Squeezed Light Source Characterization for the QUEST Quantum Gravity Experiment

Stephanie Montoya
Montclair State University

Advisors: Dr.Hartmut Grote, Dr.Katherine Dooley, Nikitha Kuntimaddi
Cardiff University

(LVK Collaboration, University of Florida, NSF)
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The QUEST Quantum Gravity is attempting to detect quantum gravity phenomena by looking at correlations in signals between twin co-located interferometers. These types of measurements require extreme sensitivities, which can be achieved by injecting squeezed light states into the interferometer. This method has been used at LIGO to increase sensitivity. In this experiment, an independent squeezer must be characterized for each interferometer. Each squeezer is estimated to be sensitive to spatial perturbations of $10^{-19}\mathrm{m}/\sqrt{Hz}$. This report details my progress on the characterization of the second squeezer, which includes mode matching the input beam into the squeezer's input and configuring the cavities inside the setup to produce squeezed light.

I. INTRODUCTION

The world as we know it can be described by two theories: general relativity and quantum mechanics. Despite these two theories being derived from classical mechanics, there has yet to be a theory that unifies these two realms of physics. They work exceptionally well independently, relativity allowing us to understand the universe on a large scale such as the motion between galaxies, and quantum mechanics giving us insight into the small, probabilistic world of fundamental particles. The standard model has attempted to link these two worlds with particles like the graviton, however experimental proof of such a link has yet to be discovered. Other theories such as superstring theory or quantum loop theory require an introduction of new laws of physics that only appear at these plank scales[1], making them impossible to measure given the precision of contemporary equipment.

The QUEST Quantum Gravity experiment attempts to measure quantum gravity phenomena to aid the unification of the laws of physics. Through repeated measurements using co-located twin interferometers, we should be able to measure correlations in a given volume of space-time[1]. Given the extreme sensitivity necessary to make these measurements, injecting squeezed light states into the interferometer's input beams is necessary.

A. Theory

The holographic principle states that the universe, and by extension information, is fundamentally 2-dimensional. This information is projected into the 3-dimensional space that we experience life through every day. In other words, the information contained within a volume of space can be described by the information at the boundary of that volume. Following this principle, we arrive at the covariant entropy bound, which implies these quantum disturbances in space-time can be measured in an arbitrary volume of that same space-time. Following the line of thought that the universe can be described using fewer degrees of freedom, we should be able to observe correlations due to these quantum space-time fluctuations experimentally [1].

B. Experimental Layout

The QUEST experiment aims to use two 5-km-long twin interferometers. At the moment, two 2-km long interferometers are being used and commissioned. These interferometers are 40 cm apart. The distance between the two systems is much smaller than their arm length, making it possible to determine correlations when taking multiple measurements. In other words, analyzing the measurements taken will allow us to either determine a signature of quantized gravity or will allow us to set a limit under which the strength of the perturbations must abide [2].

We can think of finding correlations between the interferometers as taking the average between the two detected signals. Cross-correlating the signals allows us to reduce the shot noise in the system even further. Like traditional gravity theories, we can think of quantum gravity as being locally flat, meaning we'd see the same signal on both systems (given the distance is small). Even with great sensitivity, the random noise combined with the signal makes it difficult to comb out what is noise vs an actual signal. By cross-correlating the two signals, the random distribution fades into a general background noise, whereas the main signal increases in amplitude. Having a cross-correlation of zero indicates completely independent signals, which in this case would reject the notion gravity is quantized, and vice versa.

The measurements taken will be sensitive in a frequency band from 1 to 250 MHz [1], meaning it would

