Arm-length stabilisation for interferometric gravitational-wave detectors using frequency-doubled auxiliary lasers

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Abstract: Residual motion of the arm cavity mirrors is expected to prove one of the principal impediments to systematic lock acquisition in advanced gravitational-wave interferometers. We present a technique which overcomes this problem by employing auxiliary lasers at twice the fundamental measurement frequency to pre-stabilise the arm cavities' lengths. Applying this approach, we reduce the apparent length noise of a 1.3 m long, independently suspended Fabry-Perot cavity to 30 pm rms and successfully transfer longitudinal control of the system from the auxiliary laser to the measurement laser.

OCIS codes: (120.2230) Fabry-Perot; (120.3180) Interferometry.

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1. Introduction

Direct detection of gravitational radiation, predicted by Einstein's general theory of relativity, remains one of the most exciting challenges in experimental physics. Due to their relatively weak interaction with matter, gravitational waves promise to allow exploration of hitherto inaccessible processes and epochs [1]. Unfortunately, this weak coupling also hinders detection with strain amplitudes at the Earth estimated to be $\lesssim 10^{-21}$. Nevertheless, the network of advanced gravitational wave detectors currently under construction [2–5] is widely expected to operate with sufficient sensitivity to observe several events per year (see e.g. [6]).

Modern gravitational-wave detectors are Michelson-style interferometers, enhanced by the addition of resonant cavities at their inputs, outputs and, generally, in each of their arms (see Fig. 1). When all of these cavities are held within their respective linewidths by interferometer control systems we say that the interferometer is *locked*. When the interferometer is not locked no meaningful scientific data can be recorded. Due to interactions between the optical cavities, lock acquisition is a non-trivial problem.

The second generation of interferometric gravitational-wave detectors will employ higher finesse (narrower linewidth) arm cavities. Recent investigations indicate that it is these arm cavities which will pose the greatest challenges during the lock acquisition process [7,8]. In this work we develop a tool, an *arm-length stabilisation system* or *ALS*, to address these challenges.

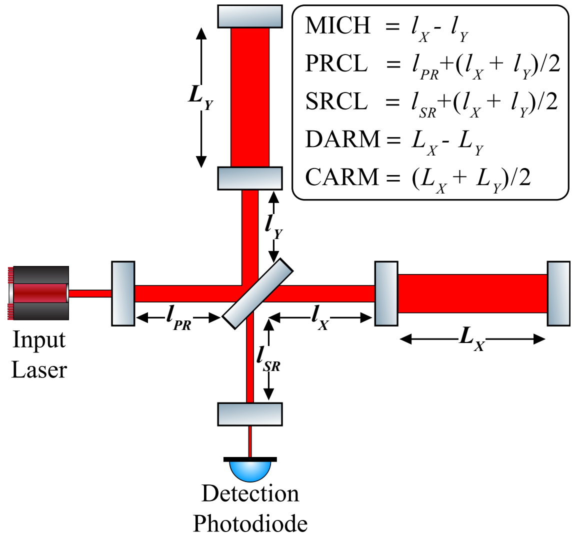

Fig. 1. (Colour online) Schematic of a contemporary gravitational-wave interferometer indicating primary length degrees of freedom. In this work MICH, PRCL and SRCL are described as *central* degrees of freedom. The arms have lengths $L_{X,Y}$ of order 1 km; the other cavities, PRCL and SRCL, are significantly shorter ($\lesssim$50 m).

2. Arm-length stabilisation

The length degrees of freedom of all gravitational-wave interferometers are controlled using an extension of the Pound-Drever-Hall (PDH) technique [9] – radio-frequency phase-modulation sidebands are impressed upon the input laser light at multiple frequencies and the circulating field is detected and demodulated at selected interferometer output ports [7, 8].

