Lock Acquisition Scheme For The Advanced LIGO Optical Configuration

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Abstract. The lock acquisition scheme for the Advanced LIGO optical configuration, which makes use of "resonant sideband extraction", is under investigation in the 40 meter prototype interferometer at Caltech. The 40m has a similar optical configuration to the one planned for Advanced LIGO which has 5 degrees of freedom for length control. So far we have succeeded in locking the 5 degrees of freedom routinely. The differential mode of arm cavities was locked in the same state as the final setup, and the peak of optical resonance was verified to be around 4 kHz. Currently, since an offset remains in the common mode of the arm cavities, another optical resonance can be seen in common mode optical gain.

1. Introduction

Currently, several gravitational wave detectors are operated all over the world, such as LIGO[1], VIRGO[2], GEO[3], TAMA[4]. The present detectors are called first generation observatories which have sufficient sensitivity to detect the gravitational wave sources within or near our galaxy. In order to increase the event rate to detect gravitational waves, further improvements in the sensitivity are required. The Initial LIGO detectors will be upgraded to have high power lasers, multi-stage seismic isolation systems and a more complicated optical setup, etc. These new detectors are referred to as Advanced LIGO (AdLIGO)[5, 6], which will start observation in 2013. However AdLIGO's optical configuration, which has 5 degrees of freedom in length control, is much more complicated than that of Initial LIGO. Therefore it becomes necessary to establish a lock acquisition scheme using an interferometer with an optical configuration as close as possible to AdLIGO.

2. 40m prototype interferometer

The 40m interferometer at Caltech[7] is a prototype gravitational wave detector that is currently being used to investigate the AdLIGO optical configuration. This configuration is a Michelson

based interferometer, employing Fabry-Perot cavity arms, a power recycling mirror (PRM) to enhance effective laser power, and a signal recycling mirror (SRM) to enhance the signal bandwidth and overcome the standard quantum limit (SQL)[8, 9, 10]. This type of interferometer employs resonant sideband extraction (RSE) which was proposed by Mizuno[11].

The 40 m has an Initial LIGO type 10 W pre-stabilized laser (PSL) which has a pre-mode cleaner (PMC), frequency stabilization system (FSS), intensity stabilization system (ISS), and a 13 meter length suspended mass mode cleaner (MC). There are ten core optics and each of them is suspended by an Initial-LIGO-type single pendulum and locally damped by a digital servo system.

RF phase modulation at 33 MHz and 166 MHz are applied to the main laser beam within a Mach-Zehnder interferometer, and demodulation processes are used to extract the length sensing control (LSC) signal of the 5 degrees of freedom of the interferometer. These two modulations make it possible to use double/differential demodulation techniques where the signal is produced by a beat between two RF sidebands. This signal is used to control 3 degrees of freedom at the central part of the interferometer in order to eliminate disturbances by the arm cavities.

All LSC signals are digitally sampled just after the demodulation. These digital signals are then manipulated in software before being fed back to the cavity lengths. Signals can be added and subtracted, multiplied and filtered by software that can be changed in real-time to react to changing needs.

