LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY
- LIGO -
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Technical Note	**LIGO-T22xxxxx–**	2025/05/14

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1 Introduction

The Laser Interferometer Gravitational-Wave Observatory (LIGO) detects gravitational waves by measuring incredibly small distortions in spacetime using highly sensitive laser interferometers. One critical limitation to LIGO's sensitivity, particularly at low frequencies, is quantum noise, which includes shot noise and radiation pressure noise. Squeezed light injection — a technique that reduces quantum noise — is thus vital to LIGO's performance enhancements.

This project directly contributes to this effort by developing a detailed noise budget analysis for a Waveguided Optical Parametric Amplification (WOPA) experiment. In this experiment, several decibels of quantum squeezing at 1064 nm are generated by pumping a Periodically Poled Lithium Niobate (PPLN) waveguide with 532 nm light. The squeezed 1064 nm beam is then combined with a local oscillator (LO) to prepare it for eventual injection into an interferometer similar to those used in LIGO. Calculating the noise budget for frequency noise and phase noise in this system is essential to ensuring that we meet the squeezing levels ($> 6dB$) required for meaningful improvements in LIGO sensitivity.

2 Objective

The main goals of this project are:

- To calculate and quantify the noise budget, particularly focusing on frequency noise and phase noise contributions, for the WOPA setup described. Additionally, to address and quantify other sources of noise such as polarisation mismatch, gain imbalance at the balanced homodyne detector (BHD), mode-matching errors between the local oscillator (LO) and signal fields, and residual intensity noise.
- To establish tolerances for phase stability that ensure more than 6 dB of observed squeezing.
- To determine the necessary length scale for suppressing laser frequency noise, such that the difference in path lengths between the interferometric arms in LIGO is less than 10 cm, given the current frequency variation of 70 MHz. This will involve quantifying how frequency noise translates into path length variations and setting requirements for laser stabilization to meet stringent interferometric precision.

3 Approach

The project will be conducted in the following manner:

- Model the squeezed light source using the theoretical framework of quantum optics, particularly the impact of frequency noise and phase noise on the squeezed quadratures.

- Analyze the WOPA optical setup, including the PPLN waveguide, LO phase shifter, and detection optics, using parameters extracted from the experimental layout.
- Develop noise transfer functions that describe how laser frequency noise and LO phase noise couple into the measured squeezed quadrature.
- Simulate the noise degradation using the mathematical relationship between squeezing, anti-squeezing, and phase noise.
- Validate noise budgets experimentally against squeezing degradation thresholds, setting allowable noise levels to meet $> 6\,\mathrm{dB}$ observed squeezing.
- Propose methods to control phase noise, such as active feedback stabilization and passive noise reduction.

4 Timeline

Timeframe	**Milestone/Task**
Week 1–2	Familiarisation with the WOPA experimental setup. Extract relevant optical and electronic parameters from the design. Model the variances of the squeezed and anti-squeezed quadratures using quantum optics formalism. Characterize the laser frequency noise spectrum using a frequency discriminator and spectrum analyzer. Identify dominant noise contributions from the laser cavity, current source, and external optics. Implement initial modifications—such as optical isolation, improved mode matching, and thermal stabilization—to mitigate frequency noise coupling into the squeezed quadrature.
Week 3–4	Derive and simulate the noise coupling transfer functions that quantify how frequency and phase noise couple into the measured squeezing spectrum. Use these models to simulate squeezing degradation due to phase noise. Calculate tolerable RMS phase noise levels to ensure observable squeezing exceeds 6 dB. Initiate measurements of nonlinear gain in the PPLN waveguide by varying pump power and temperature conditions.
Week 5–6	Continue nonlinear gain characterization and begin the first iteration of squeezed light detection using a balanced homodyne detector (BHD). Assess optical visibility and interference contrast between the local oscillator (LO) and squeezed signal field. Simulate and quantify the impact of laser frequency noise on the squeezing spectrum. Compare theoretical predictions with initial experimental measurements and identify stabilization requirements.

Week 7–8	Implement a coherent phase-locking system between the LO and signal beam using an electro-optic phase modulation scheme with active feedback. Characterize the phase lock's stability and residual noise. Finalize the noise budget by quantifying all significant degradation sources, including polarization mismatch, gain imbalance in the BHD, mode-matching inefficiencies, and residual intensity noise. Suggest system-level improvements.
Week 9–10	Optimize all experimental parameters to maximize the observed squeezing level. Evaluate squeezing in dB via spectral noise measurements and compare to theoretical predictions. Quantify the final level of quantum noise suppression achieved. Complete documentation and prepare final presentation/report, emphasizing readiness for integration with LIGO-like interferometric detectors.

References

[1] Authors. *Paper Title*. Journal Abbreviation, Vol, Page numbers (YYYY).

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