Final Report for IREU 2013

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Background Information

Albert Einstein’s revolutionary idea that gravity is caused by curves in the fabric of space and time was the foundation for his theory of General Relativity. An immediate consequence of this idea is the existence of gravitational waves, or ripples in the fabric of space-time, which are created by rapidly spinning astronomical systems as well as the super-powerful explosions of stars. While Einstein’s theory has been proved indirectly through the study of energy loss in binary systems (combinations of black holes and neutron stars orbiting each other rapidly) (Taylor *et al.*, 1979) direct proof would have to come from the detection of gravitational waves.

The quest for detecting gravitational waves began in the 1960’s with Joseph Weber’s unsuccessful attempts at using acoustic bar detectors (1960). Today, the main focus of scientists working to detect gravitational waves is the construction of detectors which are basically large Michelson type interferometers. These detectors use laser light which is split into two perpendicular paths. These two beams are then recombined to interfere with each other. The signal of the recombined beam is constantly monitored by a photodiode. When a gravitational wave passes the detector, it will cause both of the paths of the split laser beam to change length (one will expand, the other will shrink). This means that the two beams will interfere in a

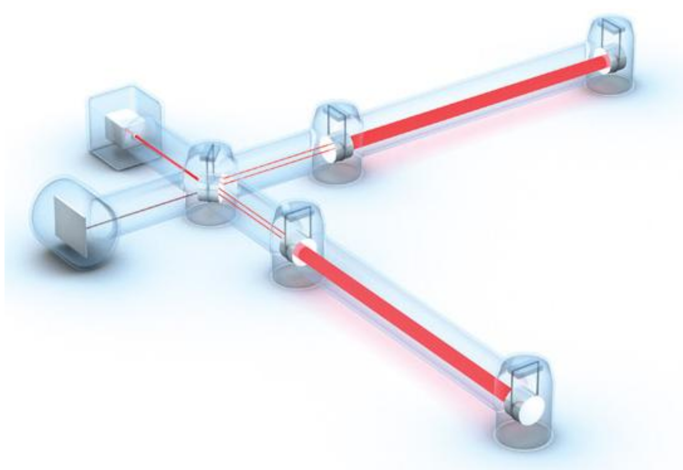

Figure 1 A basic layout for a Michelson interferometer type gravitational wave detector

different manner than before, therefore causing the photodiode to report an irregular signal: the detection of the gravitational wave.

This may sound like a simple idea, which would not require too much effort, but there is a caveat. By the time gravitational waves reach Earth, they are so much less powerful than when they started that the change in the length of the beam path is very small (on the order of $10^{-21} Hz^{-1/2}$). So even with the construction of detectors with arm lengths of several kilometers, the length change is only on the order of $10^{-18} m/\sqrt{Hz}$ which could easily be caused by many different types of signal noises (seismic, acoustic, phase, Newtonian, quantum, etc.). Therefore, it is necessary for many different types of stabilization techniques to be implemented into the construction of these detectors so that it is possible to detect gravitational waves.

