Double Pass Locking and Spatial Mode Locking for Gravitational Wave Detectors

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Abstract. We present novel techniques for overcoming problems relating to the use of high power lasers in mode cleaner cavities for second generation laser interferometric gravitational wave detectors. Rearranging the optical components into a *double pass locking* regime can help to protect locking detectors from damage. Modulator thermal lensing can be avoided by using a modulation free technique such as *tilt locking*, or its recently developed cousin, *flip locking*.

1. Overview

High laser input powers improve the sensitivity of a gravitational wave interferometer with respect to shot noise [1]. As much as 200W of laser input power is planned for Advanced LIGO, with kilowatts of power resonating within power and arm cavities [2]. Such high powers can cause difficulties: transmissive elements such as substrates, modulators and isolators, become heated causing thermal lensing and distortion [3]; high powers can potentially damage detectors used in cavity locking schemes.

Here, we discuss a variety of techniques for locking optical cavities that avoid these problems. These techniques are intended for use in input and output mode cleaner cavities, and reference cavities, for gravitational wave detectors and associated research experiments. In Section 2, we discuss a rearrangement of the optical components, known as *double pass locking*, where the detector is put safely beyond the reach of the high power input beam. Section 3 discusses two locking techniques based on spatial mode interference which do not require a modulator, thus removing one potentially problematic transmissive element. Specifically, *tilt locking* is discussed in Section 3.1, and a new variation on the theme, *flip locking*, is discussed in Section 3.2.

2. Double Pass Locking

A typical Pound-Drever-Hall locking system [4] for a ring mode cleaner cavity is shown in Fig. 1(a). The input beam is phase modulated; the non-resonant modulation sidebands reflect from the cavity input coupler, acting as a phase reference to detect (via demodulation) any drift from resonance of the carrier field. When the laser is non-resonant in the cavity, the entire laser power is incident on the detector, causing damage for the high powers considered here. The modulation power is typically several orders of magnitude smaller than the carrier power, so simple attenuation of the

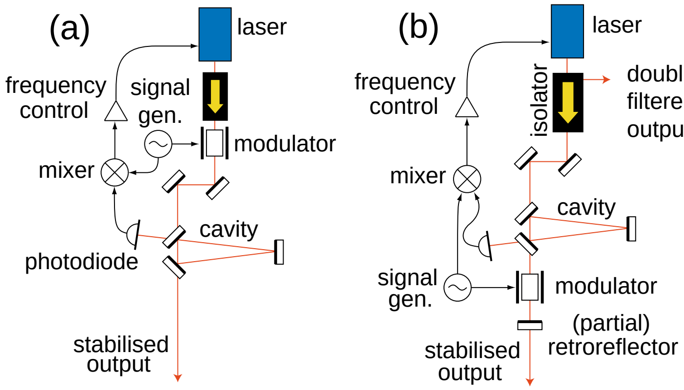

Figure 1. Configurations to PDH lock a ring mode cleaner cavity in the (a) single pass and (b) double pass regimes.

reflected beam alone does not solve the problem. A common solution is to protect the detector with a fast shutter which triggers when the cavity drops lock.

A double pass Pound-Drever-Hall locking system solves the problem in a simple way by placing the detector out of range of the input beam, as shown in Fig. 1(b). A retroreflector sends a small fraction of the output beam back into the cavity in the reverse direction. The resonance of this second pass is locked, which is enough to ensure that the first pass is on resonance. The modulator and detector are placed accordingly, to modulate the retroreflected beam, and detect at the second pass reflected port, respectively. In a variation, 100% retroreflection can be employed, and the twice-mode-cleaned output is obtained from the isolator.

It is clear that very little power lands on the detector of a double pass locking system whether the system is locked or not. The maximum amount of power that the detector ever sees must be a quarter of the input power, when at the half maximum of resonance and hence when the cavity is transmitting and reflecting equally. The maximum is much less if only partial retroreflection is used. In any case, the detector sees this maximum power for a short time of order milliseconds during lock acquisition, and hence the risk of damage to the photodetector is greatly reduced.

Fig. 2 shows photodetector powers at the four possible ports of a cavity in a double pass arrangement during a sweep through resonance: the transmitted and reflected outputs associated with the first pass, and those associated with the second pass. The second pass transmission profile is narrower than its first pass counterpart by a factor of 2 as we would expect. Clearly, the second pass reflected output (the output that is detected and demodulated) has a minimum on resonance and two maxima at (first pass) half-resonance, as predicted above. In fact, this output is simply the product of the transmissivity and reflectivity of the cavity.

Another advantage of using a double pass is that the detector sees virtually no parasitic mode mismatch, thus reducing shot noise contributed from non-resonant higher order modes.