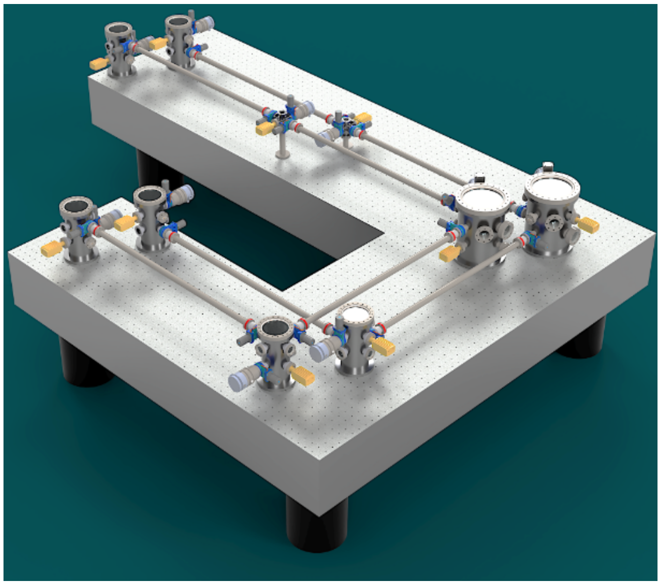

FIG. 1. A simplified diagram of the twin interferometers placed in one of the labs at Cardiff University, from [3]

also be sensitive to dark matter proponents such as WISPS and VULFs, as well as high-frequency gravitational wave sources such as primordial black holes [4].

As of now, both interferometers are in place in one of the labs at Cardiff, along with one of the squeezers having been characterized and integrated with the main experiment. Before doing the same with the second squeezer, it is my job to characterize it and lock all the cavities. To do so we have set up an experiment in another lab to do just that.

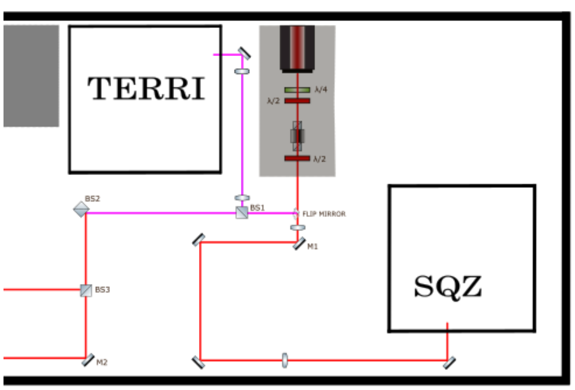

FIG. 2. A portion of the lab table that demonstrates the setup used to characterize the squeezer before being integrated into the main experiment. This is done in a separate lab from the main experiment, however, it is placed on a similar U-shaped optics table.

Since multiple experiments were being run using the same laser, there was a coordinated effort on the setup to make sure everyone received the power needed to take measurements. Since the squeezer needs the entirety of the laser power being provided (400-500mW), a flip mirror was placed near the lasing output. When flipped down, the squeezer gets the full extent of the power.

II. BACKGROUND

A. Mode Matching

The field of optics takes on the Gaussian beam approximation, which follows the notion that light beams have a focus point and proceed to diverge [5]. A beam of light is not constant and as it propagates through space it will focus at a certain point and then diverge.

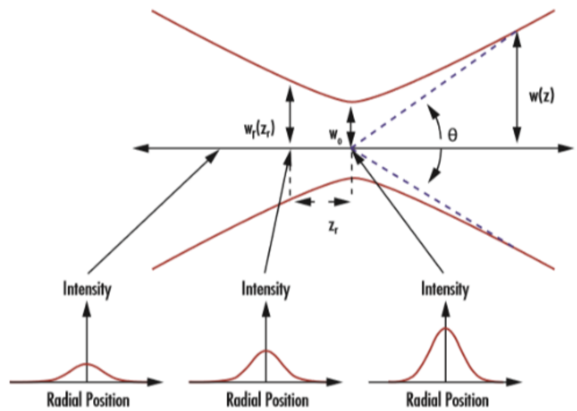

FIG. 3. From [5], showing how a beam propagates through space and how this affects the beam intensity with respect to the radial position.

The point of focus has some radius, which is the beam waist. Knowing the size of the beam's waist and the location of this waist can give us a lot of insight into the laser beam and what its parameters will be at an arbitrary point in space. Each beam will have a distinctive angle it will diverge which we can also use to define the beam waist.

$$w_0 = \frac{\lambda}{\pi\theta}$$

We can take into account other parameters and arrive at a proper way to find the beam waist at a location, z, from the beam waist given, which can easily be found experimentally. These parameters include w_0 which is the beam waist, λ as the wavelength, w(z) as the beam size at an arbitrary location, z, and M^2 is a factor that tells us how "gaussian" a beam is [5]. Having an M^2 value of 1 means a beam is perfectly gaussian.

