LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY
- LIGO -
CALIFORNIA INSTITUTE OF TECHNOLOGY
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Technical Note **LIGO-T22xxxxx–** 2023/05/13

WOPA Squeezing SURF Proposal

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1 Introduction

Gravitational waves are distortions in spacetime produced by accelerating masses. Their existence was predicted over 100 years ago with the development of general relativity and the first experimental observation was made on September 14, 2015 by the Laser Interferometer Gravitational Wave Observatory (LIGO) of gravitational waves produced the a merger of 2 black holes.[1].

The Advanced LIGO detector is a pair of Michelson interferometers in Washington State and Louisiana with 4km arms containing Faby-Perot cavities to increase sensitivity [4]. A diagram of the interferometer is shown in figure 1.

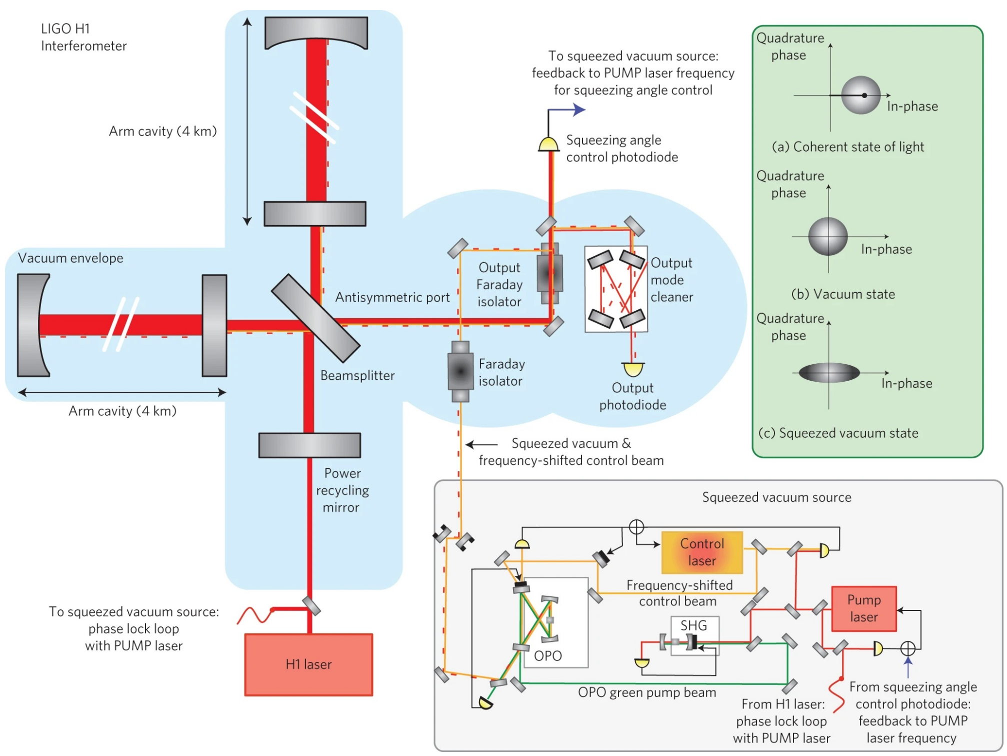


Figure 1: A diagram of one of the Advanced LIGO detectors, including the injection of squeezed vacuum [3].

Gravitational waves cause the arms of the interferometer to lengthen and contract relative to each other as the wave propagates through the detector. This changes the phase of the interfered beams and produces a detectable signal for a sufficiently sensitive detector. Advanced LIGO's sensitivity curve is shown in figure 1.

A dominant source of noise in the LIGO detectors is of quantum origin. At higher frequencies, this is shot noise from quantum fluctuations in the amplitude of the light. At lower frequencies, this is largely radiation pressure noise from the fluctuations in the momentum imparted to the mirrors from the light. LIGO utilizes squeezed light to minimize the effects of these noise sources. LIGO currently employs optical parametric oscillation techniques to generate squeezed light with 10db squeezing factors [3]. This proposal will focus on a waveguide optical parametric amplification as a alternative technique with certain benefits.