3. Lock acquisition scheme

Lock acquisition of the 40 m is done in three major steps. With the LSC servos for all 5 degrees of freedom turned on, the first step is to lock the central part of the interferometer which is made up of the Michelson interferometer (MICH), power recycling cavity (PRC) and signal recycling cavity (SRC) (See Fig. 1). The second step is then to lock the arms, bringing the whole interferometer into lock. Actually, the feedback signals for the arms are switched on/off based on power levels in the interferometer. The last step is to change the control topology by switching the input signals as shown in Fig. 2. The details of lock acquisition will be discussed in the following sections.
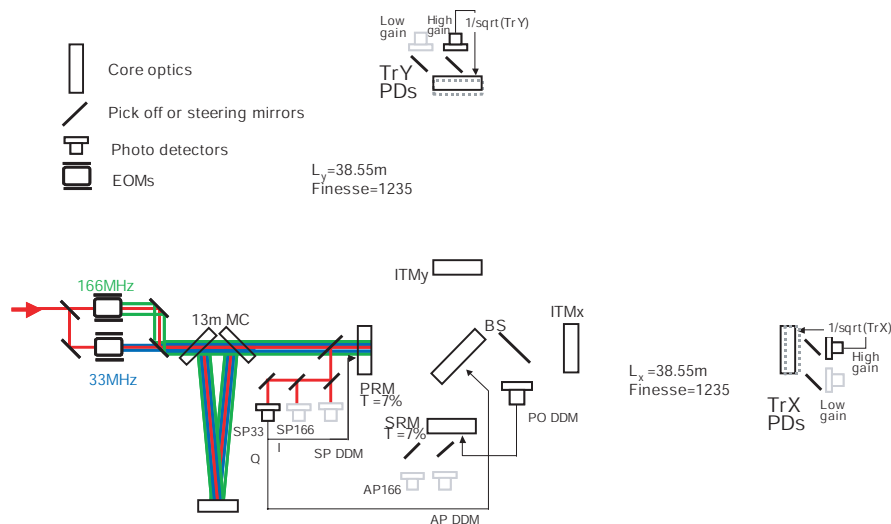
Figure 1. Sensing and control topology for the first step of lock acquisition.
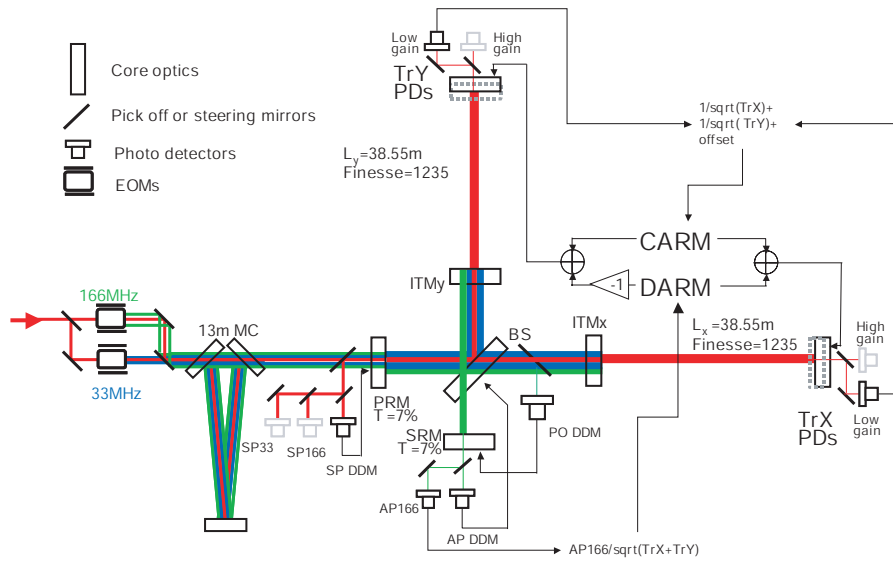
Figure 2. Signal switching after lock acquisition.

3.1. Dual recycled Michelson (DRMI)

Lock of the central part is acquired using a separate signal for each of its three parts: the quadrature-phase of the 33 MHz single demodulation signal at the symmetric port (SP) for MICH, the in-phase of 33 MHz single demodulation signal at the SP for PRC, and the 199 MHz (33+166 MHz) differential demodulation signal at the pick-off port (PO) for SRC. Once lock is acquired, the MICH signal is switched to the 133 MHz (33−166 MHz) differential demodulation at the anti-symmetric port (AP), and the PRC signal is switched to the 133 MHz differential demodulation at SP. Lock is typically acquired within ten seconds, and lasts several hours or more. This lock acquisition might also be done by a mechanical modulation scheme or double demodulation scheme[12], but differential demodulation is easier for now. Both differential demodulation and double demodulation make use of the beats between the RF sidebands, and are thus independent of the phase of the main carrier light. Therefore, when the carrier light begins to resonate in the arms, it does not disturb the control of the central part of the interferometer.

