the SPDC process by placing it in a locked optical cavity. This lock helps to maintain resonance which allows for the build up of optical field and continuous generation of squeezed vacuum. However, the use of OPO is experimentally challenging as it requires the locking of several cavities. In order to reduce this requirement of cavity locking, a new approach of squeezed light generation was introduced, the Waveguide Optical Parametric Amplification (WOPA).

2.3 Coherent Locking Field(CLF)

LIGO currently uses coherent control using CLF[4]. In this method a coherent locking field is generated sending in a coherent light through acousto-optic modulators (AOM) . The coherent beam is then sent into the OPO alongside the squeezed vacuum. Since both of these fields go through the same cavity and non-linear optics, the coherent beam provides the information about the phase of the squeezed vacuum relative to the local oscillator. The output signal is then demodulated at the coherent field's frequency. This then provides the error signal and correction signal to be applied to the squeezer pump laser to lock the squeezed field with the interferometer field.

2.4 Waveguide Optical Parametric Amplification (WOPA)

In WOPA, the squeezed vacuum is generated by the Waveguide Periodically Poled Lithium Niobate Crystal(PPLN). It offers an efficient method to generate squeezing because of its strong non-linear interactions [5].

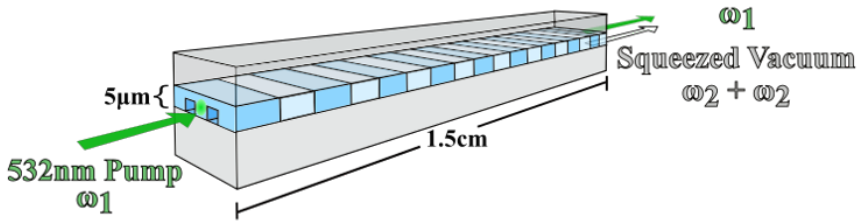


Figure 4: Waveguide PPLN
[6]

The process of stabilizing the squeezed angle is being studied simultaneously, as phase noise presents a challenge in observing the generated squeezing accurately. The process used to detect quantum noise by canceling the classical noise in WOPA is called Balanced Homodyne Detection(BHD). This analyzes the quantum noise by splitting the generated squeezed light and a much brighter local oscillator (LO) using a 50/50 beam splitter. The two outputs from the beam splitter pass through the two photodetectors(PD). The photo-currents are then subtracted, which results in the cancellation of the classical noise while preserving the quantum noise. But for the accurate detection and reading of squeezing measurement, the local oscillator's phase has to stay aligned with the squeezed quadrature. This can be achieved through Quantum noise locking [7]. The Quantum noise lock achieves the best optimum local oscillator path so that its phase can align with the squeezed vacuum phase.

3 Objective

The main objective of this project is to optimize the quantum noise lock to reduce the residual phase noise. This will include improving the loop design and taking the transfer function of components in the feedback control system.

4 Approach

4.1 Optical Setup

The 1064nm and 532nm laser beam are released from the main laser system that is comprised of the main 1064nm laser and a SHG doubling cavity that is used to produce the 532nm laser beam. These two beams travel through separate mirrors that are then sent through Half wave plate (HWP) and Polarizing Beam Splitter (PBS) which are useful in adjusting the polarization of light. The 1064 nm beam provides the bright coherent state needed as a local oscillator, while the 532nm is sent into the waveguide and used to generate squeezed vacuum via the SPDC process described above. The local oscillator and the squeezed vacuum then combine at the BHD setup.

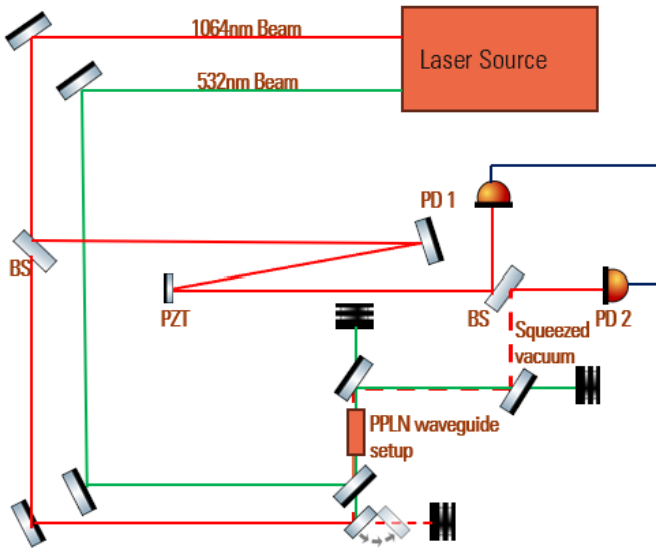


Figure 5: WOPA optical setup

The local oscillator path goes into a mirror and into the PZT which is made of lead zirconate titanate. This is important as it used to align the LO path to the squeezed vacuum phase according to the error signal and servo correction signal designed in the electronic setup. It has the advantage of making slight changes to paths precise and ideal for optical set up.