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

Mode matching refers to matching the wavefront's radius of curvature of the beam we are looking at to the radius of curvature of a cavity's mirror [4]. To execute this we must generate a beam waist at a specific position depending on the mirrors present, which can be achieved by using lenses, mirrors, and applying ABCD matrices. Doing this incorrectly leads to higher-order modes, which are usually undesirable and take away intensity from the main beam and disrupt the signals we're observing.

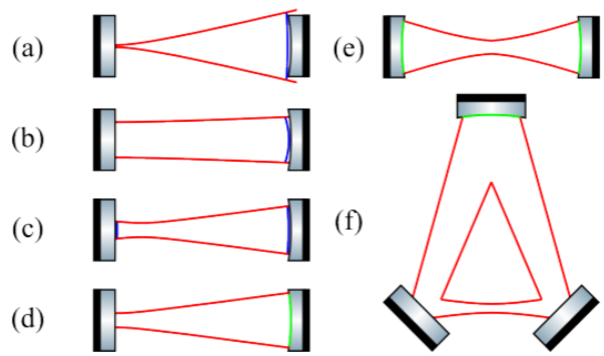

FIG. 4. From [4], which shows examples of successful mode matching (green) and mode mismatch (blue). Every instance of mode mismatch stems from the radius of the beam's wavefront not matching the wavefront of the mirror. This can be due to having a beam waist that too small(a), too big (b), or not at the correct position (c).

This is typically done mathematically first, luckily the creators of the squeezer at the Albert Einstein Institute in Hannover, Germany have provided us with the exact beam waist size and location necessary to have the input beam mode matched to the first cavity inside the squeezer. With this information, all left for us was to figure out how to get the laser's input to match these parameters.

B. Squeezing

To fully understand what squeezing is and how it is generated, one must first understand the quantum nature of light. In a laser beam, photons are not evenly distributed and tend to bunch up into groups. Their arrival point in space follows a Poisson statistic and leads to noise when taking precise measurements [6].

This randomness in the measurement causes random modulations to be measured in the optical power of the local oscillator field, leading to fluctuations. In systems like LIGO, this causes a fluctuation in the gravitational wave readout. At the photodiodes reading these signals, quantum shot noise describes the normalization of this variance to the mean photon number[4]. For LIGO this limits the amount and types of events that can be detected[6]. For QUEST, the quantum perturbations we are attempting to read are buried within and under this shot noise.

To go from the classical to the quantum nature of light, one must first quantize the electric field via canonical quantization[4]. This, along with the bosonic nature of photons, means we can describe the dynamic nature of a specific mode. In other words, we can describe the quantum state of a mode, j, of the Hilbert space, and alter these states using operators. The classical Hamiltonian for an electromagnetic field is defined as:

$$H = \frac{1}{2}\int(\epsilon_0 E + \frac{B^2}{\mu_0})\,dV$$

If we perform another canonical quantization and enact the boundary conditions of the mode functions u_j, as well as apply the equivalent expression for the magnetic field, B, we arrive at the Hamiltonian operator, which represents how many photons are in each mode multiplied by the corresponding photon energy.

$$\hat{H} = \sum_j \hbar w_j(\hat{a}_j^t \hat{a}_j + \frac{1}{2})$$

Operators allow us to act on quantum states; applying the position operator on a quantum state represents the action of measuring the position of the state, and applying the Hamiltonian operator on a state tells how the energy of that state is distributed.

Eigenvalues of the hamiltonian operator are $\hbar w_j(n_j + \frac{1}{2})$ that have corresponding eigenstates $|n_j>$, are called fock states. Each oscillator at frequency w_j has a nonzero energy, showing us there are fluctuations in energy even at the vacuum state. The raising and lowering operators $\hat{a}_j^t, \hat{a}_j$ of a harmonic oscillator indicate the creation and annihilation of photons, and are sometimes referred to as such. These operators can also be thought of as raising or lowering the number of quanta (i.e. photons in a mode) by 1. We can obtain any higher-ordered state by applying the creation operators multiple times to the vacuum state, under which the resulting eigenstates form a complete basis for a Hilbert space. For most optical fields, there are so many photons that we take these fields as a superposition or a mixture of Fock states [4].

