Danila Korytov

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Setting up for a Backscatter Rate Experiment

Introduction

Optical cavities are used frequency for gravity wave detectors. Optical cavities help to reduce to recycle strength of various part of the detector and increase the signal of a gravity wave by requiring light to travel multiple arm lengths before it escapes the arms and falls onto the detector. Since the mirrors that are used for optical cavities are not perfect light scatters from the cavities onto the surrounding materials which may be baffles, walls or some other surface. The vast majority of the focus in designing gravity wave detectors is on stabilizing the test masses and other optics in gravity-wave detectors. Therefore the scattering surfaces are extremely unstable compared to other controlled aspects of the detector. For example, LIGO has a cavity in each arm to reduce the shot noise of the system. Due to the long arms, the far mirror only forms a small solid angel so a small deviation on the mirror could cause the reflected light to miss the far mirror. If it does not cause light to miss the far mirror is still could cause the light to go out of mode and eventually drift after multiple reflections from the mirrors onto the surrounding surfaces.

The light hat is scattered back to the mirrors has a different phase. That phase shift highly depends on the length of the trip between the scattering surface and the one of the cavity mirrors. Since so much effort has been invested into the stabilizations of the optical elements of the gravity wave detectors, the baffles and other surfaces have much higher noise than the rest of the system.

Again, since the mirrors and other optics are not perfect, the backscattered light has a finite chance to scatter back into the main mode of the cavity. Then the backscattered light would accumulate and increase the noise much more significantly. The assumption so far has been that the scattering rate from the main mode from a cavity is the same as scattered rate back into the main mode. No paper has been published proving this assumption. The goal the experiment is measure the backscatter rate into the main mode where it has much more of an effect.

Optical Cavity Overview

Optical cavities (also known as optical resonators) are commonly used throughout the design of gravity wave detectors. Optical cavities are able offer the advantages of reflecting back optical power into useful sections of the detector and increasing average round trip for the arms so that small length changes accumulate.

The simplest optical cavity is setup with two parallel mirrors. Laser light is directed through one side of the mirror. Most of the light is reflected (depending on the reflection coefficient), but some amount of light is transmitted through. This transmitted light will be reflected back at the first mirror by the second mirror. The light will reflect again from the first mirror, but this light will be the sum of reflected light and the newly transmitted light. If an integer number of wavelengths of the light fits into a round trip between the two mirrors the light will constructively interfere and there would be a buildup of optical power depending on the reflectivity of the mirrors. If the single round trip light is out of phase compared to the newly transmitted light, light would be even more out of phase for each time is circulated. The attenuation of multiple round trips light is partially dependent on the reflection coefficient of both mirrors. The higher the reflection coefficient the more light cycles and the more intolerant the cavity is frequency mismatch with the cavity length.

Light accumulates when the frequency and cavity length matches up. Light cannot accumulate indefinitely since some light leaks from both ends of the mirrors. Light will accumulate as long as the amount of light entering the resonator is greater than amount of light that is lost either due to imperfections or leaking through the mirrors. The amount of light leaked through the back mirror, the light that is transmitted through the cavity is a simple function of the reflection coefficient and the light that is accumulated between the mirrors.

The light that is leaked through the front mirror is the same, a simple function of the light accumulated and the reflection coefficient. But, It is easy to show that the light of the promptly reflected beam is 180 degrees out of phase from the light leaked through the first mirror and so the promptly reflected light would destructively interfere with the leaked light. The amount of power lost through prompt reflection is dependent on the amount of light allowed to accumulate and what ratio of the light leaked through both ends of the mirrors. The optical power will continue to accumulate in the resonator until the amount of power lost is equal to the amount of power that enters the system. If the front and back mirrors have the same reflection coefficient, light that is leaked back would completely cancel the promptly reflected beam, so no power will be lost through that mechanism. Most of the power loss would result from light leaking from the back mirror, so most of the light would be transmitted through the cavity. The rest of the light would lost from the imperfections such as the sum of the squares of the reflection and the transition coefficients not adding up to one.