The error signal power is reduced if a partial retroreflector is used (equivalent to placing an attenuator in front of the photodetector), with a corresponding drop in the shot noise limited sensitivity. However, this becomes less important if the main interferometer of a gravitational wave detector imposes tighter locking constraints on

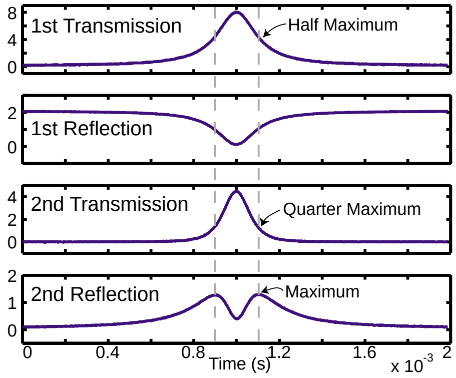

Figure 2. Powers at the four cavity outputs while sweeping the laser frequency through the cavity resonance: transmission and reflection of the first pass, and transmission and reflection of the second (retroreflected) pass. The second pass transmission resonance is half as wide as the first pass transmission resonance as expected. The second pass reflection has two maxima when the first pass transmission is at half maximum, as explained in the text. A glass wedge was used for retroreflection; the latter two traces represent approx. 2 orders of magnitude less in power than the former two.

the laser frequency, which is typically the case [5].

Another apparent drawback of placing the modulator after the cavity is that the mode-cleaned output beam now has relatively strong modulation sidebands. This could be turned to advantage in a gravitational wave detection system: a subsequent mode-cleaner stage, or even part of the main interferometer, could be single pass locked using these “extraneous” modulation sidebands without the addition of a second modulator.

3. Spatial Mode Locking

This section describes two cavity locking techniques, based on spatial mode interference, that are suitable for rigid mode cleaner cavities in gravitational wave detectors. Both are modulation-free, and hence avoid the difficulties of modulator thermal lensing in high power systems. *Tilt locking*, in the single and double pass regimes, has previously been presented elsewhere [6, 7, 8, 9]; here we give a brief overview in the context of mode cleaner cavities. For the first time, we introduce and demonstrate *flip locking*, a relative of tilt locking. Many unexplored variations of flip locking are possible; some of these hold promise for locking suspended, as well as rigid, mode cleaners.

3.1. Double Pass Tilt Locking

An experimental arrangement for the double pass tilt locking of a ring cavity is shown in Fig. 3(a). Compared with double pass PDH locking, the modulator is removed and the detector is replaced with a two-element split detector. In addition, a tilt is given to the retroreflector to misalign the beam’s second pass slightly, such that a small amount of the light couples into the antisymmetric, non-resonant TEM_{01} spatial mode, and reflects off the cavity.

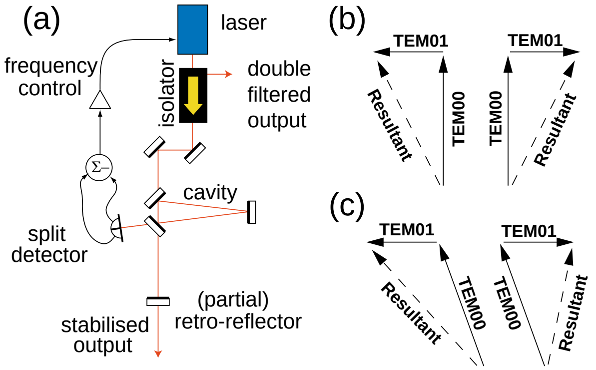

Figure 3. (a) Double pass tilt locking configuration. The retroreflector is given a slight tilt. (b) & (c) Phasor diagrams for TEM$_{00}$ and TEM$_{01}$ modes showing interference on the two sides of the split detector, when (b) on resonance and (c) near resonance. Subtraction of the resultant powers provides an error signal.

Tilt locking is similar in principle to PDH locking in that the dispersive phase shift of the near-resonant cavity is compared to some non-resonant local oscillator to produce an error signal. For PDH locking, modulation sidebands play the role of the local oscillator; for tilt locking it is the TEM$_{01}$ mode. Demodulation is replaced by subtraction of the signals from the two halves of the split detector. An error signal is obtained in this way since the near-resonant TEM$_{00}$ mode interferes with the TEM$_{01}$ mode constructively on one side of the split detector, and destructively on the other side (see Fig. 3(b) and (c)). The resulting error signal is equal to the imaginary component of the cavity reflectivity.

Previous demonstrations of tilt locking have shown that its noise suppression performance matches PDH locking [6]. One experiment involved tilt locking two lasers to a single cavity, and a fractional locking stability of 1.3×10^{-14} was demonstrated [9].

3.2. Double Pass Flip Locking

In tilt locking, the tilt added to the beam at the retroreflector is equivalent to a linear lateral phase shift across the beam profile. Here, we consider the possibility of adding a stepped phase shift to a TEM$_{00}$ mode. Such a mode should have improved efficiency of interference with the TEM$_{00}$ mode when split-detecting. The transverse electric field profile of a *flipped mode* is shown in Fig. 4(a).

One way to generate a flipped mode is by using a modified half wave plate, shown in Fig. 4(c). A regular half wave plate is cut into quarters, and two opposite quarters are joined such that the optical axis of one is at 90 degrees relative to the other. A TEM$_{00}$ gaussian beam with vertical (or horizontal) polarisation is directed exactly at the interface between the wave plate quarters. Just as a regular half wave plate gives a 180 degree phase shift between horizontal and vertical polarisations, this modified wave plate gives the required 180 degree phase shift between the left and the right side of the transverse beam profile. Fig. 4(d) shows the intensity profile of a laboratory flipped mode generated in this way [10].