Fock states allow us to know the photon number accurately, but not the phase. On the other hand, coherent states give us some knowledge of how the amplitude and phase can be found. Coherent states can be described as eigenstates of the annihilation and creation operators with complex eigenvalues and can be described in terms of Fock states. This means we can also define the mean photon number of the coherent state, $\bar{n}_j$, and the probability distribution of photons in a coherent state, $P(n_j)$, that follows. The most important thing to take away from this is the variance of a quantum observable at the vacuum state is 0, ensuring there are no photons present at the vacuum state.

A quadrature refers to the components of the electric field that describe the state of that light field, such as the amplitude and phase quadratures which also contain statistical distributions of these properties. We find that the quadrature operators can be defined as:

$$\hat{X}_1 = \hat{a}^t + \hat{a}, \hat{X}_2 = i(\hat{a}^t + \hat{a})$$

Where $\hat{X}_1$ represents the amplitude quadrature operator and $\hat{X}_2$ represents the phase quadrature operators. Any quadrature between amplitude had a quadrature angle, θ, and has the relationship:

$$\hat{X}_\theta = \hat{X}_1 cos(\theta) + \hat{X}_2 sin(\theta) = \hat{a}^t e^{i\theta} + \hat{a}e^{-i\theta}$$

Comparing the uncertainty of a coherent state to the uncertainties of a vacuum state via the Heisenburg uncertainty principle can be done by finding the variance of the amplitude and phase quadrature operators. Doing this gives you 1 for both coherent and vacuum states, meaning they both fulfill the special case for the uncertainty principle.

Uncertainty isn't equally distributed along both quadratures. The quadratures can be smaller than the vacuum noise, making it squeezed, while its counter quadrature would be anti-squeezed[7].

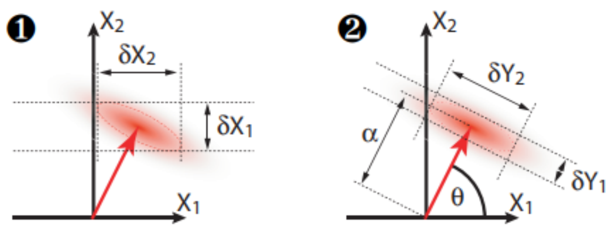

FIG. 5. From [7], shows a bright squeezed state on the left and that same bright squeezed state in a new coordinate system that's coaligned with the coherent amplitude on the right. This allows us to measure the maximum amount of squeezing.

With newly defined rotated quadrature operators $\hat{Y}_1$ and $\hat{Y}_2$, one can define β which is the rotated complex amplitude. We can observe the quantum state of light in the phasor space, which allows us to draw a frequency dependence representing the classical field with a specific frequency[4].

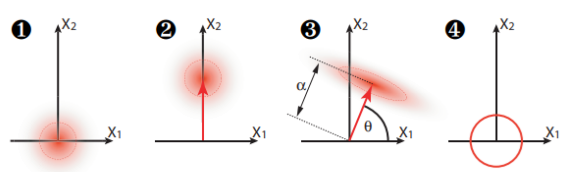

FIG. 6. From [4], shows from left to right the quantum phasor picture in a vacuum state, a coherent state, an amplified squeezed state, and a fock state.

After understanding what a squeezed state is, comes understanding how one generates a squeezed state. The first step is sending the infrared beam through the second harmonic generator, or the SHG, cavity. This cavity is the nonlinear experimental stage (along with the OPA) and uses upconversion to take two infrared photons with the same frequency and spit out one photon with double the frequency, or half the wavelength [8]. In the case of our 1064nm light, this results in one green photon being emitted for every two infrared photons going through the crystal. In Figure NUMBER, we can see the SHG along with the other cavities.