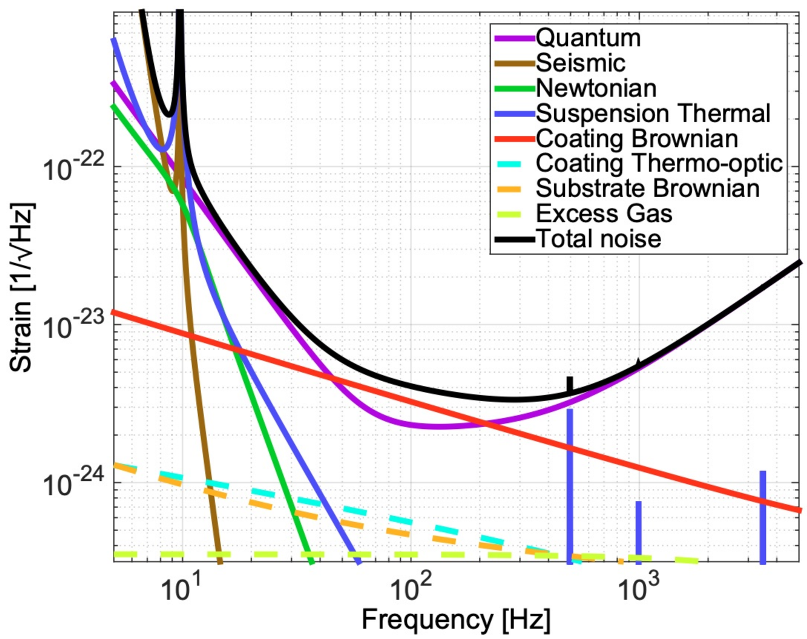


Figure 2: The sensitivity curve of Advanced LIGO [2].

1.1 Squeezed States

Squeezed states of light are minimum uncertainty states where the variance of the amplitude noise or phase noise is reduced while the other is increased. Squeezed states are defined, as in equation 1, as the eigenstates of the operator $\hat{A}_R$ [5].

$$\hat{A}_R \left|\alpha, R\right\rangle = \alpha \left|\alpha, R\right\rangle \tag{1}$$

Where α is a complex number, R is a real number and $\hat{A}_R$ is an operator analogous to the annihilation operator [5].

$$\hat{A}_R = \hat{a}\cosh R + \hat{a}^\dagger \sinh R \tag{2}$$

The field quadratures Q and P can then be defined in terms of $\hat{A}_R$.

$$Q = e^R\left(\hat{A}_R + \hat{A}_R^\dagger\right) \tag{3}$$

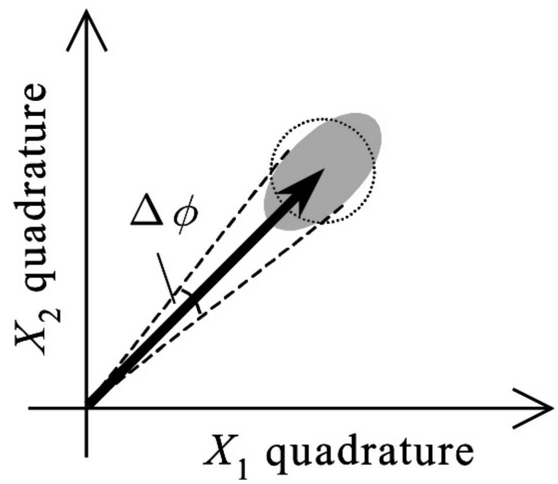
$$P = -ie^{-R}\left(\hat{A}_R + \hat{A}_R^\dagger\right) \tag{4}$$

The variance of the quadratures for squeezed states can be then be calculated.

$$(\Delta Q)^2 = e^{2R} \tag{5}$$

$$(\Delta P)^2 = e^{-2R} \tag{6}$$

The variances in the two quadratures is a function of R, but their product remains constant and satisfies the Heisenberg uncertainty relation. The factor e^{2R} is known as the squeezing factor. When $R = 0$ the light is in a quasi-classical state where the uncertainty in both quadratures is equal. For positive values of R, the variance in the P quadrature is reduced and the state is said to be phase-squeezed. An example of this is visualized in figure 1.1 as



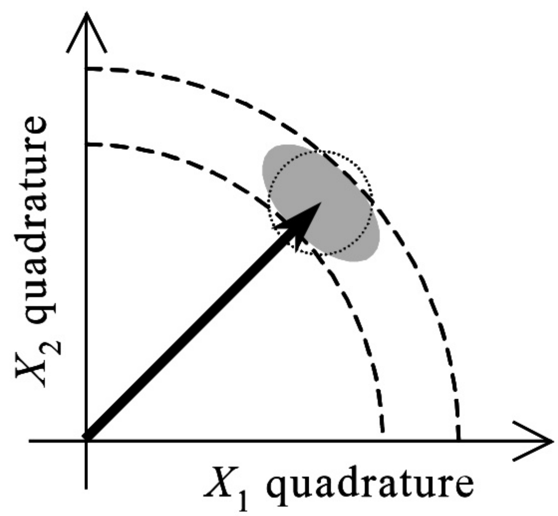


Figure 3: Phasor diagrams for two squeezed states are shown. Depending on the sign of R, the phase or the amplitude of the state can have reduced uncertainty [6].

a phasor with its uncertainty region shaped by the squeezing factor. For negative R, the variance in the P quadrature is decreased and the state is said to be amplitude squeezed as shown in figure 1.1. In theory, the squeezing factor can be arbitrarily large, but in practice it is strongly limited by optical losses.