4.2 Electronic setup

This is where the feedback control system is introduced into the system. It is useful in the WOPA setup since it provides the electronic information of how aligned and misaligned the phase is so as to improve the setup and acquire lock. This is achieved by designing and implementing a feedback control loop. A simple schematic of quantum noise locking is presented below:

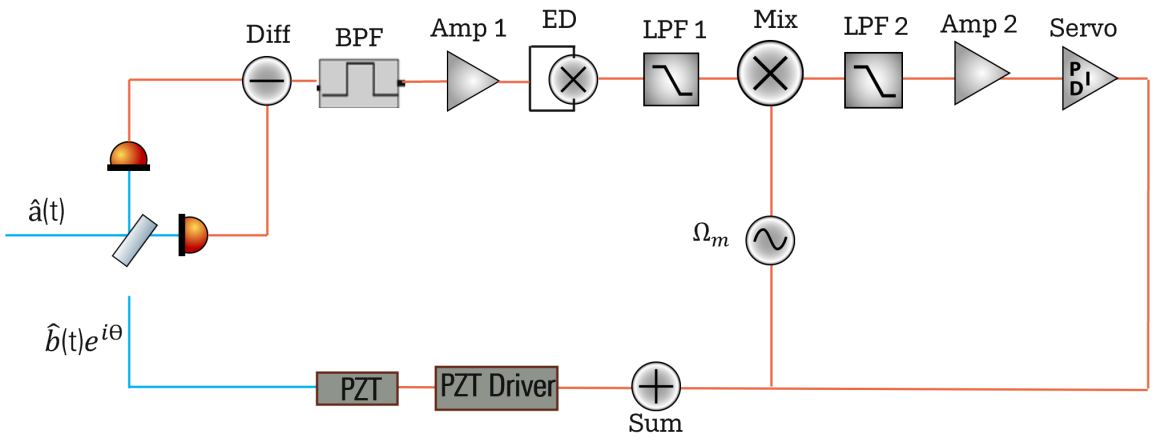


Figure 6: Quantum Noise Lock Schematic

The $\hat{a}$ represents the squeezed vacuum state while $\hat{b}e^{i\theta}$ is the local oscillator's. The PD indicates the photodetector.

The feedback loop drives the PZT mirror, which changes the LO mirror by small amounts, changing the optical length of LO path. The change in the LO path affects the relative phase between the LO and the squeezed vacuum. This relative phase provides information on the phase alignment of the homodyne detector with the squeezed vacuum. When that alignment is reached, the system locks to observe the squeezing quadrature. The control loop used in WOPA is applied using Moku instruments.

4.3 Feedback control loop

The QNL feedback control system consists of three main parts:

1. **The Plant**: This is where the optical response is converted into an error signal:
    - **Classical noise subtraction**: The first part of the control loop is to remove classical noise while preserving the quantum noise. This is achieved through common-mode rejection, where the balanced photodetectors output of the photocurrent information is electronically subtracted. Due to the common classical

noise fluctuations in both PD's , they are canceled during this process while quantum fluctuations are preserved in the resulting signal.

- **Extracting Error signal**: The subtracted signal with quantum noise information is sent through a Band Pass Filter (BPF). This electronic component isolates the chosen frequency range. This is then sent into an amplifier. Afterwards, the signal is sent through the Envelope detection where the signal wave is squared through a multiplier. By using a Low Pass Filter (LPF), the low frequency is extracted and sent into a mixer, where it is combined with a reference signal generated by a wave form generator at the desired frequency.The final steps in this part of the loop is to use another LPF to remove higher frequency points. Finally, this signal is sent to an amplifier.