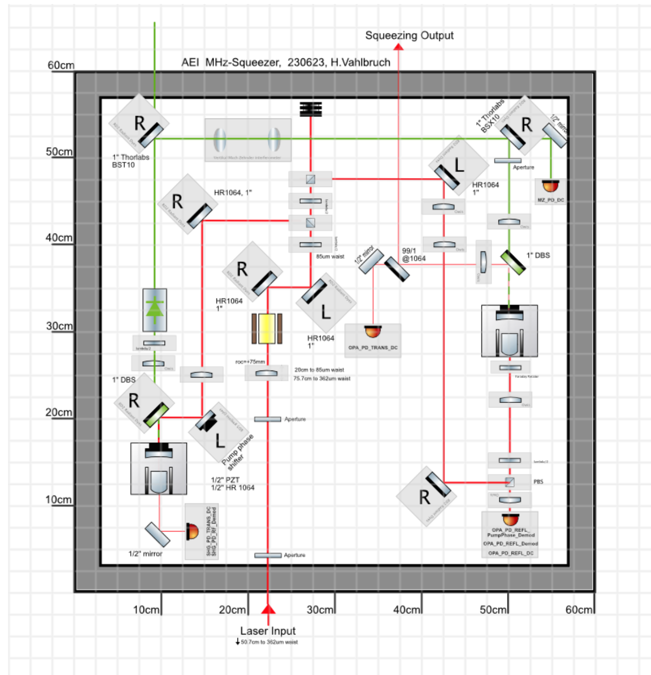

FIG. 7. A squeezing interface diagram made by Henning at AEI [9] This shows the inside of the squeezer and the path the beam must take to produce squeezed light. The beam parameters provided by this document mode match the input beam to the first cavity, the SHG, pictured in the bottom left corner. The beam travels from the SHG to the MachZhender pictured on the top left. The green beam then gets directed into the OPA cavity, pictured on the far right. An IR bright alignment beam is also sent into the OPA. The squeezed IR light is sent out of the OPA after being phase locked by the pump (which is to the right of the SHG) towards the output towards the top of the squeezer

We can alter the amount of green light being sent into the optical parametric amplifier, or OPA. This is done by locking and adjusting the servo offset on the vertical MachZhender, or MZ, inside the squeezer. Before sending the green light straight into the OPA, we see there is a polarizing beam splitter than sends the light into the SHG to begin with. The other part of the beam not being sent into the SHG is sent into the OPA, acting as a bright alignment beam which is used to align the squeezed light to the optics outside the squeezer and to align the input into the OPA. When no green light is injected into the OPA, the output is a coherent infrared beam. Once the OPA is aligned and able to lock, we can send in the green light from the MZ. The OPA is the opposite of the SHG, employing downconversion instead of upconversion. From here we can engage the pump next to the SHG to phase-lock the green and the coherent infrared. After the green light is sent in and the pump is locked, two quantumly entangled squeezed infrared photons are emitted (instead of the coherent beam we'd see if we didn't have green light injected into the OPA) [8].

III. RESULTS

A. Mode Matching

As mentioned earlier, the group at AEI [9] provided us with the necessary beam waist and location to have the input beam mode matched to the first cavity, the SHG, which required

$$w_{0,sqz} = 362 \; , z_{0,sqz} = -50.7cm$$

We know that if we have the laser source's parameters, we can apply ABCD matrices to find the output parameters at any point. Before my coming here Terri, a Cardiff PhD student also working in our lab, found the source parameters:

$$w_{0,seed} = 215.8 \; , z_{0,seed} = -18.54cm$$

We can use the seed parameters and input them into software that allows us to figure out what lenses to place where to generate our desired squeezing input parameters. To do this initially, I used a git repository called alamode, which is a mode matching and beam propagation repository that provides various scripts. After this, the available lenses (in terms of focal length in meters) are provided along with the seed and target beam parameters.

An issue I ran into with this script was that it only chose the 500mm and 1000mm lens options, no matter what input parameters I chose, which leads me to believe there was a bug that caused this. It also required the second lens (1m) to be placed further downstream from the actual lens position, which wasn't possible in our setup. I used this as a starting point and moved to a different mode-matching software called JamMT.

After some trial and error, I found the best configuration to have a 500mm lens about half a meter from the location of the seed waist (or about 0.315 meters from the lasing output) and a 400mm lens about 2.15 meters away from the seed waist (or about 1.97 meters from the lasing output). To ensure this waist occurred at the projected 2.421 m, I added a total of 3 mirrors between the first and second lens and ended up with the configuration shown in Figure 9.

