LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY
- LIGO -
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PPLN Crystal Nonlinear Gain Measurements for Tabletop Waveguided Optical Parametric Amplification

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1 Introduction

LIGO (Laser Interferometer Gravitational-Wave Observatory) enables the detection and study of black hole mergers (and theoretically other astrophysical phenomena such as binary neutron star (NS) systems, asymmetric NSs, and a stochastic gravitational wave (GW) background) where matter is in conditions unacheivable even on a scaled level on Earth. The information detected with LIGO will give insight into how fields like general relativity and nuclear physics behave in the strong field regime as well as potentially reveal new astrophysical phenomena and the physics of the early universe from before the cosmic microwave background [1] .

In order to detect gravitational waves from black hole mergers and other phenomena, LIGO has two Michelson interferometers positioned 2000 miles apart (10ms of light travel time) each with 4km long arms whose lengths are changed when a passing gravitational wave moves a suspended mirror at the end of one interferometer arm on the order of $10^{-21}m$, causing a phase shift in one beam. LIGO's strain sensitivity in best at 100Hz-1kHz, allowing us to detect anything on the order of strain $h = 10^{-23}$. At frequencies above this range, the shot noise of the laser causes amplitude noise due to the random (Poisson) distribution of the number of photons detected in a given time interval [2]. At frequencies $< 100Hz$, quantum back action increases uncertainty due to the exchange of momentum between photons and the suspended mirrors which cause random low frequency oscillations in the mirrors that are reflected in the phase of the beam. Shot noise and quantum back action contribute to the overall noise level in LIGO which is a result of various environmental noises such as earthquakes and other vibrations, phase drift in the laser also contributes to this uncertainty, among other sources. The shot noise is given by

$$S = \sqrt{2\hbar P\nu}$$

where P is the average laser power and ν the laser frequency. To limit noise and uncover these signals, we adopt a frequency-dependent quantum squeezing method with which we can reduce uncertainty in amplitude at high frequencies and reduce uncertainty in phase at low frequencies, at the cost of increasing noise in the other quadrature. This is achieved by generating vacuum state squeezed 1064nm light via spontaneous parametric down-conversion (SPDC) from a 532nm laser and injecting this squeezed light into LIGO at a frequency-dependent squeeze angle to squeeze the LIGO signal in the necessary quadrature for the GW frequency.

This project, waveguided optical parametric amplification (WOPA), aims to simplify the current squeezing method by generating squeezed light in a single pass through a periodically-poled Lithium Niobate (PPLN) crystal. This will limit possibile losses that exist in the current optical parametric oscillator cavity used for squeezing the LIGO signal. SPDC is a nonlinear optical parametric process in which a pump wave (532nm in our case) interacts with vacuum fluctuations within a nonlinear crystal, resulting in the conversion of a pump photon into a pair of signal and idler photons (1064nm) such that the frequencies of the signal and idler photons sum to the frequency of the pump in order to preserve energy and momentum. PPLN preserves the polarization of our pump wave so we have type 0 SPDC where the polarizations of the pump, signal, and idler waves are equal. Because the polarizations and frequencies of the signal and idler photon pair are equal, they are indistinguishable and therefore coupled. This is the source of our squeezing, because the state of one photon within a pair must be exactly the state of its partner this reduces uncertainty in whichever quadrature we choose to squeeze the light in. This interaction between the vaccum and pump wave in the crystal is enabled by the second order nonlinear susceptibility $\chi^{(2)}$ of PPLN, a dielectric medium, which allows for the contributions to the electric field of the E^2 terms in the following equation from [5]

$$\tilde{P}(t) = \epsilon_0(\chi^{(1)}\tilde{E}(t) + \chi^{(2)}\tilde{E}^2(t))$$

Where P is the polarization of the wave. Parametric amplification is the process in which in addition to the pump beam, we also send a nonzero signal beam (1064nm) into the crystal. The pump wave then interacts with the signal in the crystal similarly to the vacuum fluctuations in SDPC and amplifies the signal wave by converting pump photons to pairs of signal and idler photons. We use this process to generate enough pairs of 1064nm photons to measure with our photodetectors.