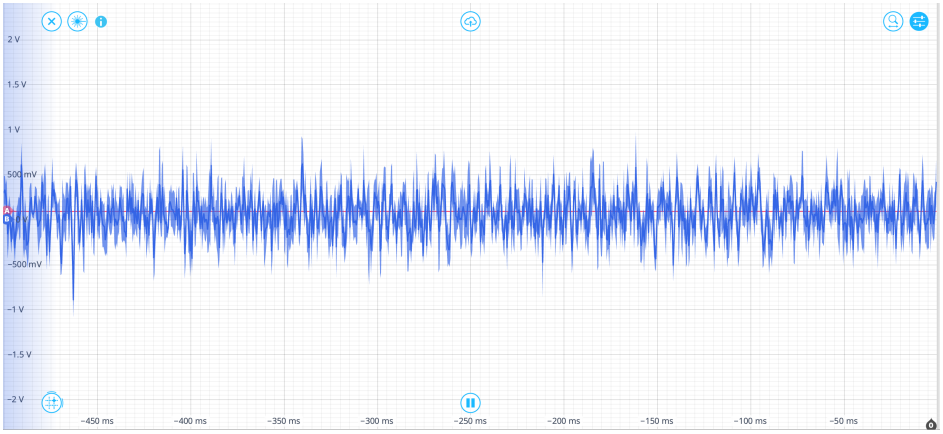


Figure 7: Error Signal

2. **The Controller**: In this experiment, this is primarily performed by a PID controller which processes the error signal from above to generate a correction signal for a stable LO phase. However, in this set up, only the proportional and integrator terms are used. These controller terms are vital for a stable feedback loop and maintain lock. The PID output is then sent into the PZT used for applying the mechanical shifts in the LO path.

3. **The PZT and Piezo controller**: This is the part in the control loop that applies the correction from the PID controller to the optical set up. In the case of QNL, the electronic correctional signal has to be converted to a physical displacement. This is achieved using a PZT actuator driven by a Piezo controller. As mentioned above, the Moku instruments are used for the control loop which has a limitation in the output voltage generated. The Piezo controller amplifies the voltage output from the PID controller to provide the required input for the PZT. The PZT then produces an accurate and precise mechanical displacement of the LO mirror, altering the LO path.

By achieving and perfecting this feedback control system, it is possible to then find the point allowing for the system to lock.

4.4 Mathematical calculation of the error Signal

As mentioned above, the error signal is essential in generating the accurate correction signal and achieve lock. The error signal is mathematically calculated as follows. [7] The squeezed vacuum and the local oscillator interfere in a balanced beam splitter, resulting in two photo currents that are electronically subtracted after the BHD setup. Both of these fields have a mean and fluctuating component for which squeezed vacuum has no coherent amplitude ($\bar{a} \approx 0$) while the local oscillator contains a strong mean amplitude ($\bar{b}$). The difference in the photocurrent fluctuations is calculated:

$$\delta i^- = hv(\bar{a}\delta\hat{X}^{(b)} sin\theta + \bar{a}\delta\hat{P}^{(b)} cos\theta + \bar{b}\delta\hat{X}^{(a)} sin\theta - \bar{b}\delta\hat{P}^{(a)} cos\theta), \tag{4}$$

$\delta\hat{X}^{(b)}, \delta\hat{P}^{(b)}$ are the fluctuating amplitude and phase quadratures of the LO and $\delta\hat{X}^{a}, \delta\hat{P}^{(a)}$ are the fluctuating amplitude and phase quadratures of the squeezed vacuum where θ is the relative phase between the two fields. The variance of the difference photocurrent is obtained by squaring the fluctuating component.

$$\begin{aligned} V(i_\theta^-) &= \langle(\delta i^-)^2\rangle \\ &= h^2v^2(\bar{a}^2(V_1^{(b)} sin^2\theta + V_2^{(b)} cos^2\theta) + \bar{b}^2(V_1^{(a)} sin^2\theta + V_2^{(a)} cos^2\theta)) \end{aligned} \tag{5}$$

$V_1^{(a)} = \langle(\delta\hat{X}^{(a)})^2\rangle)$ and$V_2^{(a)} = \langle(\delta\hat{P}^{(a)})^2\rangle)$. Since the local oscillator is designed to be significantly stronger than the squeezed state, the $\bar{a}$ term is negligible.

$$V(i_\theta^-) = h^2v^2\bar{b}^2(V_1^{(a)} sin^2\theta + V_2^{(a)} cos^2\theta), \tag{6}$$

The variance in relation to shot noise can be described as $hv\bar{P}_{LO}V_\theta$ for which $V_\theta = V_1^{(a)} sin^2\theta + V_2^{(a)} cos^2\theta$. $\bar{P}_{LO} = hv\bar{b}^2$ is the power of the Local oscillator. To generate the error signal, the resulting homodyne is dithered sinusoidally at θ_0. β is the dither depth while Ω_m is the chosen dither frequency.