The resonant state of the modulation sidebands, the demodulation frequencies and phases, and the macroscopic cavity lengths are all carefully chosen to provide low-noise sensing signals for each of the degrees of freedom when the interferometer is locked. In particular, the modulation frequencies are chosen such that the control sidebands do not resonate inside the arm cavities.

Due to the optical couplings between the various cavities, these detection schemes do not always provide reliable sensing signals during lock acquisition. In this respect, the arm cavities are singularly troublesome.

Advanced gravitational-wave interferometers utilise multi-stage seismic isolation systems which offer excellent performance above ∼1 Hz (see e.g. [10]); however, it remains difficult to suppress noise from lower frequency sources (e.g. double-frequency microseism). Consequently, the residual arm cavity length noise is expected to be ∼1 µm rms, 1000 times greater than a typical arm cavity's linewidth (∼1 nm). Displacements of this magnitude are problematic for two reasons:

Firstly, the carrier and control sideband fields will occasionally become resonant in the arms. Sensing signals for the central degrees of freedom are derived from the interaction between the carrier and sidebands or between the sidebands themselves. When one component of either pair becomes resonant, control signals for the central degrees of freedom become invalid.

Secondly, for reasons of noise, second generation detectors will employ significantly weaker test mass actuators (see e.g. [11]) and utilise heavier test masses (∼40 kg). As a result of these choices, the test mass actuators will often lack sufficient authority to gain control over the arm cavities when they are freely swinging.

Although it is possible to acquire lock under these conditions, this acquisition cannot be realised in a repeatable, systematic manner. The goals of the arm-length stabilisation system are therefore twofold:

a) Maintain both arm cavities at a fixed offset from resonance so that the central degrees of freedom may be locked without obstruction.

b) Reduce rms cavity motion to within one linewidth (∼1 nm) so that arm cavity lock acquisition signals can be usefully applied.

Implicit in these requirements is the ability to methodically remove the fixed offset from arm resonance to arrive at a state where the arm cavity acquisition signals are valid.

3. Technique

We now describe the approach adopted to achieve the above goals, providing a general description of the strategy applied followed by explanatory details concerning one possible practical implementation. Compared to other techniques considered for arm-length stabilisation, this approach relies on proven technologies, offers greater sensitivity [12] and is less invasive [13].

3.1. Design philosophy – dual-wavelength locking

An additional *auxiliary* laser is placed behind each end test mass. These lasers are independently locked to their respective arm cavities by actuating on the lasers' frequencies, circumventing the weak test mass actuators.

By comparing the frequencies of the auxiliary lasers to the frequency of the main interferometer's pre-stabilised laser (PSL), one can construct ALS signals describing the offset of the PSL from resonance in the arms. Outside of the cavity linewidth, conventional length sensing signals are often non-linear and cannot be used to effect closed-loop control. In contrast, these ALS signals remain valid even when the PSL is far removed from resonance; hence they can be used to actively stabilise and adjust the detunings of the arms during lock acquisition by actuating on the end test masses.

To avoid cross-coupling between main interferometer and arm-length stabilisation signals, the auxiliary lasers operate at 532 nm. This wavelength was chosen for its harmonic relationship to the wavelength of the PSL (1064 nm). The use of two distinct wavelengths demands that the arm cavity mirror coatings be dichroic. The choice of cavity finesse (i.e. mirror reflectivities) at 532 nm is relatively free. Low values ease auxiliary laser lock acquisition whilst higher values provide improved mode filtering and noise performance. A finesse of around 100 represents a reasonable compromise. Dichroic mirrors compatible with this specification are not expected to increase the observed mirror thermal noise significantly [14, 15].

3.2. Practical implementation

We now proceed through our realisation of this arm-length stabilisation strategy sequentially (see Fig. 2). For clarity, we consider only a single resonant cavity, representing one arm of an advanced interferometer.

1. The 532 nm output of a dual-wavelength (1064 nm and 532 nm) auxiliary laser is locked to the arm cavity using the PDH technique. This wide-bandwidth (>10 kHz) control loop provides the reference measurement of the arm's resonant frequency. The auxiliary laser remains tightly locked to the arm cavity at all times whilst the ALS system is active.