We are currently working to measure the nonlinear gain of parametric amplification which will enable us to calculate the level of expected squeezing by [3]

$$Sq(dB) = 10 \log 10(R_{\pm})$$

with

$$R_{\pm} = (1-\eta) + \eta e^{\pm 2\sqrt{aP_{2\omega}}}$$

where $P_{2\omega}$ is the coupled pump power, η is the total detection efficiency, and $a = L^2 NCE$ is the intrinsic SPDC efficiency with $L = 15mm$ waveguide length and NCE (waveguide normalized conversion efficiency $(\%/W/cm^2)$) given in the HC Photonics Waveguide Manual by

$$NCE = G_{nl}(1-R_{out})(1-L_{loss})\frac{1}{L^2} \times 100\%$$

where G_{nl} is the nonlinear gain of the squeezing process, $R_{out} = 14\%$ is the chip endface reflectivity, and L_{loss} is the loss in the high NA lens after the crystal. The nonlinear gain will help us get an estimate of how many dB's of squeezing we will get, and identity sources and loss in our set up.

2 Approach

Our first method of measuring the nonlinear gain was to align to the nonlinear axis of the crystal (which lies along the x-axis in the below figure, orthogonally intersecting the ridge channel face noted) by adjusting the crystal position and signal path incoupling optics to maximize second harmonic generation of 532nm light from our 1064nm signal beam. The nonlinear axis is the path through the crystal along which the nonlinear susceptibility, $\chi^{(2)}$, has the most effect on a wave passing through the crystal. Second harmonic generation is another second order nonlinear process that is a result of this susceptibility. It is characterized by the conversion of two photons at the pump frequency to one photon at double the pump frequency. Optimizing this process will confirm that we are aligned to the nonlinear axis along which all nonlinear processes occur in PPLN, and should therefore approximately

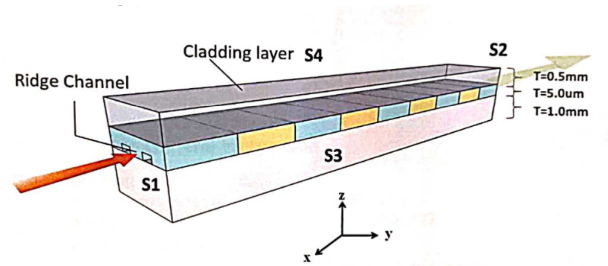

Figure 1: Diagram of PPLN waveguide from HC Photonics manual. The nonlinear axis normally intersects the face of the 2-3μm tall 6μm wide channel pointed out in the figure.

align the crystal for SPDC. SHG is a nonlinear process in which the second order terms of the 1064nm field are amplified in the crystal and the interaction of the field with electrons within the PPLN destroys two 1064nm photons to create one 532nm photon through the excitation and emission of an electron. The power output in SHG is higher than that output in SPDC because SHG is the stimulated emission of photons of power equal to the two photons converted to create it and SPDC the conversion of one photon to two photons in a squeezed vacuum state from the interaction of the initial pump with vacuum fluctuations and therefore has very low output power (pW range). We then maximized the 532nm pump power measured after the crystal on a power meter by adjusting the crystal position (while still maintaining SHG) and the 532nm path incoupling optics. This was done to get as much SPDC production as possible because the output SPDC power increases with increasing pump power. The maximum pump power while SHG was still observed was typically $4 \pm 1mW$. We then lowered the power of our signal beam so that $100\mu W$ of signal power was incident on the south(lower) PD shown in the WOPA setup diagram below.

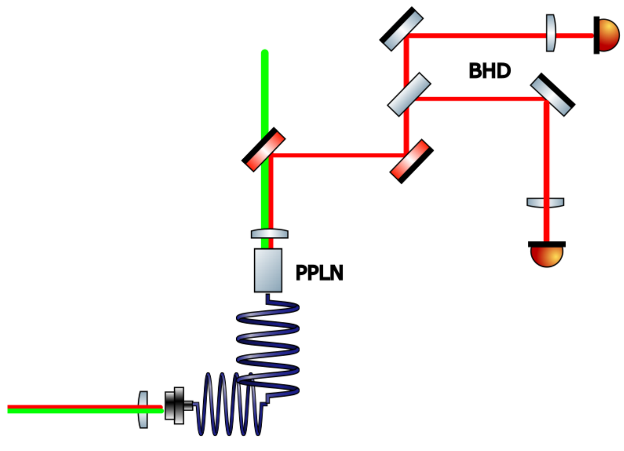

Figure 2: Simplified current WOPA experimental setup showing incoupling fiber, PPLN crystal, and focusing optics with Balanced Homodyne Detector (BHD)

We averaged the PD readout (which has a conversion of $\sim 10mV/100\mu W$) on the Moku:Pro in oscilloscope mode over 10 second intervals for constant signal power and at evenly incremented pump powers between 0 and the maximum pump power achieved. We compared these averages to the reference case of no pump power to calculate the SPDC power and calculate the gain with the previously mentioned equation.

