LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY
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# Low-noise Nonlinear Cavity for Cryogenic Interferometers

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# 1 Introduction

First detected by LIGO, gravitational waves (GW) offered valuable insights into astronomical phenomena that are crucial to our understanding of the universe. At its core, LIGO is modeled after the famous Michelson interferometer with arms of 4 kilometers and suspended mirrors to reflect a powerful laser beam. The passage of GW introduces changes in the arm length on the order of $10^{-21}$ meter. By analyzing the interference pattern taking place at the photodetector, the change in arm length due to GW can be detected. Due to the sensitive nature of its measurements, LIGO continually seeks to improve its sensitivity. Currently, scientists are currently aiming for a 100-times better sensitivity than the first-generation instruments [1]. Achieving this improvement requires keeping the mirrors at cryogenic temperature, which also requires changing the material that the mirrors are made of [4]. The new material, crystalline silicon, absorbs the wavelength of the existing laser. Hence, a laser with a new wavelength, 2128 nm, is needed for LIGO to operate at cryogenic temperature. A high-intensity laser with the desired wavelength is not readily available for commercial use. Therefore, the conversion from 1064 nm to 2128 nm is done in a lab using a Degenerate Optical Parametric Oscillator (DOPO). Due to many noise sources, the wavelength conversion process is not perfect. The goal of my project is to characterize DOPO's frequency noise, creating a noise budget to account for noise sources, and finally develop a noise-elimination scheme to make the conversion process as effective as possible.

# 2 Background

A DOPO is a device that is used to generate electromagnetic waves of desired frequencies through nonlinear processes. Typically, there is an intense laser source that is pumped through a nonlinear crystal, Potassium Titanyl Phosphate (PPKTP), which in turn converts the pumped frequency to the desired value. As shown in Fig. 1(b), a laser beam of frequency $\omega_p$ is pumped into an optical cavity that contains a dielectric non-linear medium of second-order susceptibility, $\chi^{(2)}$. Through the non-linear processes that take place inside the crystal, a new frequency is generated: $\omega_s$ (signal frequency) and $\omega_I$ (idler frequency). In our case, this is a degenerate OPO, so $\omega_I = \omega_s = \omega$, as shown in Fig. 1(b). For optimum nonlinear frequency conversion, the phase mismatch value $\Delta k = k_3 - k_2 - k_1$ needs to be as close as possible to zero. To fulfill the $\Delta k = 0$ condition, a periodically-poled crystal is used to ensure that the field strength of the generated wave grows linearly with the propagation distance [2]. On a microscopic level, the frequency conversion process is parametric, meaning that the initial and final quantum-mechanical states of the system are identical. In effect, the ground state population is only temporarily removed for brief intervals of time to reside in virtual levels, as shown in Fig. 1(a) [2].

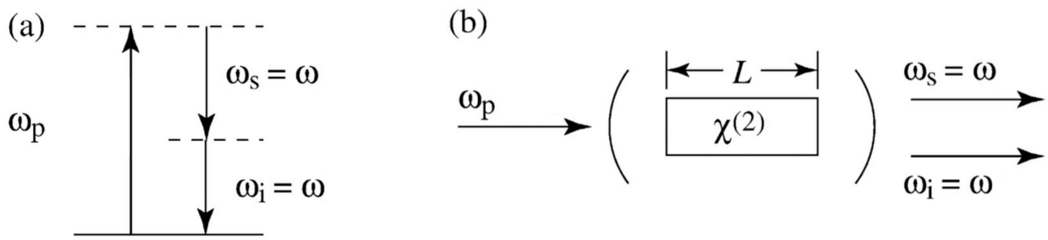


Figure 1: (a) A microscopic view of the processes inside the nonlinear medium. The dashed lines represent virtual energy levels, whereas the solid line represents the ground state. (b) The experimental setup of an Optical Parametric Oscillator. The curved lines surrounding the non-linear crystal represent mirrors that reflect waves with frequency $\omega$. [2]

# 3 Current Work

## 3.1 The DOPO Setup

DOPO is currently set up in the lab on an optical table, as shown in Fig. 2. The goal of the optical cavity is to increase the intensity of the laser beam after converting its wavelength to 2128 nm. In this setup, a 1064 nm laser beam with approximately 34 $\mu$m beam waist is fed to the optical cavity. The input coupler is a highly reflective mirror with a 15 mm radius of curvature and plano concave 7979 infrasil substrate with 99.95% high reflectivity coating at both 1064 nm and 2128 nm. The high reflectivity of the input coupler prevents the amplified beam from being reflected back to the laser. The output coupler is also a mirror with a 25 mm radius of curvature and plano concave 7979 infrasil substrate with 99.95% high reflectivity coating at 1064 nm but 97% at 2128 nm. That way, there is a high probability for 2128 nm photons to be transmitted through the output coupler.