It simple to describe an optical resonator in one dimension but that for most part too simplistic since the optics are three dimensional. Not only does the light have the right frequency compared to the cavity length, it has to propagate through the mirrors and maintain its propagation shape. If it cannot maintain its shape light would eventually drift outside of the mirrors. These self-sustaining shapes are called modes.

Pound-Drever-Hall Cavity Locking Technique

The goal is to adjust the laser frequency or the cavity length so that the light would maximally accumulate. If the laser light has the right frequency through a symmetric cavity, almost all the power will transmitted through the cavity and none will be reflected. If the laser frequency of the laser drifts or the cavity length changes, light would no longer perfectly constructively interfere in the resonator so less light would accumulate. Less light accumulation means that less light is leaked back through both mirrors. The light leaked through the back mirror will no longer perfectly interfere with the promptly reflected beam. This could be used to lock the cavity, but the problem is that the sign information lost. If there is no light reflected and there is an increase of light reflected its not known if the frequency of the laser should slightly lowered or increased. Before the development of the Pound-Drever-Hall (PDH) locking technique the cavity was not kept at minimum reflection but to one side so that a change in the cavity could further increase the reflected light or decrease. The PDH technique does not rely on this. The PDH technique relies on adding sidebands to main laser. So the laser could seen as three overlapping beam. One beam is the original beam, and two beam with a frequency offset from the main beam in, above and below the carrier frequency by the same amount. Although the carrier beam will not see the difference between the cavity lengthening or shorting, the sidebands will since they are on the slope of the reflection function. Through these sideband the PDH lock is able distinguish between a need increase or decrease the laser frequency or cavity length.

The function of the reflected electric field without the sidebands is

$$E_{reflected} = \sqrt{P_c} F(\omega) e^{i\omega t}$$

P_c is the default power of the electric field reflected from the front mirror. $F(\omega)$ is the function of the amplitude due to the cavity back mirror light leaking and canceling the reflected beam. If side bands are added the function becomes.

$$E_{reflected} = \sqrt{P_c} F(\omega) e^{i\omega t} + \sqrt{P_s} F(\omega + \Omega) e^{i(\omega+\Omega)t} + \sqrt{P_s} F(\omega - \Omega) e^{i(\omega-\Omega)t}$$

Photodetectors measure the incoming power from the laser so it is electric field squared and it is not difficult to derive the power measured from the reflection.

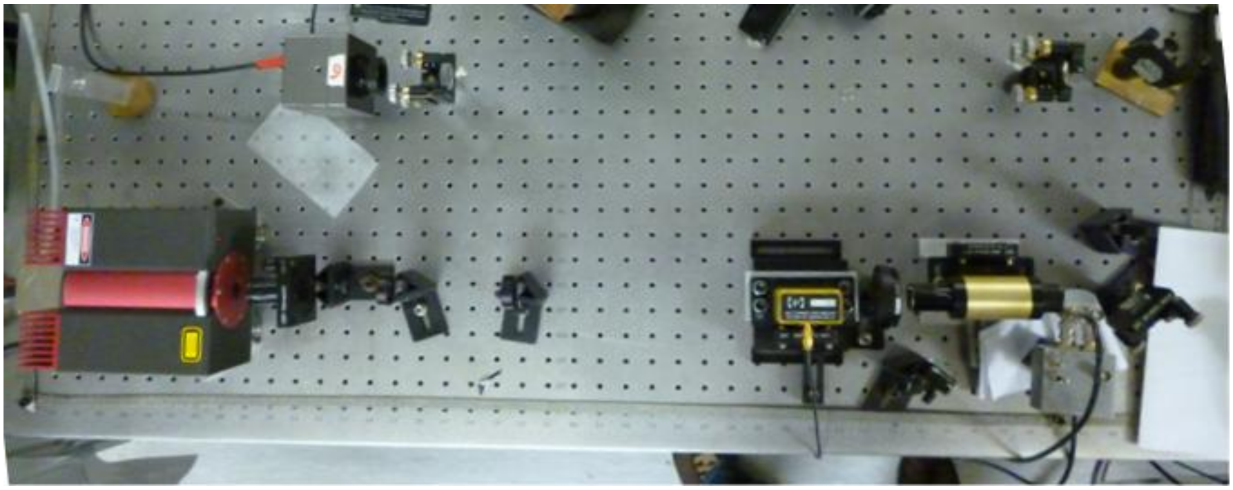
$$\begin{aligned} P = {} & P_c|F(\omega)|^2 + P_s|F(\omega+\Omega)|^2 + P_s|F(\omega-\Omega)|^2 \\ & + 2\sqrt{P_c P_s} Re[F(\omega)F^*(\omega+\Omega) - F^*(\omega)F(\omega-\Omega)] \cos\Omega t \\ & + 2\sqrt{P_c P_s} Im[F(\omega)F^*(\omega+\Omega) - F^*(\omega)F(\omega-\Omega)] \sin\Omega t \quad + \text{Higher Order Terms} \end{aligned}$$