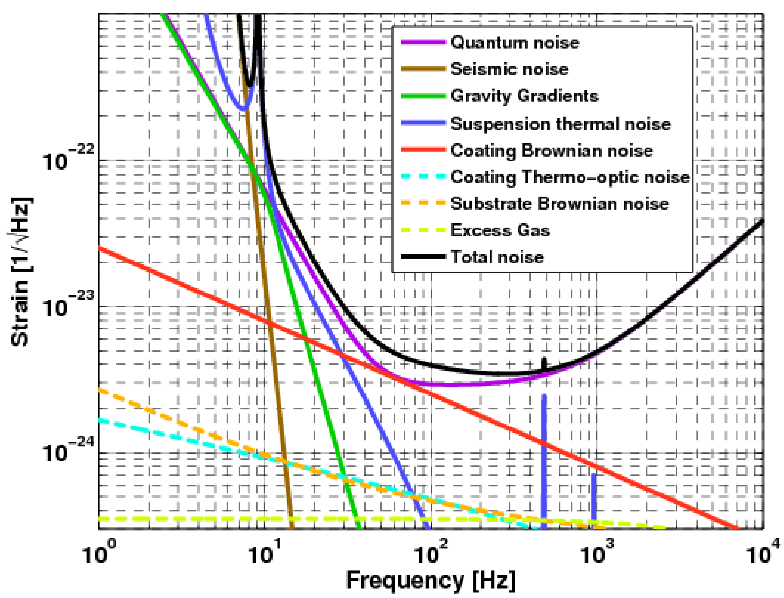

Figure 2 The noise budget for the Advanced LIGO detectors

The Laser

One of the most important parts of these detectors is the laser which provides the beam for the interferometer. Because of the extreme sensitivity required for the detection of gravitational waves, it is necessary to use a very stable, high powered laser. Laser noise comes in three forms: power noise, frequency noise, and beam pointing fluctuations, which all required unique forms of stabilization.

The laser currently installed for use in the two LIGO detectors in the United States were designed and built by Benno Willke and his group of scientists at the Max-Planck Institute and Laser Zentrum in Hannover, Germany (Kwee *et al.*, 2012). The output beam is an approximately 200 W beam with a wavelength of 1064 nm. It consists of three lasing stages, the master laser, initial amplifier and high power oscillator, as well as several stabilization elements. The master laser is a commercially available non-planar ring-oscillator (NPRO) which uses a neodymium-doped yttrium aluminum garnet (Nd:YAG) crystal as the laser medium and resonator. This laser has an intrinsically stable frequency, and includes a power stabilization system called noise eater (see Kwee and Willke, 2008). Before the next stage, the beam passes through an electro-optic modulator, which can alter the phase of the beam, and a Faraday isolator, which prevents the

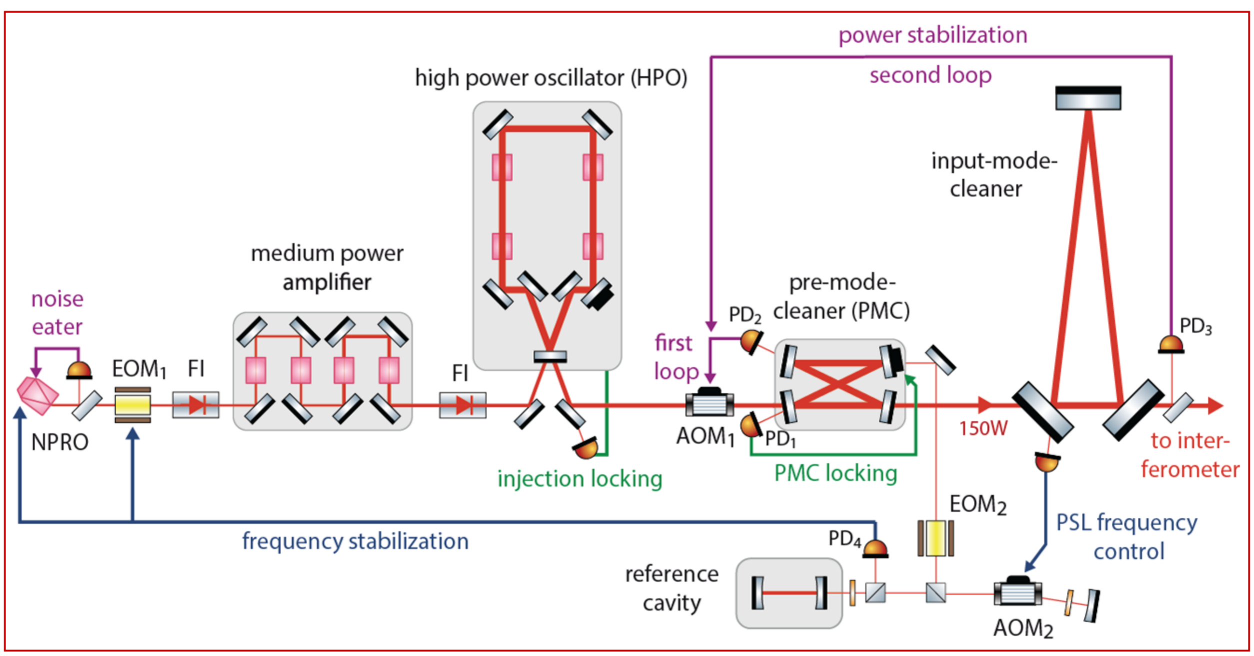

Figure 3 Simplified layout of 200 W laser system for Advanced LIGO

beam from travelling backwards towards the master laser.