With everything in place, we made measurements on the size of the beam as it propagates after L2. We can fit this to the equation defined earlier for a gaussian beam defined at an arbitrary point z, and after many rounds of trial and error, we found the most optimal mode matching we could without opening the squeezer. We analyzed this using a wave metric software called IGOR Pro.

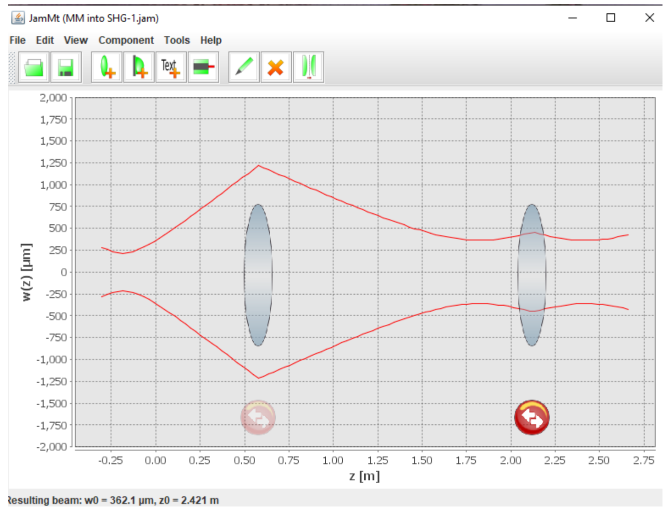

FIG. 8. The final mode matching solution we came up with gives us our desired target waist at a feasible location.

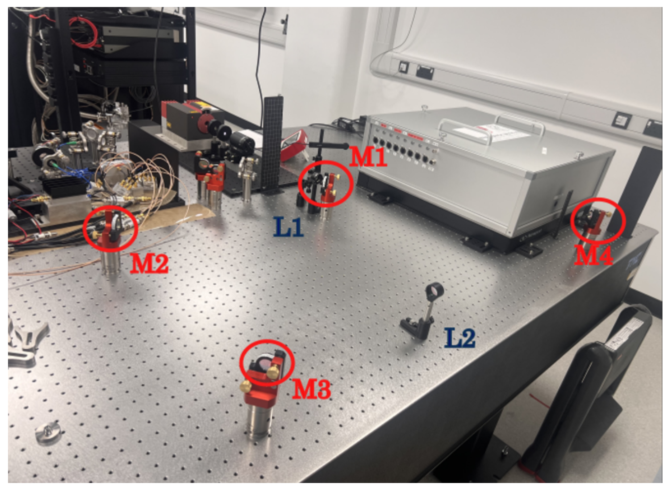

FIG. 9. This is analogous to the diagram shown in FIGURE 2. M2, and M3 were placed strategically to have our waist end up at a specific location. M3 and M4 serve as a steering mirror to beam walk the laser into the squeezer's input.

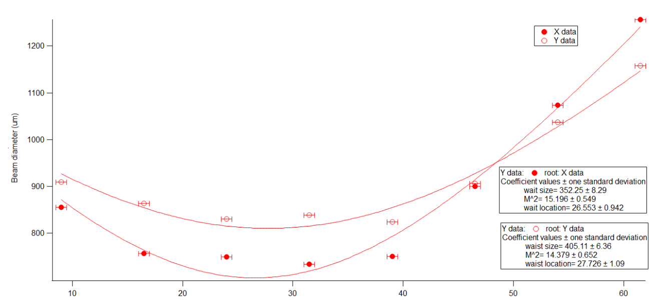

FIG. 10. The x-axis represents the distance in cm from lens 2, and the y-axis represents the size of the beam in μm.

An issue we ran into here was the presence of higher-order modes, which is evident given the M^2 values being much greater than 1 [5]. For characterization purposes this was sufficient, so we were able to move on to beginning the characterization of the squeezer.

B. Squeezing

To characterize the squeezer, we need to produce squeezed light. The simplified process of this includes mode matching into the SHG cavity, sending the resulting green light through the MachZhender, and then steering the green light into the OPA cavity. The electronics for the squeezer allow us to control each of these cavities by putting them in either scan or lock mode. When producing squeezed light, all cavities must be able to be locked.