$$\theta(t) = \theta_0 + \beta sin(\Omega_m t) \tag{7}$$

$$V_\theta(t) = V_1^{(a)} sin^2\theta(t) + V_2^{(a)} cos^2\theta(t) \tag{8}$$

$$V_\theta(t) = \frac{V_1^{(a)} + V_2^{(a)}}{2} + \frac{V_2^{(a)} - V_1^{(a)}}{2} cos2\theta(t) \tag{9}$$

By using the Bessel function the cos $2\theta(t)$ can be expanded. By keeping the DC and the first harmonics only the resulting formula gives us:

$$V_\theta(t) \approx \frac{V_1^{(a)} + V_2^{(a)}}{2} + \frac{V_2^{(a)} - V_1^{(a)}}{2}(J_o(2\beta)cos2\theta_o - 2J_1(2\beta)sin2\theta_o sin\Omega_m t) \tag{10}$$

The demodulated error signal is then calculated by multiplying the dither-frequency component by a reference signal and low pass filtering to remove the harmonics and only use the DC component of the signal which is the difference between the squeezed and anti-squeezed variances. $\theta_0 = 0$ and $\theta_0 = \frac{\pi}{2}$, are the lock points for which the information is sent to the actuator (PZT in the WOPA setup) to lock the Local oscillator at the chosen quadratures

$$\varepsilon = -\frac{1}{2} hv P_{LO}(V_2^{(a)} - V_1^{(a)}) J_1(2\beta) sin2\theta_0 \tag{11}$$

5 Project Progress

In order to use the feedback control system for QNL and achieve the desired squeezing value, there are two main parts of this project:

5.1 Quantum Noise Lock

The next part of the project includes recreating and optimizing the quantum noise lock. In the current set up of the quantum noise lock, the transfer function has resonance readings in the kHz range. By optimizing the current setup, a good transfer function reading with lower Unity Gain Frequency (UGF) can be calculated. To attempt the lock, there were a few parts of the loop that need evaluation and troubleshooting.

Resolving actuator saturation:

Prior work in the lab had revealed saturated output signals from the controller which became the motivation to test and confirm the efficiency of the PZT controller. This included using a waveform generator and sending input signals with varying amplitudes and frequencies into the controller and observing the output signals being sent to the PZT using an oscilloscope. This showed clear output signals encouraging the next step in the process. The next part included observing the Piezo Controller connected to the Moku. This was designed by using the quantum noise lock design mentioned above and observing the output signal from the controller using an oscilloscope. The modulation frequency and output frequency from the Moku were changed so as to observe the saturated signals. A PZT controller offset of 75V was applied in both attempts of testing. This offset was introduced to shift the voltage range of the PZT controller, allowing it to account for the correction signals that may include negative voltage values from Moku. The table below shows the varying frequencies and voltage inputs attempted by both the waveform generator and the Moku :

Frequency inputs (kHz)	**Moku Voltage inputs (Vpp)**	**Waveform generator Amplitude (Vpp)**
1	1-5	3-4
5	1-5	3-4
10	1-5	3-4
20	1-5	3-4

Table 1: Settings for PZT controller inputs

To remove the saturation observed in the output, troubleshooting attempts were made. The control matrix of the PID controller in the Moku which affects input voltages was varied to observe for any resolve. When this was not observed, the frequencies were also varied, which did not change the saturated and ringing oscillations from the controller. Once it was confirmed that saturation could not be resolved for the existing controller, another controller was introduced to the loop to test for any saturation. At increasing frequencies, saturation was observed. However, by implementing the same troubleshooting methods, the saturation was resolved. This helped in making the next decision for the controller.

With the information about the resolution in saturation by varying frequency and voltage, a gain plot was generated. This helped to observe how the controller behaved as the frequency increased, providing the information about the ideal modulation frequency for our design.