Our current method of nonlinear gain measurement is similar to the one previously described, but we drive the piezo on the 1064nm path at a frequency between 10Hz-50Hz to overcome potential phase mismatch between our input signal beam and the SPDC generated by the crystal. We align the crystal and beams as described above and again lower signal power such that $100\mu W$ is incident on the south PD. We drive the P-810.10 piezo from Physik Instrumente L.P. with a triangle wave from 0-15V at a frequency within 0-50Hz using a function generator whose output is amplified by the MDT694B Piezo Controller. We adjust the voltage range and frequency until at least 2 peaks (1 wavelength) are seen within the overall sinusoid of the PD readout in one period of the driving function when only the signal beam is incident on the PD. This corresponds to a triangle wave of 1Vpp with a 500mV offset from the function generator being fed to the piezo driver which has a gain of 15V/V. This ensures that we are driving the piezo such that the signal beam cycles through its phase at least once, so the signal and SPDC beams will be phase matched at least once in a period of the driving function. This oscillation between phase matching and mismatch of the signal and SPDC beams as the piezo moves can be seen in the following figure:

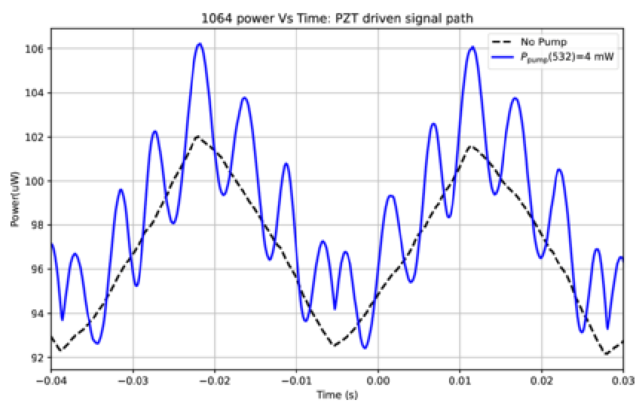

Figure 3: PD readout converted to W of signal beam with 0 and 4mW of pump power. The 0mW pump case shows the triangular oscillation we expect due to the change in fiber coupling as the piezo motion changes the path of the signal beam. The 4mW case shows the oscillations from the interaction of SPDC output and the seed signal beam atop this underlying low frequency oscillation.

We use multi-instrument mode in the Moku:Pro to record the power spectral density (PSD) of the incident beam for even increments of pump power from 0 to its maximum. We measure the increase in power at a frequency only present with nonzero pump power as the SPDC power and use this to calculate the nonlinear gain.

We are in the process of calculating an expected nonlinear gain and if this value is at least an order of magnitude of 10 off of our gain measured by the previous method, we will use a lock-in detection method by modulating the laser frequency using a chopper wheel. We will place the chopper in the beam path before the PD and operate it at a frequency ω which corresponds to a frequency above the DC range of the PD at which we know our PD is sensitive below the shot noise based on previous noise characterizations. The piezo on the 1064nm path will also be driven at a frequency ω_0 and voltage range such it cycles through its phase at least once per period. We will record this AC signal in the Moku:Pro in lock-in amplifier mode after putting it through a bandpass filter around 4ω and demodulate it with the function $\sin 4\omega$ generated in the Moku:Pro. This method limits the effect that low frequency noise has on our gain measurement.

3 Progress

The first two weeks we attempted to measure nonlinear gain via the first mentioned method. This was unsuccessful due to random fluctuations in laser power of at least equal magnitude (15uW range) to the power increase due to SPDC (we expect change $\sim 10\mu W$ if similar efficiency to SHG is assumed) with the current achievable pump powers. This low level of pump power while maintaining alignment for SHG is another issue that impeded our measurement. Because these power fluctuations masked any nonlinear gain, we would ideally like to increase the pump power to increase the expected output power from SPDC above the amplitude of these fluctuations. The 532nm beam power reaches a maximum of $106mW$ at the fiber incouple to the crystal and the most observed after the crystal has been 11.2mW without SHG alignment, and 7.5mW with SHG alignment. We would need at least 33mW of pump power measured after the crystal to see SPDC caused power fluctuations above the noise. We see up to -30dB of loss through the fiber and crystal which is limiting our nonlinear gain and therefore our squeezing capability. This could be due to fiber damage, a lack of 532nm beam polarization fidelity in the fiber, crystal damage, mode mismatch of either beam to the crystal and/or fiber, and missing poles in the crystal. The alignment of the crystal is unstable, requiring a realignment to maximize SHG before every measurement session.