1.2 Optical Losses with Squeezed States

A general optical loss can be modeled with a beam splitter whose transmission and reflection coefficients are t and r where $t^2 = 1 - r^2$. After transmission through the beam splitter, the squeezed state has been both attenuated and mixed with the vacuum state that entered through the other port. By mixing the squeezed state with vacuum, the squeezing is reduced. For a given input squeezed state of $|\alpha, R\rangle$, the output quadrature variances are given by

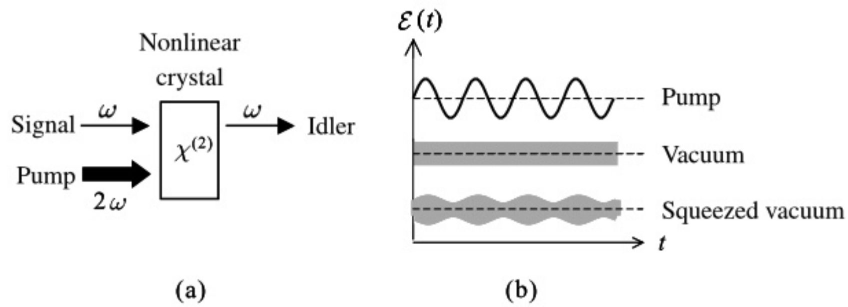


Figure 4: In figure (a), optical parametric amplification in a $\chi^{(2)}$ material is shown with a degenerate signal and idler. Figure (b) depicts field of the pump and vacuum fields input to the crystal in the top two graphs. The bottom graph shows the vacuum fluctuations are amplified and deamplified by the interaction in the crystal [6].

equations 7 and 8.

$$(\Delta Q)^2 = t^2 e^{2R} + r^2 \tag{7}$$

$$(\Delta P)^2 = t^2 e^{-2R} + r^2 \tag{8}$$

When the optical losses become significant, the variance in both quadratures approaches the same value, regardless of the initial squeezing factor. It is important to minimize optical losses when generating and manipulating squeezed light.

1.3 Waveguide Optical Parametric Amplification

Squeezed states can be generated with optical parametric amplification in nonlinear media. Figure 4(a) depicts a signal beam at frequency ω that is amplified by a pump beam at ω by interfering them in a $\chi^{(2)}$ material [6]. Since the idler and the signal are degenerate, the relative phase between the pump and signal determines whether amplification or deamplification of the signal occurs. When the signal is a vacuum, state, the vacuum fluctuations in the field are amplified and deamplified by their relative phase with the pump. The result is shown in figure 4(b). The input vacuum state has equal noise at all times, but the output state is modulated has been modulated. This output is a squeezed vacuum state.

Optical parametric amplification for squeezing can done in a nonlinear waveguide. This technique, called WOPA, produces high intensities of the pump beam throughout the length of the media which generates a strong nonlinear interaction and produces more squeezing that can be achieved by a single pass through a nonlinear crystal. In addition, waveguides provide a compact platform that can easily be made compatible with other optics. In addition, WOPA setups are less sensitive to noise from mechanical vibrations than squeezing setups with optical resonators. A reduction in this type of noise allows for improved squeezing at low sideband frequencies.