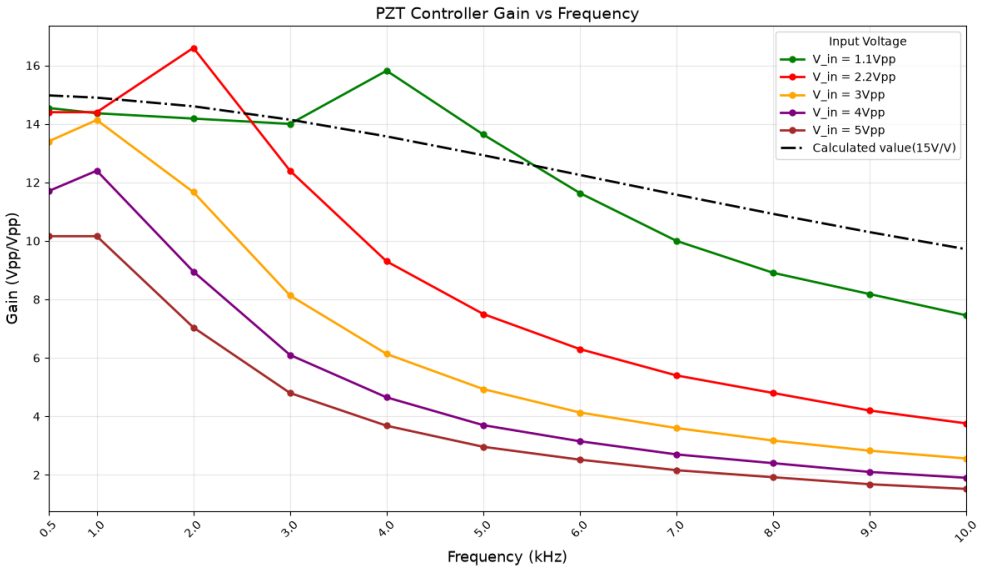


Figure 8: PZT controller gain plot

From the plot it can be observed that the ideal range to use the controller would be in the lower frequency range from 1-3.5kHz with lower input voltages. The saturation that can be observed at 2kHz and 4kHz can also be resolved by adjusting the input voltages by less than 1Vpp at those points. Since the modulation frequency in the QNL process will be at a specific frequency value this gain plot will provide information on the ideal input voltage and slight adjustments if needed.

Generating squeezing and quantum noise lock:

During the project the optical setup was being optimized mainly focused on beam profiling the local oscillator's beam. Once this work was complete, squeezing was observed which is needed for quantum noise lock as the squeezed vacuum is one of the inputs into the PD. This progress enables the lock optimization to progress further. The next step involved taking the transfer function of the PZT and the controller. In order to do this, a two beam interference was set up which converted the phase shift difference into an intensity signal at the PD's providing the error signal. One of the PD's DC input was connected to the Moku go which was sent into a PID controller with adjusted integration crossover values. The output from the PID was then sent into an FRA to observe the transfer function and also the PZT controller.

Updated loop design and Quantum noise lock performance:

After observing some remaining peaks in the transfer function, the last few weeks were spent optimizing the loop and inputting certain filters. The main change was using the

laser lock box function in the moku instruments to utilize the various filter options present. The Chebyshev ll was used as the filter to add a notch at the modulation frequency and its harmonics. The chebyshev ll filter provides a more steeper roll off compared to the smoother roll off by the butter worth filter. As a last part to getting an accurate transfer function reading, a butterworth filter was used after the addition of the correction signal and before being sent into the frequency response analyzer. Once the observed resonant peak was resolved, a finalized transfer function was plotted to observe the loop stability and calculate the total phase noise. Based on the in loop disturbance such as electronic noise, and out of loop disturbances, such as acoustic and thermal noise sources, an optimal Unity Gain Frequency (UGF) was calculated. These two noise sources have an indirect impact on the loop bandwidth: increasing UGF applies the feedback control for a wider frequency range while also increasing the in loop sensing noise contribution. Decreasing the UGF would only suppress the out of loop disturbance for a lower frequency range. The optimal UGF is determined to be a balanced point between the two tradeoffs.
The open loop gain helps in understanding the performance of the loop in applying the control feedback across the frequency band width. It is calculated by injecting a known sweep sine wave to the correction signal. The total phase noise (ϕ_{RMS}) is calculated by integrating the resulting noise over the frequency bandwidth.

5.2 Experimental setup optimization

PD Noise Characterization

As mentioned in the objective the photodetectors are a vital part for acquiring the quantum noise locking since this is where the system gets the electronic signal needed to provide the error signal that changes the LO path. By having good PD, it is possible to observe squeezing at various frequencies . By creating the PD noise characterization, the frequency range to observe squeezing can be determined. The current PD records the squeezing measurement in the Mega Hertz range. Observing the performance of the PD will help determine PD performance at lower frequency in the audio band. This is important as this is LIGO's detection band. The first step then to check the PD's functionality is to do a noise characterization plot. This is performed by using the spectrum analyzer function on Moku Pro. The DC output from North and South PD's are connected to the Moku Pro input and the AC output of the PD's are also connected as inputs to the Moku pro. The PD's are also provided a power source. With the inputs set up, there are two set of data that is taken. One with having the 1064nm laser beam hitting the PD's at a power of 500μW. The other data is taken by blocking this beam light from reaching the PD's. The frequency range for which this will be measured is 1Hz-10MHz. The settings for the spectrum analyzer is arranged according to the inputs of the Moku Pro as following:

Inputs	**Impedance**	**Bandwidth**
AC output North PD	1MΩ	300MHz
AC output South PD	1MΩ	300MHz
DC output South PD	50Ω	300MHz
DC output South PD	50Ω	300MHz

Table 2: Moku Pro settings

With the above measured data, plots will be generated and compared with the calculated shot noise. This shot noise is calculated by using the following formula:

$$\boldsymbol{S}_N = \sqrt{2hvP} \tag{12}$$

h is Planck constant, v is the frequency at the 1064nm wavelength laser beam, and P is the power coming from the LO path. This value is then multiplied with the manufacturer's specifications about the PD: transimpedance gain and the responsivity. The following shows a plot of the current PD performance using a spectrum analyzer:

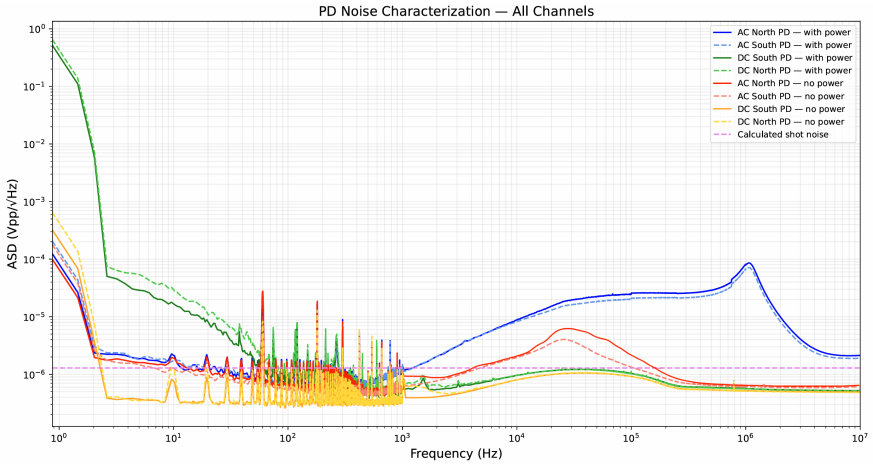


Figure 9: PD Spectrum Analyzer plot

Scattered Light Search

This process is a vital part of the optical table where experiments are performed as it affects the path of the laser beam. To search for potential scattered light on the optical table, sensor cards were used following the beam path in the WOPA setup. The observed scattered light was resolved using blade beam dumps and other potential sources were also fixed with the finalized set up for taking squeezing measurements.

6 Results

6.1 Quantum Noise Lock

6.1.1 PZT and Piezo controller transfer function

Once the Piezo controller was optimized to identify the frequency range in which to use it, the next part was to observe how the actuator and the actuator amplifier behaved at varying frequencies. This was achieved by generating a bode plot to calculate the transfer functions.