Figure 3 shows the output of an optical spectrum analyzer placed at the SP. It has a carrier peak at the center, ±33 MHz sidebands near the carrier, and unbalanced 166 MHz sidebands, due to the detuned SRC, at the edge of the graph. Two 166 MHz sidebands can be seen on each side of the carrier. The outermost pair belong to the carrier seen here, and the inner pair actually belongs to the carrier at ± one free spectral range of the optical spectrum analyzer. The macroscopic length of SRC is chosen so that one of 166 MHz sidebands is perfectly resonant in the dual recycling cavity, and the other is perfectly anti-resonant. The ±33 MHz sidebands are resonant in the PRC but anti-resonant in the SRC. Figure 4 shows the output of an optical spectrum analyzer placed at AP. One of the 166 MHz peaks is hidden below analyzer noise.
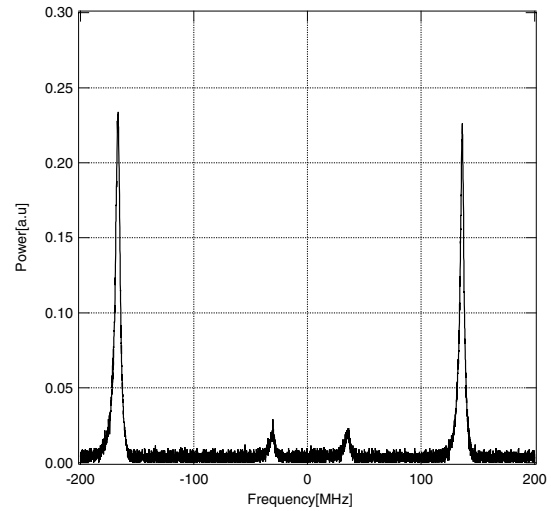
3.2. Arm cavities

After DRMI lock is acquired, each arm cavity is locked using the carrier light transmitted through the arms (Tr). The transmitted light is sampled by an ADC and the signal is digitally re-formed as

$$\frac{1}{\sqrt{Tr}} + \text{offset}. \tag{1}$$
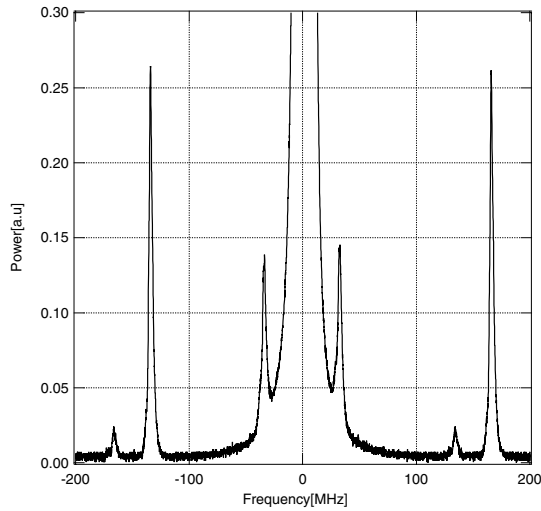
Figure 3. Response of the optical spectrum analyzer at the symmetric port.

Figure 4. Response of the optical spectrum analyzer at the asymmetric port.

This signal has a much wider linear range than the normal RF signal but is not useful around resonance. Around resonance, this signal has no gain due to the flatness of Tr.

The offset makes it possible to adjust the locking position. We have chosen this position to be where the cavity power is $1/160$ of the full resonance, and where the differential mode has no offset and the common mode has an offset by flipping the sign of feedback signal. The reason why the transmitted light is used is that the signal 1 has sufficiently small coupling to the other degrees of freedom when the locking point is away from resonance.