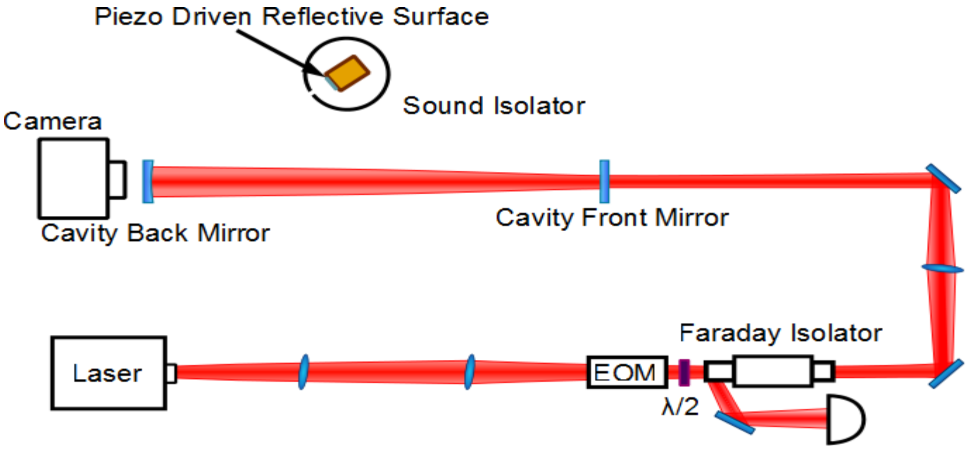
Some the terms are constant and uninteresting and the higher order terms are not useful either. What is useful is the two terms that contain the

$$F(\omega)F^*(\omega+\Omega) - F^*(\omega)F(\omega-\Omega)$$

The ability to measure this quantity is at the heart of the PDH technique. Depending on the frequency of the modulation, either the only the imaginary (for smaller modulation) or the only the real part (for faster modulation) survives. To remove the $\cos\Omega t$ or the $\sin\Omega t$ term multiplying by another $\cos\Omega t$ or the $\sin\Omega t$ to obtain a DC value signal. This signal can be used to drive the frequency of the laser or the length of the cavity.