The second and third stages of the laser system account for the high power of the beam. The second stage of amplification is done using a medium power amplifier; a single-pass four-head Neodymium-doped yttrium orthovanadate (Nd: YVO4) amplifier with an output power of around 35 W. Then, after passing through another Faraday isolator, the beam is used to injection lock the high power oscillator, which is a fully functioning laser on its own. The process of injection locking means that the oscillator is adjusted according to the frequency of the injected beam, so the high power, 200 W, beam that leaves the oscillator inherits the stable frequency of the first two stages. Now the beam is fully amplified, and is subjected to several different forms of stabilization.

Stabilization

All of the beam stabilization techniques are centered on the passive bow-tie resonator called the pre-mode cleaner (PMC). The main purpose of the PMC is to improve beam quality by suppressing higher order modes so that most of the beam power is in the fundamental (TEM_{00}) mode, but it is also used to improve the pointing stability of the beam, and to filter power fluctuations at radio frequencies. It consists of four low-loss mirrors glued to an aluminum spacer which creates a bowtie beam path of 2 m, as can be seen in Figure 3 above. One of the mirrors is also connected to a piezo-electric element, so that the cavity can be locked to the resonance of the laser using a signal from a photodiode placed in reflection of the cavity (PD_1 in the diagram above) and locking technique called the Pound-Drever-Hall method.

The Pound-Drever-Hall method is worth discussing as it is implemented several times in the stabilization of the laser. A laser is sent through a Pockel's cell, which can modulate the frequency of the beam, controlled by a local oscillator and into a cavity of some sort. Because

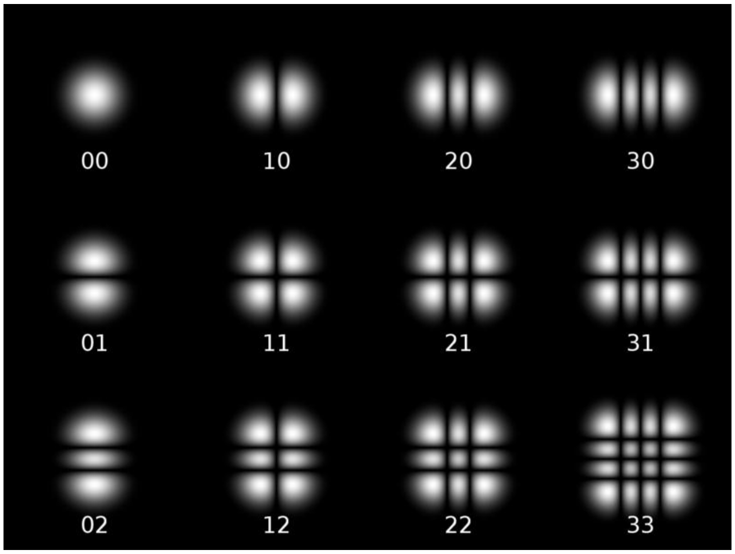

Figure 4 Hermite-Gaussian modes

only laser light of a certain mode (usually the fundamental mode) can pass through the cavity, the light that is not transmitted is reflected; it is then redirected and measured by a photodiode. This signal is then combined with the signal from the local oscillator, processed by a system of filters and servo amps and used to control some sort of actuator (usually the master laser or a piezo) which is adjusted for any error so that the entire beam is able to pass through the cavity. The PMC, for example, uses the Pound-Drever-Hall method to make small adjustments to the length of the cavity thereby changing the resonant frequency of the cavity to fit that of the laser. For further explanation of this method of locking see (Black, 2001).