Flip locking is very similar to tilt locking where a small amount of flipped mode replaces the small component of TEM$_{01}$ tilt mode generated by the tilted retroreflector.

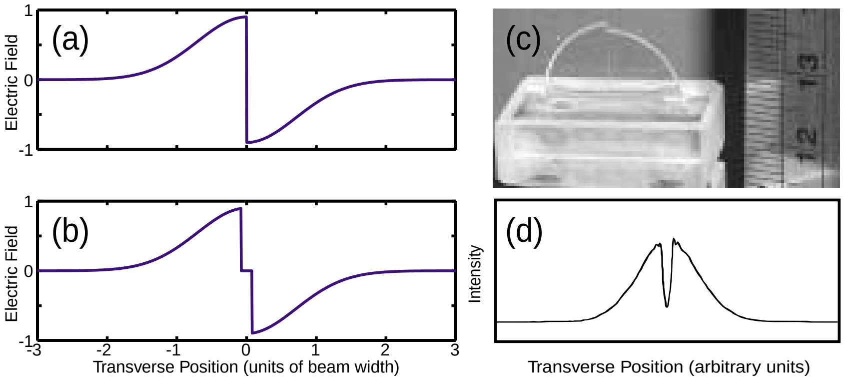

Figure 4. Ideal electric field amplitudes of (a) flipped mode and (b) spatial jitter immunity flipped mode (see text). (c) The modified half wave plate "flipped mode generator", used to generate (d) a laboratory demonstrated flipped mode, from [10].

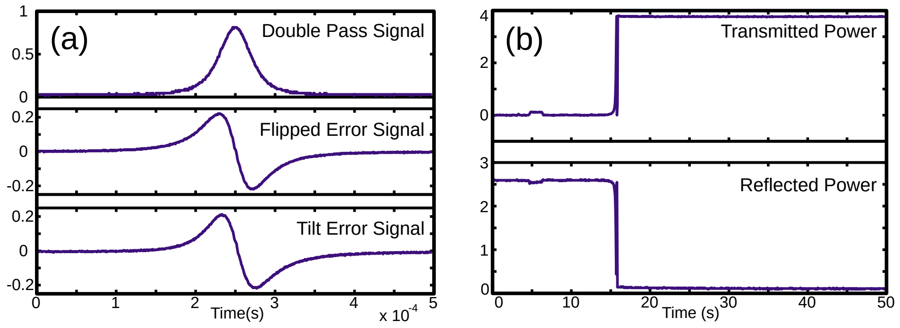

Figure 5. (a) Resonance sweep signals from a double pass locking experiment simultaneously generating tilt and flip locking error signals (arbitrary units). (b) Cavity transmission and reflection power (arbitrary units) during lock acquisition.

The configuration in Fig. 3(a) can be used where the modified half wave plate is placed in front of the retroreflector; the retroreflected beam passes through the wave plate twice, effecting a 360 degree phase shift between the two halves and hence returning the original TEM$_{00}$ mode (neglecting diffraction effects). With this type of modified wave plate, a slight tilt to the wave plate is required to extend the path length and hence produce a slight phase mismatch between the two beam halves. This new beam can be thought of as a TEM$_{00}$ mode plus a small fraction of flipped mode with a 90 degree phase shift. The component of flipped mode (comprised of non-resonant odd TEM modes) then reflects from the cavity and interferes to generate an error signal in the same manner as in tilt locking.

We successfully double pass flip locked a ring cavity using the configuration discussed above. Locking was stable and repeatable; the first pass transmission and reflection during lock acquisition are shown in Fig. 5(b). For comparison, the retroreflector was tilted in the vertical direction to generate a tilt locking error signal which was measured by the vertical subtraction of a quadrant detector; both error signals are shown in Fig. 5(a).

We point out that the above configuration is merely a demonstration; a realistic locking system would use a flipped mode generator that adds only a small phase shift between beam halves such that the single pass output is still approximately a (mode-cleaned) TEM_{00} mode. The flipped mode generator need not even be a distinct optical component; a stepped dielectric coating on either the retroreflector or the output coupler would achieve the same goal.

A modified flipped mode with a central gap has also been generated (Fig. 4(b)) [10]. The gap width could be set greater than the spatial jitter noise at the split detector, in which case the error detection system would become completely immune to spatial jitter. Some variation on this theme may be appropriate for the locking of suspended mode cleaner cavities as well as rigid cavities, pending further research.

4. Summary

We offer solutions to some of the difficulties arising from the use of high laser powers with mode cleaner cavities in gravitational wave detectors. Double pass locking was suggested as a way to drastically reduce the maximum power that can ever reach the locking detector, thus simplifying the detector design. Double pass tilt locking removes the need for a modulator, hence avoiding the difficulties of high power optical transmissions. Furthermore, we experimentally demonstrated double pass flip locking, an adaptable tilt locking variation, with some potential for locking suspended mode cleaner cavities.

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