Setting up and Problems Encountered, Solutions



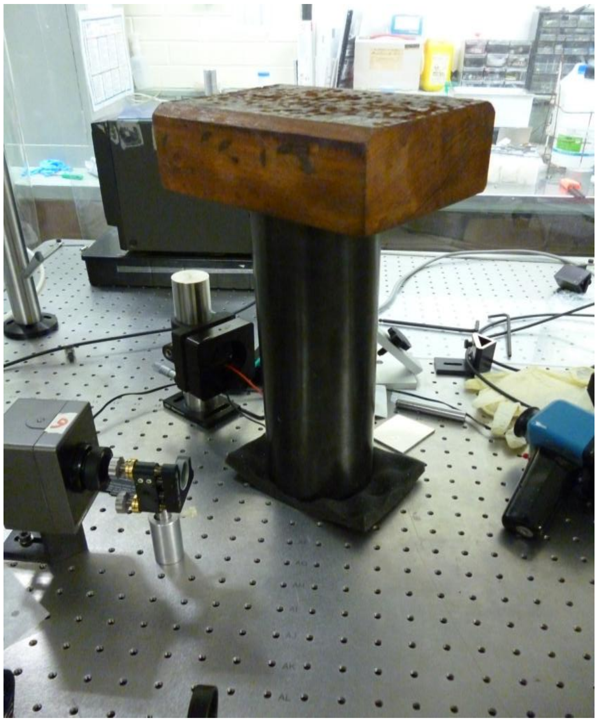


There were some interesting problems encountered while setting up the PHD system. The typical PDH system uses quarter wave plates and a polarizing beam splitter to pick up the reflected light. The quarter wave plates would have caused circularly polarized light in the cavity, but linear light is preferred since it would increase the interference from the backscattered light. A faraday isolator is able to pick up from the reflected light from the cavity mirror. The lab only had one spacer faraday isolator so it could not be used to right after the laser to avoid problems with back reflections. Lens and EOM were tilted to reduce the backscatter, but backscatter could still pose a problem later on once the experiment becomes more sensitive.

The most time consuming was the fact that the beam was not quite Gaussian. Significant portion of time was spent model what how the beam should propagating, installing lens and other components according to model, confirming that the beam followed the model. The beam was slightly elliptical which was hard to detect when using knife-edge technique of measuring the beam radius. Once a camera was obtained to look at the beam profile, it became evident that the beam had poor quality. The faraday isolator was the biggest contributor to ruining the beam. Although the beam should have been able to pass through the isolator without clipping, the alignment of the rejection port (to the left or the right of the isolator) was not symmetric. The rejection portion is a plastic cylinder with a beam splitter attached near the center. There are two holes that allow rejected light to leave from each direction. It was more convenient to setup the rejection to one side, away from the table edge. The rejection portion is not symmetric, the apertures do not line up with the rejection port to one side while it lined up quite well to other side. Once this was discovered and the port was rotated, the beam quality increased but was still not ideal. The beam still did not follow the models so a measurement and adjustment was used to mode match the beam to the cavity. Lens were changed around, shifted in position and the waist location and radius were measured, then the lens were shifted to better fit until the desired waist size was obtained.

The photo detector was used to read the reflected light was grounded to the table. The photodetector was picking up signals from the ground and the adding a lot of noise to the error signal. This caused trouble for the laser to stay locked to the cavity, it would remain locked for about half a minute before a spike would cause the laser to jump out of the resonance and lose the error signal. Electrically isolating the photodetector from the grounded table removed this problem.

Setup Backscattering Surface



The backscattering surface was mounted on a PZT which was driven at a known frequency. The surface was chosen to be a rough reflective so that alignment would not play such a large role. A lock-in amplifier was used to pick-up the driving frequency from the error signal.

Initial concerns were about vibrations coupling to the mirrors and add noise at the driven frequency. It turned out that acoustic noise played a more significant role. Driving the PZT on the table not facing the created a large peak at that driven frequency in the error signal. To investigate the role of vibration and acoustic, a small PZT that weighed a few grams suspended from its electrical wires was able to create a significant signal in the error signal. The mass of the small PZT should be move the mirrors a significant degree through the suspension. An impromptu acoustic shielding was created out of a heavy steel pipe, a heavy wooden block on top and a foam bottom to better seal the bottom while allowing the wires to enter inside to the PZT. A small hole, about 4mm, was drilled to allow light to the scattering surface and back out. The driven frequency in the error signal fell significantly with the acoustic shielding but it was still detectable. Blocking and unblocking the small hole to the scattering surface only slightly decreased the amount of the driving frequency in the error signal, but both were well above signal strength when the scattering surface PZT is not driven.

Conclusion

Currently the system is limited by the vibration and acoustic noise from driving the scattering surface PZT. A better isolation is required: ideally, a small vacuum tank to hold the scattering surface to remove all acoustic noise and a suspension system to reduce possible vibration noise. Controls are needed to separate the signals from backscattered and PZT vibration. The closed loop transfer function needs to investigated so that the driven frequency is not suppressed to a level where it would be difficult to detect.

References

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