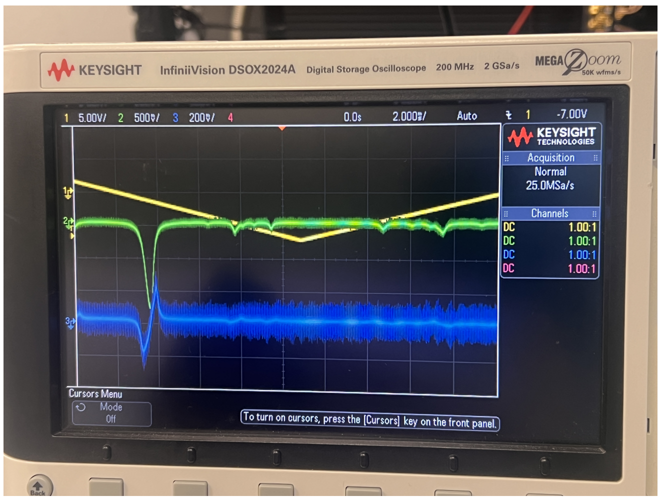

FIG. 11. Shows the signals for the SHG cavity. The yellow is the ramp signal, showing the mirror moving back and forth by the PZT, allowing us to perform a cavity scan. The green is the transmission signal read at the photodiode, and the blue is the accompanying error signal. The signals shown for the SHG are almost the same for the OPA when in scan mode, except the transmission signal for the OPA is flipped so the peaks go up instead of down.

The first step was to lock the SHG cavity, which wasn't locking due to the presence of higher-order modes which had a peak intensity 80 percent that of the main signal. This was fixed by slightly adjusting the position of the second lens. Another issue that prevented the SHG from locking was the lack of an error signal. The signal generator supplying power to the local oscillator that produces the error signal was not driving as much power as we had seen previously resulting in the error signal having a very small amplitude. To fix this we altered the amplitude on the signal generator from -3dBm (as had been used when characterizing the first squeezer) to 0dBm. This yielded an error signal with an amplitude of 400mVpp as shown in figure X.

After this came the MZ, which automatically locked once the SHG was locked. We saw a decent contrast in the signal, as shown in Figure 12.

FIG. 12. Shows the signals for the MZ when in scan mode. The yellow represents the ramp signal produced by the PZT moving the mirrors back and forth allowing us to perform a cavity scan. The green is the transmission signal from the MZ's photodiode, and the blue is the accompanying error signal.

Finally came the OPA, which had a big issue showing up in the error signal. We saw some oscillations in this error signal, which we found out ended up being caused by a parasitic cavity being formed inside the squeezer. This was resolved by placing a Faraday Isolator right before the input beam was injected into the SHG and pump.

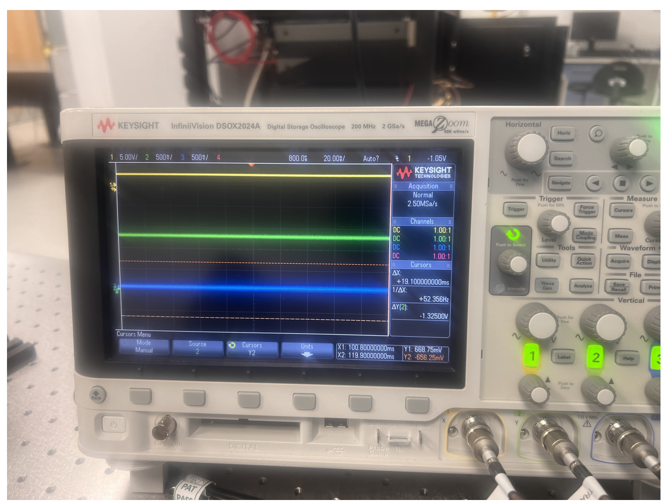

FIG. 13. A picture of the squeezer with a locked cavity. This signal looks the same for all 3 cavities.

After some more fine-tuning in the alignment, we were able to lock at 3 cavities, which can be seen in Figure 15. Once we made sure all three cavities were able to lock we could engage the pump that was placed next to the SHG. The pump acts as a tool that allows us to phase-lock the bright alignment beam to the green light. When we achieve phase locking, we can produce squeezed light via downconversion.