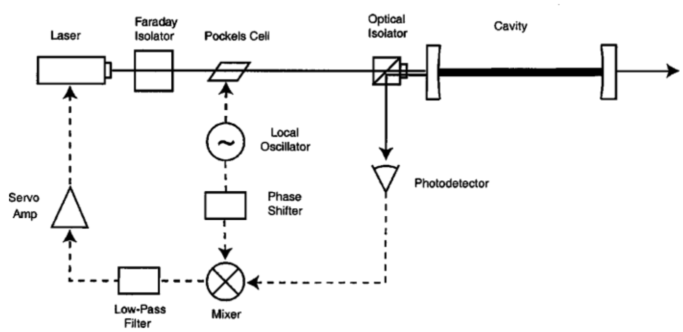

Figure 5 A general schematic of the Pound-Drever-Hall method

The PMC is able to reduce pointing fluctuations by reducing the power of the HG_{01} and HG_{10} modes, as fluctuations in the power of these modes is primarily responsible for beam pointing fluctuations. By reducing the power of these modes, the effect of their fluctuations is also reduced. The power noise is also reduced at radio frequencies by the PMC as a result of its bandwidth as seen in the figure below.

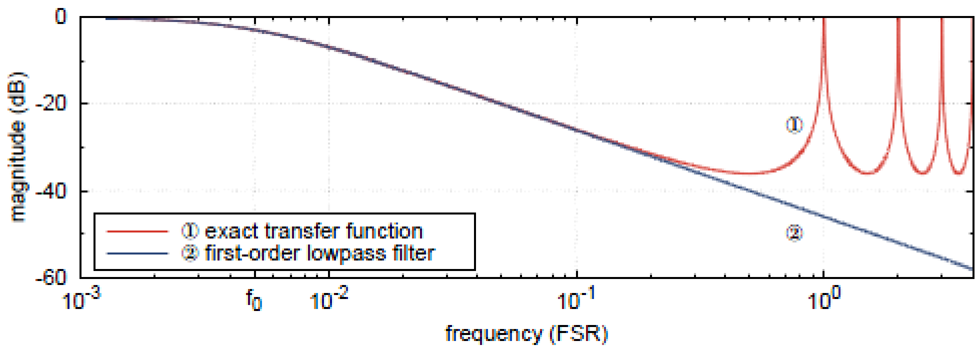

Figure 6 Power noise reduction from PMC as shown in (Kwee, 2010)

Further power noise stabilization comes from two control loops using an acousto-optic modulator (AOM) between the high power oscillator and the PMC, and two photodiodes (PD_2 and PD_3 in Figure 3). The first photodiode measures for power fluctuation picked off from the PMC while the second one is picked off of the beam right before it heads to the interferometer. These signals are then used to control the AOM which can alter the intensity (power) of the beam. The essential parts of the AOM are a piezo attached to tellurium dioxide glass. By applying a signal to the piezo, sound waves are sent through the glass causing its refractive index to fluctuate, thereby diffracting some of the light. Because the intensity of the light diffracted is related to the intensity of the sound, it is not too difficult to control. This double photodiode system, along with the passive filtering of the PMC, accounts for very low power fluctuation noise.

The frequency noise stabilization in the Advanced LIGO laser system is somewhat more complex. It mainly consists of a reference cavity made of fused silica spacer with two low-loss high-reflectivity mirrors which is suspended and isolated in an ultra-high vacuum to reduce outside noise and attain high frequency stability. The beam used for frequency stabilization is again picked off from the PMC, it then passes through and EOM (EOM_2 in Figure 3) to create phase modulation sidebands necessary for the Pound-Drever-Hall method. Next the beam is passed through an AOM twice to shift the frequency of the beam before it enters the reference cavity. The beam that comes out of the cavity is redirected to a photodiode (PD_4). The signal from a photodiode in reflection of the cavity is used to control the NPRO for low frequency signals and the EOM between the NPRO and medium power amplifier for high frequency signals. While the main frequency stabilization will need to take place in the actual arms of the interferometer detector, this pre-stabilization is sufficient for the requirements of advanced LIGO. More information about the advanced LIGO laser system can be found in (Kwee *et al.*, 2012)

The Diagnostic Breadboard

As can be seen in the stabilization scheme described above, there are four main beam characteristics which are important for stabilization: power, frequency, beam quality and beam pointing. In order to ensure that the stabilization methods of this system are working properly, a diagnostic breadboard (DBB), designed and built by the same scientists as the laser system, is installed on the optics bench to allow for quick characterization of the beam parameters. The DBB is used to measure the beam after the first amplifier (35 W).