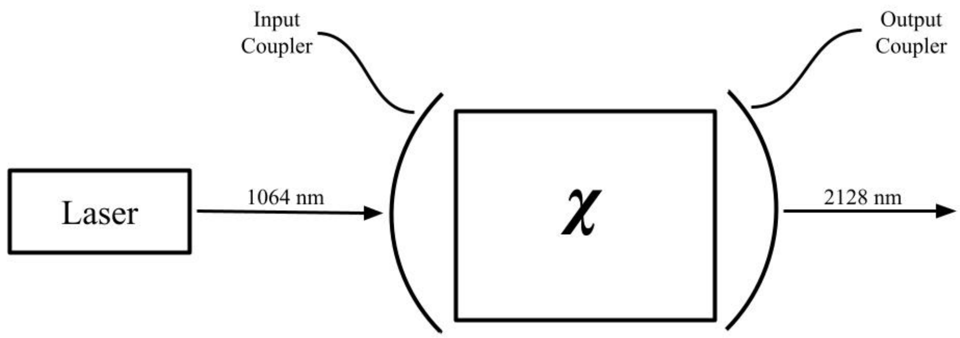


Figure 2: The setup of DOPO that is mounted on an optical table. The distance between the input and output couplers is 47.5 nm.

### 3.2 Noise Detection

DOPO is currently working and our goal is to measure its frequency noise. There are two possible schemes to measure the frequency noise of DOPO: heterodyne and homodyne, as shown in Fig. 3 and 4. We are currently working on deciding which scheme works best in our project. Specifically, the scheme that works best is the one that introduces the least noise relative to the reference signal (the beam from the laser source). In other words, we will pick the scheme with the smaller phase difference between the two beams coming into BS2. Either of these schemes will allow us to measure the noise produced by DOPO assuming that we know the amount of noise introduced by all other components in the setup. We know from reference [3] the upper limit of the Second Harmonic Generation (SHG), so we need to calculate the noise that other components introduce.

#### 3.2.1 Heterodyne Detection

Heterodyne detection measures the phase difference between two light beams by interpreting their interference pattern. As shown in Fig. 3, a heterodyne detection scheme requires a local oscillator that introduces frequency shift (usually on the order of mega Hertz) to one of the arms. After the laser beam is passed through the AOM, the new beam's frequency will be the sum of the laser frequency and AOM's local oscillator's frequency ($\omega_L + \omega_A$). When the two arms combine in BS 2, the intensity of the new beam is a function of the phase difference between the two incoming beams. Thus, measuring the light intensity of the combined beam will allow us to calculate the phase difference between the two arms. Specifically, I calculated the photodetector's intensity to be

$$I_{detected} = I_0\Big[1 + \cos\big((\omega_A - \omega_D - \omega_s)t\big)\Big] \tag{1}$$

where $\omega_A$ is the frequency introduced by AOM, $\omega_D$ is the frequency introduced by DOPO, and $\omega_s$ is the frequency introduced by SHG. The intensity, $I$, for a heterodyne scheme is time-dependant. It also depends on the phase difference between the first arm ($\omega_A$) and the second arm ($\omega_D + \omega_s$).