In the past week, we have attempted the second mentioned nonlinear gain measurement method. This method has allowed us to see definite changes in amplitude correlated to nonzero pump power, implying that phase mismatch between the signal and SPDC was at least one limiting factor in the previous measurement method. However, we do not yet know the piezo response $\mu m/V$ so we have not been able to modulate the signal path such that we expect one peak of amplitude per period due to phase matching between SPDC and the signal. We have driven the piezo from 10-50Hz, a range which avoids resonant frequencies, within a voltage range of 0-15V, corresponding to power fluctuations of $20\mu W$ as shown in Figure 3, but have not yet been able to resolve clear peaks corresponding to the wavelength of the signal within the driving period. The PSD of our measurements also does not reveal any significant amplitude change at a specific frequency correlated to nonzero pump power. We are in the process of setting up a temporary Michelson interferometer within the setup consisting of the LO path and a reference path picked off of the 1064nm path from the first PBS pictured in setup diagram whose output is measured at the south PD. This will allow us to characterize the piezo response by driving the piezo at various frequencies and voltage ranges until we observe a wavelength within the period of our driving function, from which we can calculate the response as $\frac{1064nm}{V_0}$ for whatever maximum voltage V_0 we apply and solve for the voltage required to move the piezo $1\mu m$.

We recently began calculating the expected nonlinear gain due to SPDC. The current approach solving for the expectation value of the signal photons $\hat{N}_S$ given in [4] as

$$\langle \hat{N}_S(t) \rangle = \frac{e^{2|\nu|t}}{4} U$$

where

$$U = 1 + \langle \hat{N}_S(0) \rangle + \langle \hat{N}_I(0) \rangle + \left(\frac{|\nu|}{i\nu} \langle \hat{a}_S^\dagger(0) \rangle \langle \hat{a}_I^\dagger(0) \rangle + c.c \right)$$

where the subscript I refers to the idler photons, c.c is the complex conjugate, and ν is given by

$$\nu(t) = \eta_{PA} \hat{a}_P e^{i\omega_P t}$$

where η_{PA} is the interaction parameter for parametric amplification which we can find from the polarization density of our crystal and the subscript P refers to the pump photons. We also have the interaction operator for SPDC (parametric fluorescence)

$$\hat{H}_{PF}^C = -\hbar \sum_{l,l'} \eta_{PA}(S_l, I_{l'}) \left(\frac{1}{V} \int_V e^{i(\vec{k_P} - \vec{k_S} - \vec{k_I})\vec{r}} \hat{a}_P \hat{a}_{S_l}^\dagger \hat{a}_{I_{l'}}^\dagger d^3\vec{r} + h.c. \right)$$

where l, l' are the modes of the signal and idler waves respectively, V is the crystal volume, and $h.c.$ denotes the Hermitian conjugate.

4 Future Steps

We plan to model the mode through the waveguide using the modesolverpy package and use this with our expected nonlinear calculation to estimate the level of SPDC generation we should see with the current setup. We will also implement the previously described chopper wheel setup to achieve a more accurate nonlinear gain measurement if the expected value is significantly different from what we measure simply by modulating the signal path. There is already noticeable losses observed in the system like those described in the fiber and crystal so we will likely have to go through the setup and minimize losses which may result in a reconfiguration of the experiment. For example, if our mode matching model expects lower losses than observed, we will have to calculate what additional incoupling optics are required to correctly mode match to the crystal. We may need to replace or remove the fiber in order to maximize the mode matching. We also plan to lock the phase of the signal to the pump in order to maximize nonlinear gain, but the phase 532nm pump itself noticeably drifts overtime and the power fluctuates significantly which could affect our measurement of output SPDC power. The laser is about 20 years old and is already operating at its maximum temperature to generate the highest 532nm power possible to there are no immediate methods by which we can stabilize the pump power.

References

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