The central component of the DBB is, much like in the stabilization array, an optical ring resonator. Like the other resonators discussed above, this one consists of several (3) mirrors attached to a rigid aluminum spacer. It has a round trip length of 420 mm which can be adjusted using a piezo-electric spacer attached to one of the mirrors. It is also placed in an aluminum tank to reduce acoustic noise. Because the resonator is used in a different manner for each measurement, some of the measurements cannot be performed simultaneously.

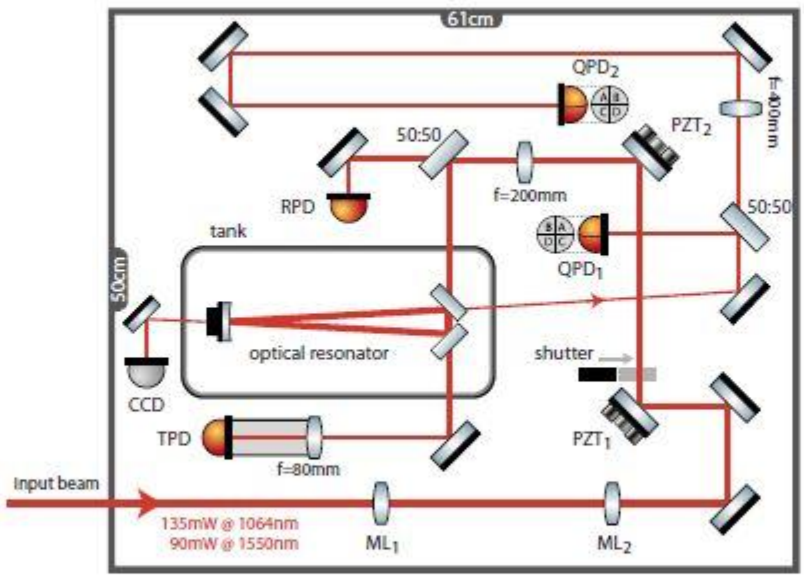

Figure 7 Schematic layout of the Diagnostic Breadboard

To measure the frequency noise of the laser, the cavity is locked using a Pound-Drever-Hall method much like the one in the PMC. The phase of the beam cannot be measured directly, with respect to the locked cavity, so the frequency is measured using the control and error signal from the photodiode QPD_1 in Figure 7.

Power noise is simply measured using a single photodiode (RPD in Figure 7). This photodiode is also used as a trigger for an automatic shutter in case of excessive power to protect the parts of the DBB.

Beam pointing fluctuation is measured using a technique called differential wave front sensing which uses the interference of an input and reference beam to measure shift and tilt. Here the input beam is the beam coming into the DBB from the laser system, and the reference beam is the beam leaking out of the resonator. Two quadrant photodiodes (QPD_1 and QPD_2) and two piezo-controlled mirrors (PZT_1 and PZT_2) are used in this method, which essentially consists of measuring changes in the four degrees of freedom at each photodiode. These changes correspond directly to fluctuations in beam pointing.

The beam quality of laser is measured using a high-resolution modal analysis called *modescan*. In this technique, the mode content of the beam is measured by changing the resonant frequency of the DBB resonator using the piezo-controlled mirror. By changing the resonant frequency of the resonator, a spectrum of different modes is transmitted. These modes are measured using a very sensitive photodiode (TPD in Figure 7) and identified using a computer program. An example of a modescan can be seen in Figure 8: the large peaks on both sides are the power of the TEM_{00} mode while the smaller peaks in the middle are higher order modes. For further information about the DBB see (Kwee, 2010).