Typically both arms are locked within 1 minute. Once arm cavities are locked, the servo topology for the arms changes from independent arm lock to common/differential mode lock (See Fig. 2).

3.2.1. Differential mode As mentioned above, an arm locking position is chosen that produces no offset in the differential mode which is very similar to the final configuration. Fig. 5 shows the measured optical gain of the differential mode of the arms. This transfer function was measured from feedback signal to error signal, and multiplied by the theoretical pendulum transfer function which goes like f^{-2} above the resonant frequency. The gain floor is normalized to unity. An RSE optical resonance peak can be seen near the design values of 4 kHz. The theoretical line is calculated using the FINESSE[13] which shows the frequency response of interferometer. The phase is different from the calculated line because of time delay in the digital servo system. Two notches around 440Hz and 880Hz are due to filters which notch out the violin mode of the pendulum.

3.2.2. Common mode The arm locking position is chosen, on the other hand, to intentionally produce an offset in the common mode. When this offset is reduced, the cavity pole moves from around 1.6 kHz to a lower frequency. Measured common mode optical gains with various offsets are shown in Fig. 6. The optical gain has a peak instead of the normal f^{-1} cavity pole because the offset is too far from a resonant point. This peak introduces phase delay around the unity gain frequency and it breaks the lock as the offset is reduced. Dynamically changing filters were implemented which compensates the additional gain loss and phase delay.

Recently we succeeded in reducing the offset to zero, which will be reported in another paper.
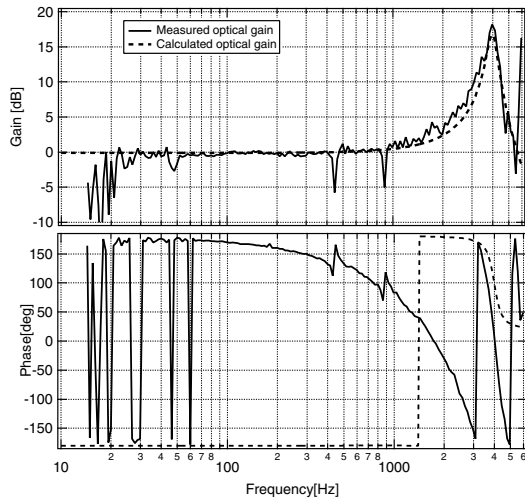
Figure 5. Optical gain of differential mode of arms. Optical resonance due to detuned signal recycling cavity can be seen around 4kHz.
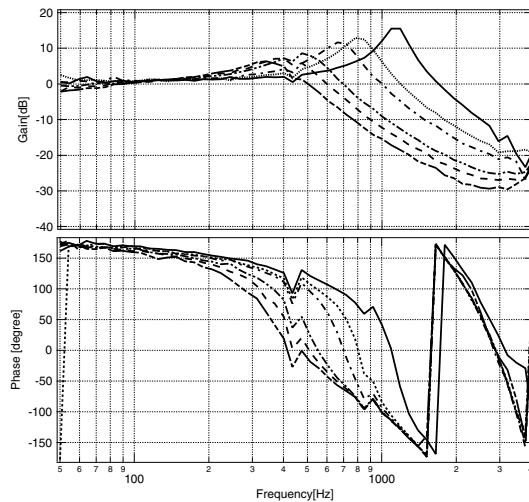
Figure 6. Optical gain of common mode of arms with various offset. Optical peaks move with the reduction of offset in the loop.

4. Result

Locking the length control for 5 degrees of freedom in the 40m prototype is now routinely achieved.. The central part is locked using double demodulation or differential demodulation signal extraction techniques. When the differential mode of the arm cavities is locked in the final configuration, an optical resonance of RSE can be seen clearly around 4kHz in the optical gain. The common mode of the arm cavities still has a small offset, which produces additional peaks in the optical gain. A full test of the Advanced LIGO lock acquisition and control scheme is in progress.

Acknowledgments

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