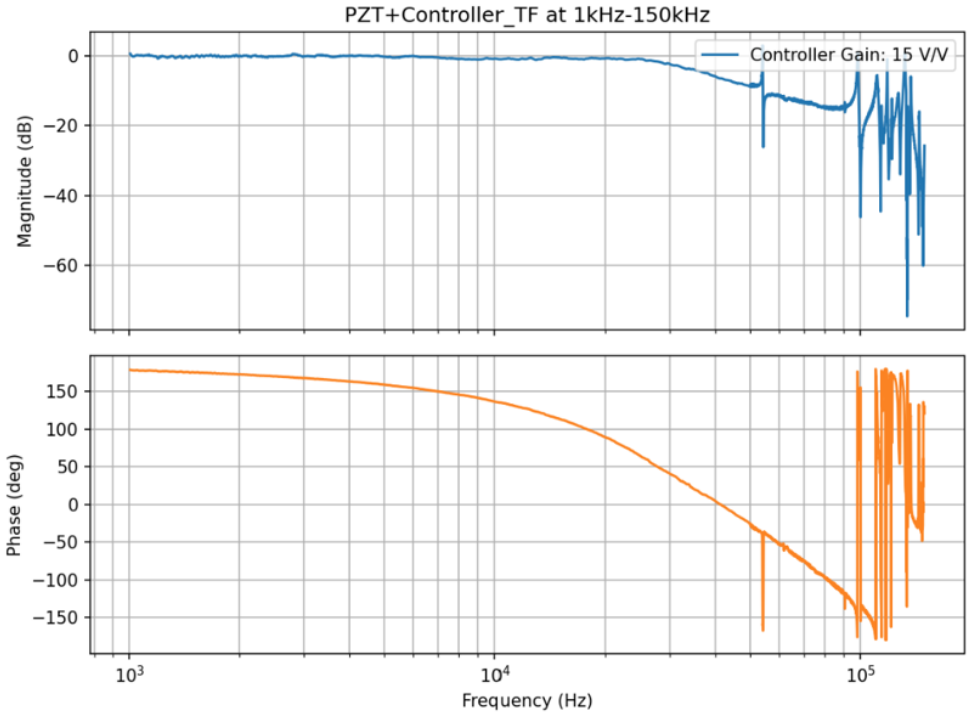


Figure 10: PZT and controller transfer function

From the plot, it can be observed that the ideal range to operate the controller is between 1kHz and 20 kHz. With this information the quantum noise lock can be attempted with the new PZT controller.

6.1.2 Updated loop design results

The change in the loop design provided a significant change to the transfer function reading by removing the peak observed which then provided a reduced total phase noise. The following represents the finalized plot which had a total phase noise of : 16.3 mrad which is comparable with current LIGO detectors measured phase noise of 20 mrad.
[4].

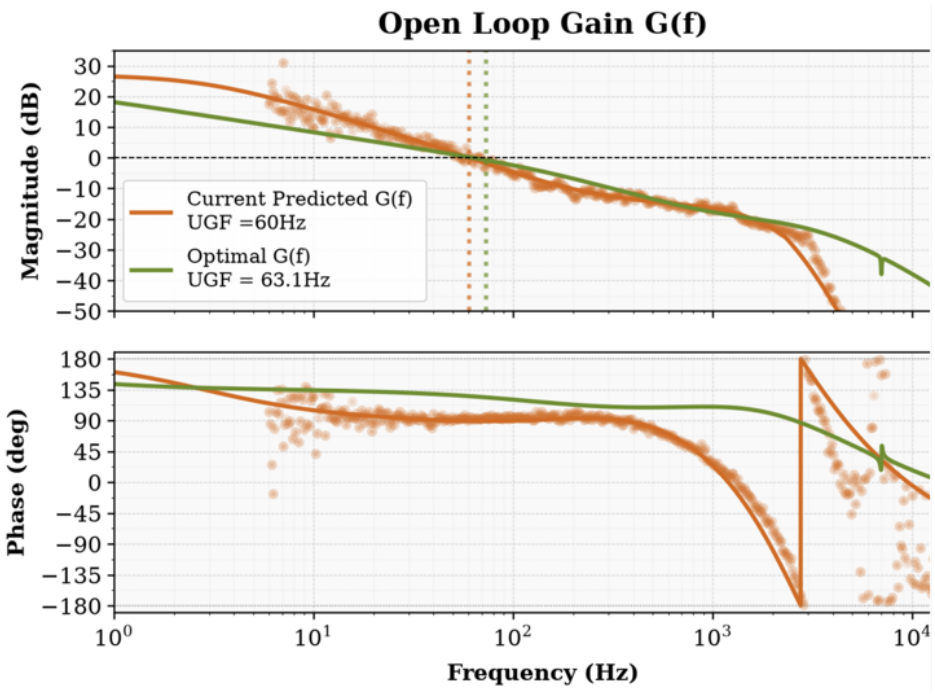


Figure 11: QNL open loop gain

6.2 Experimental setup optimization

- **PD Noise Characterization**
  The observation from *input connection* plot is the AC and DC plots below the 1kHz range where there is significant lack of signal detection. This helps confirm that the current PD's can't perform well in the audio band frequency ranges. Since LIGO's detection band is in the audio band region , the current PD will not be sufficient to use. The ideal future PD will have a comparable performance which would be a PD with low input noise, better detection at audio band region. The performance PD would look similar to the one below:

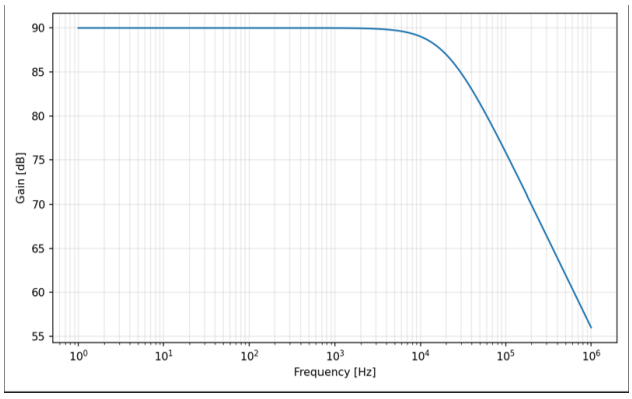


Figure 12: Ideal PD Performance for audio band range

- **Scattered Light Search**

After tracing the scattered light using an IR card, three main spots were detected, for which suggestions have been made to optimize the setup once all major optical updates to the experiment are completed. This includes using a blade beam dump to enclose around the Polarized Beam Splitter (PBS), and placement of a beam dump at the end of the LO path.

7 Future Work

Future work includes the following:

1. **The search for a better PD**: For the reasons mentioned in the result section, there is a need for a new and more effective PD to observe squeezing at audio band frequency range.

2. **Reducing more of the phase noise in the loop**: Lowering the phase noise contribution is an important step in the future work for the project. The acceptable rms value of the phase noise is dependent on the measured squeezing, but for a table-top squeezing measurement, reducing the total rms value to approximately 10-15mrad would be a reasonable target. Future improvements to achieve this lowered phase noise could include: achieving higher squeezing level, performing an updated analysis on the in loop and out of loop disturbance noise sources. This would help in working to reduce the noise sources and calculate an improved UGF value.

8 Acknowledgments

I would like to thank Dr. Rana X. Adhikari and Peter G. Carney for their mentorship. I would also like to thank the LIGO lab, California Institute of Technology and the National Science Foundation (NSF) for this SURF opportunity.

9 Appendix

Appendix A: Moku program implementation
The Moku instruments provide various electronic setups providing for an efficient method for the design and implementation of the feedback control loop. Among the several programs in the instrument, the ones used for this project are described below:

1. **FIR filter builder**: This function is useful as it filters the incoming subtracted signal and to apply a BPF in the frequency range to be studied. This will then removes/ignores the signal from before the lower end of the frequency range and anything above the higher end.

2. **Lock In Amplifier**: There are two lock-in amplifiers. One is used for performing the envelope detection while the other is used to multiply the resulting signal with the modulation frequency.

3. **Frequency Response Analyzer (FRA)**: The frequency response is where the transfer function of the loop is measured and observed. The FRA generates the bode plot that are helpful in observing the Unity Gain Frequency (UGF) which is the frequency at which the gain is 0 dB. This plot also provides information about the phase margin providing information into the stability of the loop.

4. **PID controller**: The PID controller has two functions in the setup. This function is used to apply the needed correction to the error signal as to correct the LO path to then lock it in that specific placement.

10 References

[1] The LIGO Scientific Collaboration. Advanced LIGO detector performance in the fourth observing run. Phys.Rev.D 111, 062002 (2025)

[2] Kirk Mckenzie, Nicolai Grosse, Warwick P.Bowen, Stanley E. Whitcomb, Malcolm B Gray, David E McClelland, and Ping Koy Lam. *Squeezing in the Audio Gravitational-Wave Detection Band*. Phys.Rev.Lett. 93, 161105 (2004).

[3] M C Teich and B E A Saleh. *Squeezed states of light*. Quantum Optics: Journal of the European Optical Society Part B, 1, 2 (1989).

[4] Ganapathy, D., et al. *Broadband quantum enhancement of the LIGO detectors with frequency-dependent squeezing*. Physical Review X 13.4, 041021 (2023).

[5] HC Photonics. *Squeezing Applications:Key factors/Critical requirements and PPLN for squeezing applications*, V. Jan-25.

[6] Peter G. Carney, Rana X. Adhikari, Shruti J. Maliakal, Masaya Ono, Helen Schwartz, Koji Arai, Jacob CherrySam, Sarah Gates, Mayank Chaturvedi, Tanisha Ray, Nora Dreslin, and Yehonathan Drori . *Broadband Waveguide Quantum Squeezing* GWADW (2026)

[7] Kirk Mckenzie, Eugeniy E Mikhailov, Keisuke Goda, Ping Koy Lam, Nicolai Grosse, Malcolm B Gray, Nergis Mavalvala and David E McClelland. *Quantum noise locking.* Journal of Optics B: Quantum and Semiclassical Optics, 7, 10 (2005).