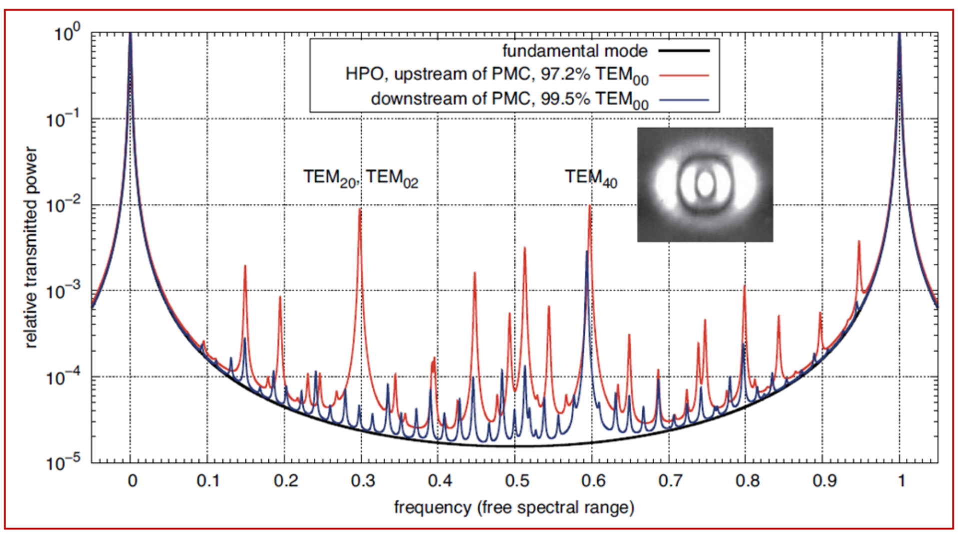

Figure 8 Modescan graph from DBB

<u>Future Developments</u>

While the laser system described above meets the requirements for the advanced LIGO detectors, the scientists at the Max Planck Institute are constantly trying to improve the system for future detectors, or even future upgrades of current detectors. Currently, they are in the process of installing a new fiber amplification system which can produce an even more powerful beam (up to 300W), but takes up much less space on the optics bench. The master laser and amplification stages all fit into a box that is much smaller than the high powered oscillator amplification stage of the current laser system.

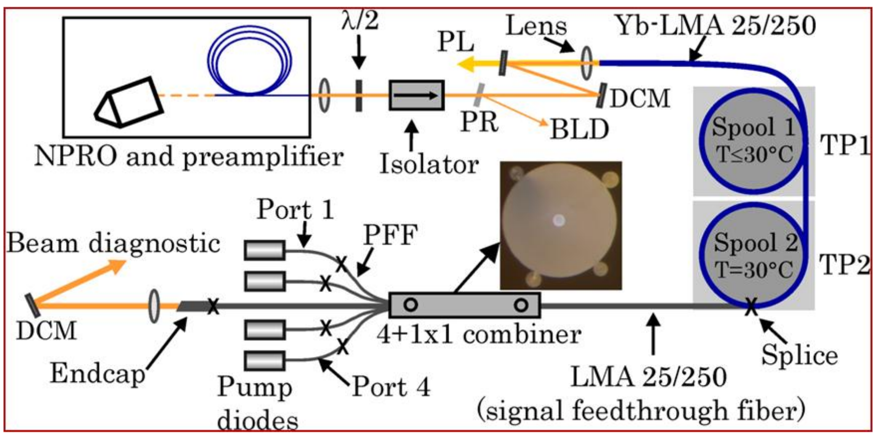

Figure 9 Layout of all fiber laser

The master laser of this system is the same Nd:YAG NPRO as the current system. It is preamplified in a 3 m long fiber before heading into the high powered amplifier (Spool 1&2 in Figure 9). The high powered amplifier is counter-propagation pumped to reduce stimulated Brillouin scattering, the main source of loss in fiber amplifiers. This means that the lasers that are pumping the master laser signal are travelling in the opposite direction of the master laser. This can be seen clearly in Figure 9 as the master laser in on one side of the high powered amplifier and the pump diodes on the other. A cross section of the amplifier fiber is also included in Figure 9 which clearly shows the signal carrying fiber in the middle and the four pump fibers on the outside. The spools around which the amplifier fiber is wound are also temperature control devices which prevent the fiber from overheating, as this could lead to the rapid aging of the fiber. For more information about the fiber laser see (Theeg *et al.*, 2012).

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