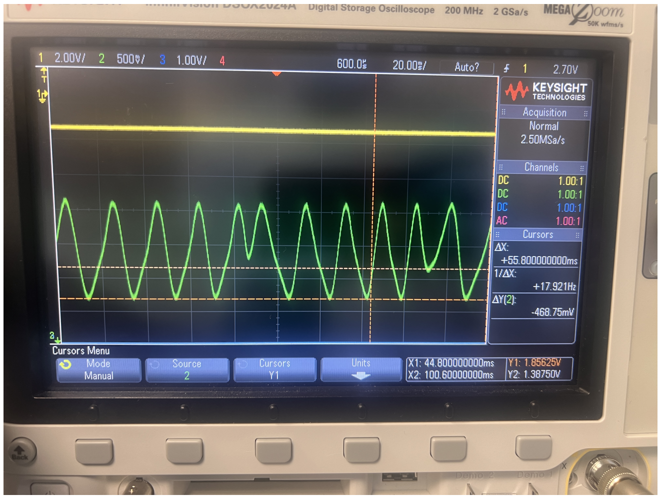

FIG. 14. The OPA signal showing the amplification and deamplification of the beam. The dashed line in the middle of the signal represents no amplification (meaning no green light being sent into the OPA) and acts as our zero line.

The gain is like a measure of how much squeezing or anti-squeezing was produced, taking into account the mode mismatch and contrast between the squeezed beam and the local oscillator. We find the gain for amplification or de-amplification by taking the ratio to no amplification. This is similar to taking the ratio between an input and output beam. De-amplification indirectly relates to seeing squeezed light and occurs at the troph of the signal. Parametric amplification indirectly refers to anti-squeezing and is seen at the crest, and tends to have a higher amplitude than the squeezed light since squeezed states are more susceptible to noise [4]. We found a de-amplification parametric gain of 0.75 and an amplification parametric gain of 1.57. These numbers aren't as big as we'd like them to be, nor as big as we see in the first squeezer. Given the time constraint, however, they provide a good starting point.

IV. CONCLUSIONS

While we were able to produce and observe squeezed light, the amount produced was less than ideal for injecting into the main interferometer. Ignoring the amount of squeezing produced, there were many issues present in the electronics controlling the squeezer. This included the electronics rapidly losing power, sometimes drawing different amounts of current day-to-day, and providing different readings on the oscilloscope to name a few. Future work would include optimizing the system, meaning fixing the electronics as well as bettering the alignment into the cavities.

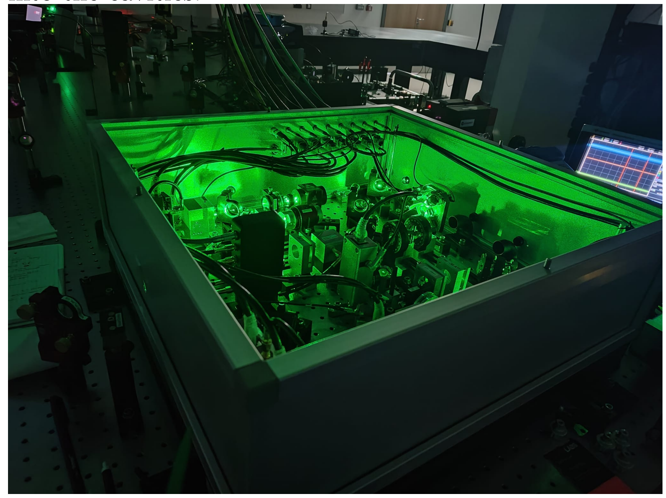

FIG. 15. A picture of the squeezer with all 3 cavities locked.

A lot of the higher-order modes present could be corrected with an output mode cleaner, which is currently in commissioning. Adding this to the current setup would provide us better insight into how much actual squeezing is being produced and how much is being lost to these additional higher-order modes.

A better way to characterize the squeezing would be to employ a balanced homodyne detector at the output of the squeezer. The balanced homodyne is a detection scheme that allows us to measure the intensity of the main signal and the corresponding intensity of noise.

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