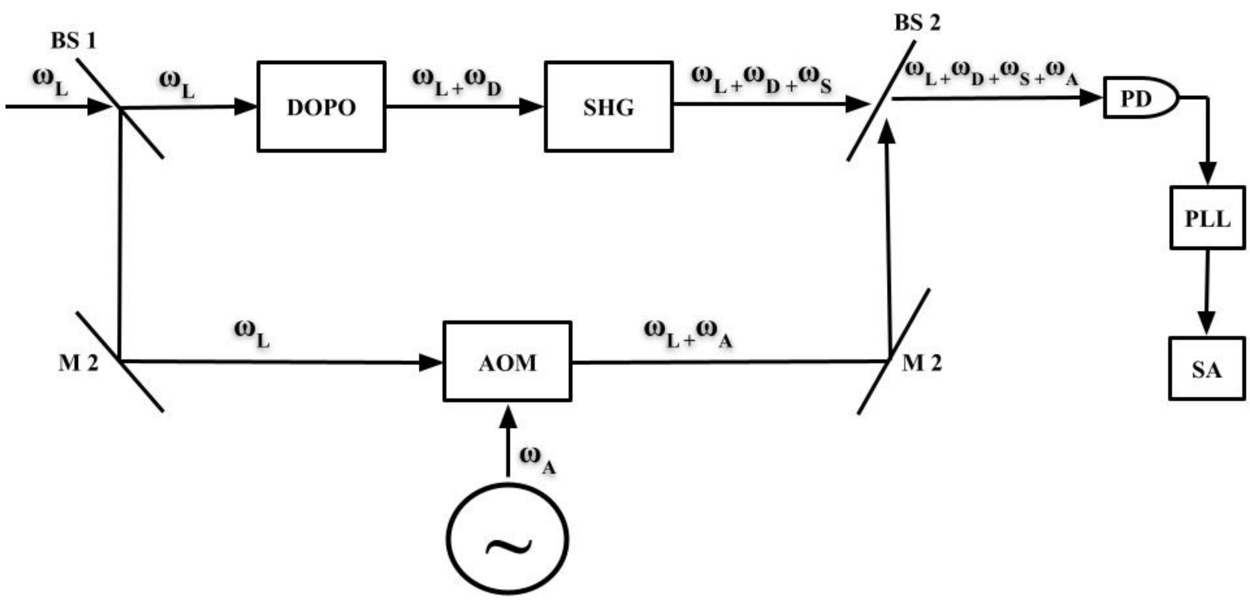


Figure 3: Heterodyne detection scheme to measure the frequency noise of DOPO. The first arm is the one including DOPO and SHG, whereas the second arm is the one including AOM. The mirrors, M1 and M2, are highly reflective. The angular frequency $\omega_L, \omega_D, \omega_S$ and $\omega_A$ represent laser frequency, DOPO's frequency, SHG's frequency, and AOM's frequency, respectively.

### 3.2.2 Homodyne Detection

Unlike the heterodyne detection scheme, homodyne detection does not require a frequency shift in one of the arms, as shown in Fig. 4. However, the goal of the two schemes is the same: measuring the phase difference between the two arms. Specifically, I calculated the photodetector's intensity to be

$$I_{detected} = I_0[1 + \cos(\phi_D + \phi_s)] \tag{2}$$

where $\phi_D$ is the phase introduced by DOPO and $\phi_S$ is the phase introduced by SHG. Unlike heterodyne detection, the measured intensity is not time-dependant.

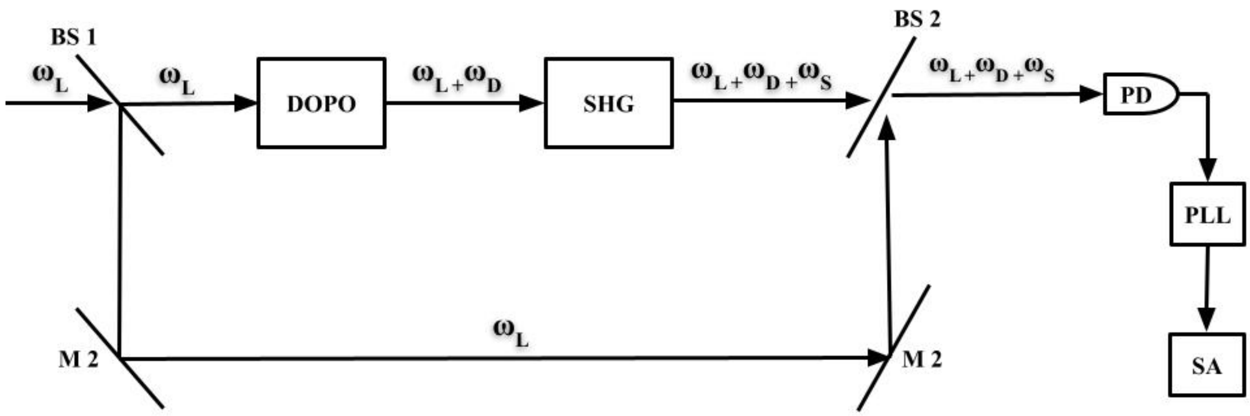


Figure 4: Homodyne detection scheme to measure the frequency noise of DOPO. The first arm is the one including DOPO and SHG, whereas the second arm is the one including AOM. The mirrors, M1 and M2, are highly reflective.

### 3.3 Next Steps

Once we decide which scheme introduces less noise to the setup, we will build it in the lab and start measuring the frequency noise. After that, we will construct a noise budget to account for the measured noise. We will consider the following noise sources: seismic motion, thermal noise in the PPKTP crystal (thermo-refractive, thermo-elastic, and thermo-optic noise), SHG noise, shot noise of the PD, and potentially more sources. Creating a noise budget will be done by calculating the power spectral density function for each noise source and then adding them up. Ideally, the difference between our calculations and the measured frequency will be minimal. Finally, knowing all the noise sources in the setup will inform the way we suppress these noise sources.

# 4 References

## References

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