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

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1 Introduction/Background

1.1 LIGO

The Laser Interferometer Gravitational Wave Observatory (LIGO) is a gravitational wave detection project consisting of two facilities in Livingston, LA and Hanford, WA. 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 gravitational waves (GW) introduce changes in the arm length on the order of 10^{-21} meter. By analysing the interference pattern taking place at the photodetector, the change in arm length due to GW can be detected. Specifically, LIGO accounts for this change by calculating the phase change of the beam arriving at the photodetector.

1.2 Next generation LIGO detectors

After the astounding results from the first-generation gravitational wave detectors, scientists are currently aiming for a 100-times better sensitivity than the first-generation instruments [1]. Achieving this improvement requires keeping the mirrors of the detector at cryogenic temperature to eliminate thermal expansion of the mirrors as well as Brownian noise. Due to the sensitive nature of the LIGO measurements, it is crucial to eliminate thermal expansion noise as it might interfere with the arm length measurements. Fortunately, the thermal expansion coefficient of crystalline silicon is zero at 123 K and 0 K, making it a suitable material for the new mirrors. Currently, mirrors are made of fused silica glass, however, at cryogenic temperature the mirrors will be made of crystalline silicon. The current mirrors can reflect lasers of wavelength 1064 nm, but crystalline silicon absorbs that wavelength. Hence, the wavelength of the laser needs to change to 2128 nm in order for the new mirrors to reflect it. Since the wavelength needs to be doubled, the frequency needs to be halved using an optical setup called Degenerate Optical Parametric Oscillator (DOPO).

1.3 Degenerate Optical Parametric Oscillator

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). 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, which in turn converts the pumped frequency to the desired value. As shown in Figure 1(b), a laser beam of frequency ω_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: ω_s (signal frequency) and ω_I (idler frequency). In our case, this is a degenerate OPO, so $\omega_I = \omega_s = \omega$, as shown in Figure 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 Figure 1(a) [2].

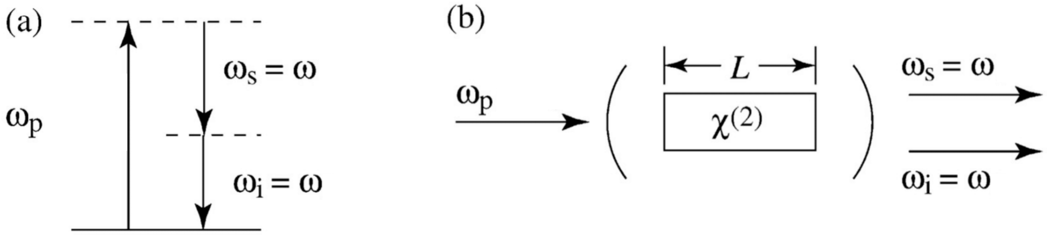

Figure 1: (a) A microscopic view of the processes inside the nonlinear medium. The dashed lines represent virtual energy levels, whereas the solid line represents the ground state. (b) The experimental setup of an Optical Parametric Oscillator. The curved lines surrounding the non-linear crystal represent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

2 Objectives

For our purposes, there is an OPO in the lab with a cavity surrounding a non-linear crystal, Potassium Titanyl Phosphate (PPKTP). Currently, there is a laser of wavelength 1064 nm whose wavelength needs to be converted to 2128 nm. Due to many noise sources, the wavelength conversion process is not perfect. Specifically, there exists amplitude and frequency noise. Our goal for this project will be characterizing the frequency noise associated with the frequency conversion process aforementioned. Furthermore, we would like to investigate the noise sources that impact the output frequency created by the DOPO. Finally, we aim to develop a noise-elimination system to make the conversion process as effective as possible.

3 Approach

3.1 Frequency Noise Measurement

The aim of the project is to develop an approach to measuring and combating frequency noise in DOPO. Hence, our plan must involve a method of measuring frequency noise. A possible set up to measure frequency noise is indicated by Figure 2. A laser beam of wavelength 1064 nm is passed through a beam splitter (BS 1) where half of the light goes to DOPO and second harmonic generation (SHG), whereas the other half is fed to the acoustic-optic modulator (AOM). When the two beams combine again in BS 2, the new beam is fed to the photodiode (PD). We can then measure the noise of this beam using a phase-locked loop (PLL) as it converts frequency to voltage that can be measured. Finally, the beam is fed to a spectrum analyser (SA) that allows us to measure the change in voltage due to frequency noise from the beam that was created by DOPO and SHG.

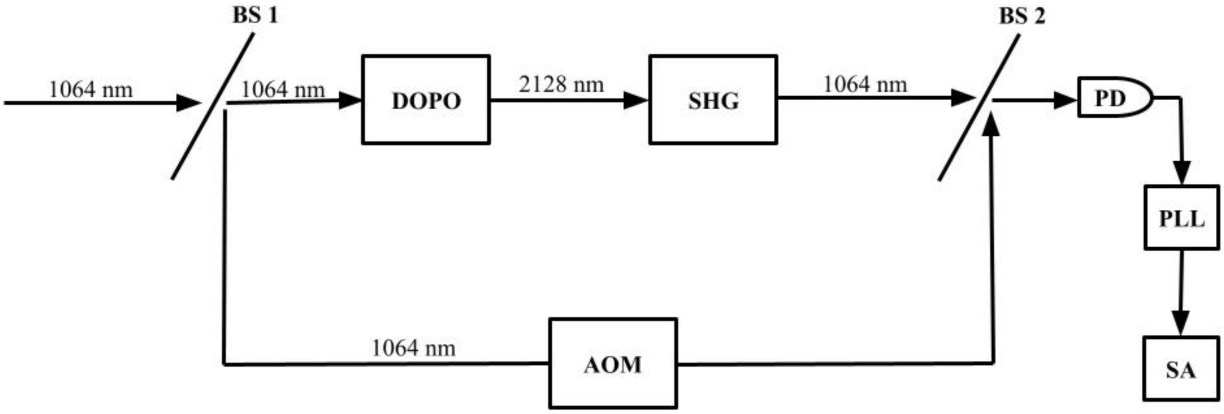

Figure 2: Experimental setup for measuring the frequency noise associated with the frequency conversion process.

3.2 Noise Sources

To accurately identify the frequency noise associated with frequency conversion, we need to create a noise budget for the experimental setup in Figure 2. In this project, we will need to 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. Though the DOPO setup will be on an optical table, it is not guaranteed that the table will cancel all noise due to seismic motion. Therefore, we need to estimate seismic noise and include it in the noise budget. As for thermal noise forms in the PPKTP crystal, they mainly occur due to temperature fluctuations that result in change of the crystal's properties such as refractive index, optical properties, or its length. The upper limit of SHG noise will be estimated by referring to the work in this paper [3]. Moreover, there will also shot noise due to the quantization of light that the PD will be detecting. Finally, there might exist more noise sources that will consider during our work.

4 Project Schedule

4.1 Weeks 1-5

During the first five weeks, we will work on creating a noise budget for the DOPO. To that end, we need to identify all noise sources that contribute to the observed noise. To construct the noise budget, we need to measure the impact of each noise source and plot all of the noise curves. The sum of these noise curves will correspond to the observed noise.

4.2 Weeks 6-10

In the second half of our work, we will be designing and implementing an experiment to measure frequency noise. After completing this step, we will aim to develop ways of combating the frequency noise we measured.

5 References

References

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[3] Adhikari, R. X., Yeaton-Massey, D. (2012). A new bound on excess frequency noise in second harmonic generation in PPKTP at the 10^{-19} level. Optics Express.