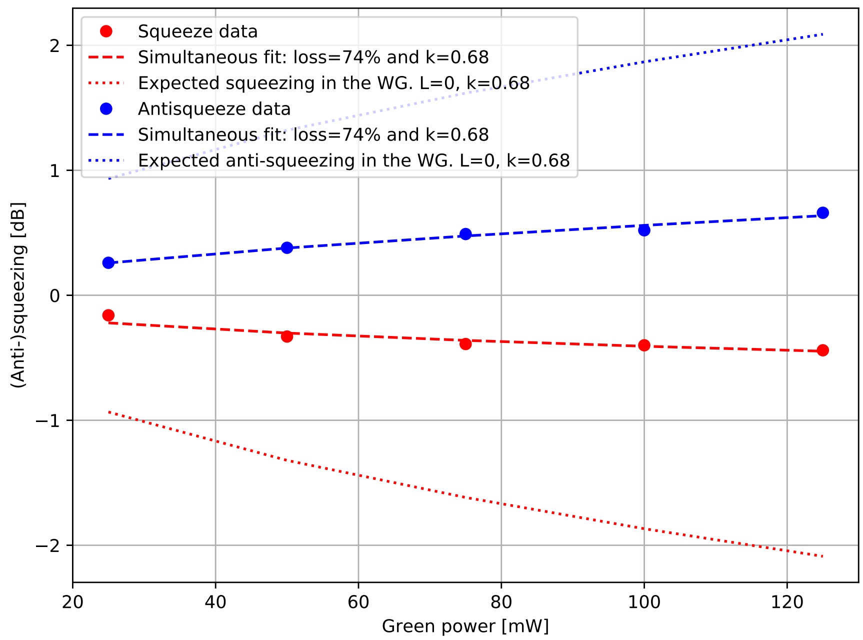


Figure 5: The squeezing and anti-squeezing amplitudes as a function of pump power are shown as red and blue data points. The theoretical squeezing amplitudes without loss are shown in the red and blue dotted lines.

2 Objective

The squeezing and anti-squeezing factors were measured in the current WOPA setup as a function of pump power. The results are shown in figure 5 as red and blue data points. This data was then fit to the beam splitter loss model and a loss of $r^2 = 74\%$ was obtained. The theoretical squeezing achieved in the waveguide, before losses, was calculated and is shown in figure 5 in the dotted lines. With losses, -0.4db of squeezing was observed at 120mw, but without losses, -2db is expected.

These results were achieved with the current in-fiber setup. The waveguide is directly connected to optical fibers on either side. The amount of pump power that can be sent through the waveguide is limited by coupling efficiency into the fiber and then from the fiber into the waveguide and by the fiber damage threshold. Low coupling efficiency from the waveguide back to the fiber causes high losses that degrade squeezing. My objective is to rebuild the setup with free-space optics to increase the pump power in the waveguide and reduced the optical losses on the squeezed light.

3 Approach

A diagram of the new setup for generation of squeezed states with WOPA and then detection with balanced homodyne detection is shown in figure 6. A NPRO Nd:YAG laser with internal second harmonic generation is used to generate a 532nm pump beam for the waveguide and a 1064nm beam that will be the local oscillator for the homodyne detection. The first half-

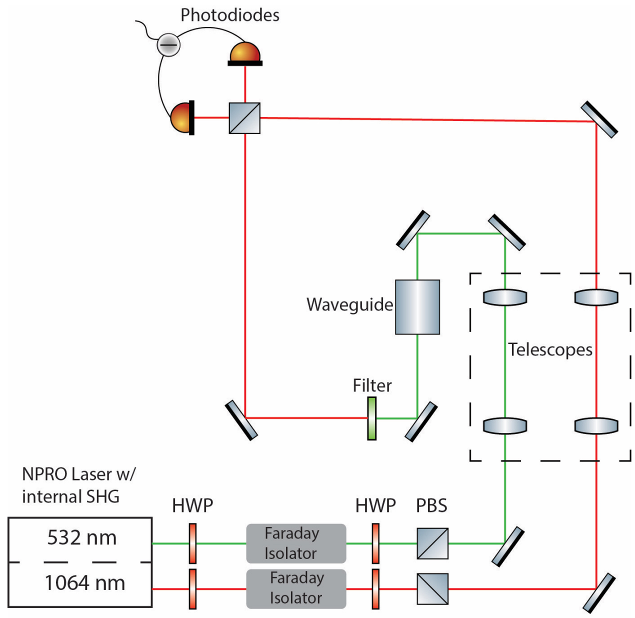


Figure 6: The setup for generation of squeezed states with WOPA and then detection with a balanced homodyne detector are shown.

wave plate allows the polarization of the laser to align to the Faraday isolator for minimum insertion loss. The second half-wave plate and the polarizing beam splitter allow the laser power into the system to be varied. A set of two lenses form a telescope to match the mode of the 532nm laser to the waveguide. A telescope is needed to match the mode of the local oscillator to the waveguide output for the homodyne detection. The waveguide is a Rubidium infused PPKTP nonlinear waveguide. The 532nm photons produce degenerate pairs of 1064nm photons that are quadrature squeezed relative to the phase of the pump beam. After the waveguide, the 532nm beam is filtered out and the 1064nm squeezed state is interfered on the last beam splitter with the local oscillator. The signals from the photodiode detectors are subtracted. The noise spectrum of the subtracted current can be analyzed to measure the variance of the squeezed field.

4 Timeline

Describe timeline of your plan, explaining what you would do every 2 weeks.

Weeks 1 - 2: Finalize the design for the new setup and order parts.

Weeks 3 - 7: Assemble the optics and test.

Weeks 8 - 10: Given time, demonstrate squeezing and noise locking or coherent control.

References

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