Technical Note	LIGO-T22xxxxx–	2025/06/14

Minimizing Noise in WOPA (Waveguided Optical Parametric Amplification) by Optimizing Mode Matching

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Contents

1 Introduction

LIGO (Laser Interferometer Gravitational-Wave Observatory) detects gravitational waves from astronomical phenomena such as black holes and binary neutron star collisions by using interferometry to measure the movement of test masses as a result of a gravitational wave. LIGO consists of two Michelson interferometers located 3000km apart. Both detectors have 4km orthogonal arms. A 1064nm wavelength laser is split at a beamsplitter and sent down the arms so that when a gravitational wave passes and stretches one arm while compressing the other, the beams will have a phase difference. The level of sensitivity required to detect gravitational waves (strain of gravitational wave is on the order of 10^{-22}) also makes LIGO's measurements susceptible to noise. To optimize the accuracy and sensitivity of LIGO, we aim to limit noise from as many sources as possible. One way noise is minimized in the laser is through quantum squeezing.

Quantum squeezing is a method in which we can minimize the laser shot noise. This shot noise arises from the uncertainty between phase and amplitude of the electric field. We are able to reduce the uncertainty in phase by increasing the uncertainty in amplitude and vice versa. Currently, both amplitude and phase squeezing are being used to reduce noise in LIGO, depending on the frequency. Waveguided Optical Parametric Amplification (WOPA) aims to improve upon the current squeezing process by using a periodically poled lithium niobate (PPLN) crystal to generate 1064nm squeezed light from 532nm wavelength light which we can combine with the 1064nm signal in LIGO to squeeze the light being detected. This method should allow for 2dB more squeezing compared to the current method as a result of higher nonlinear gain of the crystal. A lack of cavity makes the mode easier to measure out of the crystal and erases a need to lock a cavity - a potential source of loss.

2 Objective

Within the squeezing process itself there are sources of noise. One of which is a result of mode mismatch between the squeezed beam coming from the crystal and the non-squeezed beam. Loss of mode matching results in loss of measured squeezed light, given by

$$dB_{measured} = 10 \log((1 - \eta) + (\eta)10^{(dB/10)})$$

Where η is the mode matching with 1 being perfectly mode matched. 0.95 mode matching only allows for measurement of a maximum 99.77% of actual squeezing. This project aims to measure and minimize noise as a result of mode mismatch between squeezed and non-squeezed beams to optimize the accuracy and sensitivity of LIGO detections. We hope to mode match our local oscillator (LO) beam and signal beam to within $\eta = 0.97$ and generate 6dB+ of squeezing.

3 Approach

To maximize the measured dB of squeezing, we will focus on optimizing the mode matching between the signal and LO. Using ABCD matrices and FINESSE, an interferometer simula-

tion program, we will model the LO and signal beams as they propagate through the setup and adjust the WOPA setup until the beams are mode matched in the TEM00 mode. We match the beams by aligning their profiles and the positions of the beam waists which are given by

$$w(z) = w_0 \sqrt{1 + \left(\frac{z}{z_R}\right)^2}$$

where w_0 is the waist radius and z_R is the Rayleigh range.

4   Timeline

Week 1 (6/18-6/25)	Get familiarized with lab and experiment. Then measure the laser polarization drift, a possible source of noise in the system. We will also model the mode of the beam coming into and out of the crystal.
Weeks 2-3 (6/25-7/9)	Take nonlinear gain measurements of the crystal.
Weeks 4-5 (7/9-7/23)	Set up squeezing readout scheme which will be done via balanced homodyne detection.
Weeks 6-7 (7/23-8/6)	Mode matching our beams and reorienting the setup.
Weeks 8-9 (8/6-8/20)	Coherent phase locking the system to optimize the squeezing measurement

References

[1] Barry C. Barish and Rainer Weiss. *LIGO and the Detection of Gravitational Waves.* Physics Today, 52, p. 44-50 (1999).

[2] F. Kaiser et. al. *A Fully Guided-Wave Squeezing Experiment for Fiber Quantum Networks.* Optica, Vol. 3, p. 362 (2016).