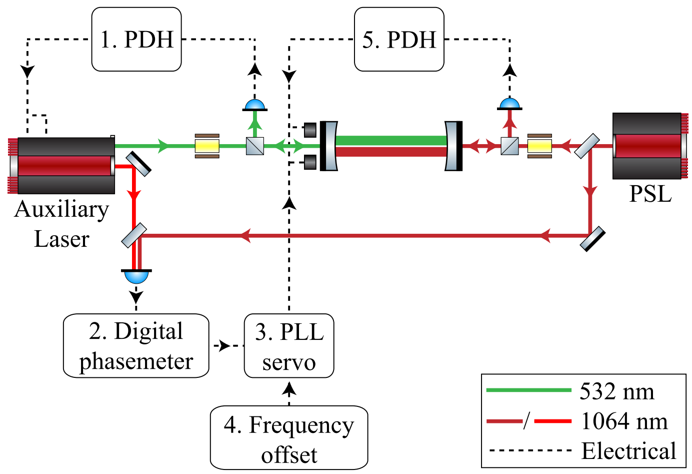

Fig. 2. (Colour online) Schematic of the arm-length stabilisation system. The numbering indicates the flow of the lock acquisition process and corresponds to the enumerated list below.

2. The frequency of the auxiliary laser is subsequently compared to that of the PSL by measuring the frequency of their heterodyne beat note using a LISA-like digital phasemeter [16]. This comparison is made at 1064 nm using the auxiliary laser's second output (which has a constant phase relationship with the 532 nm beam). The beat-note frequency indicates how far the PSL beam is from resonating in the arm cavity. The extensive linear range of this heterodyne measurement, compared to conventional PDH-based sensors, is the key feature of the ALS system.

   In an operational gravitational-wave detector this measurement necessitates the transfer of a frequency reference through $\sim$4 km of optical fibre (from the PSL to the auxiliary laser or vice versa). Well-established techniques to cancel noise induced by fibre transmission exist (e.g. [17, 18]).

3. The output from the digital phasemeter is then used to offset phase-lock the auxiliary laser to the PSL. Feedback signals are applied to the arm cavity's end test mass, effectively suppressing the cavity's motion relative to the PSL and stabilising its offset from resonance.

4. By adjusting the offset frequency of the phase-locked loop (PLL), the detuning of the PSL from resonance can be actively controlled (see Fig. 3).

   In a long-baseline interferometer, this feature can be employed to hold the arm cavities at a fixed offset from resonance, allowing the central degrees of freedom to be locked without disturbance.

5. The offset of the arm from resonance may now be reduced in a methodical fashion, bringing the cavity into a region where interferometer acquisition signals can be activated. It is also feasible that the ALS system could bring the arms fully onto resonance so that low-noise, operating-mode control signals can be engaged directly. This second approach was simulated in our experiment whereby control over the arm cavity's length was transferred from the ALS system directly to a PSL PDH error signal captured in reflection (see Fig. 4).

After control is transferred to the main interferometer, the ALS system may be stood down so that it does not introduce any additional noise to the instrument. Alternatively, the ALS system may be retained as a powerful diagnostic tool. For example, we anticipate that the phase-locked auxiliary lasers will be able to provide accurate measurements of arm cavity alignment, g-factor and absolute length. Whether these measurements can be made on-line remains to be determined.

Generalisation of this scheme to a two-arm interferometer involves combining the ALS signals from each arm (either optically or electronically) to construct signals which align with the notional common-arm and differential-arm degrees of freedom used in interferometer control (CARM and DARM in Fig. 1).

For further details on the arm-length stabilisation concept and its role in the lock acquisition process see [19].

4. Experimental test

In order to validate the fundamental approach discussed above, a laboratory-scale proof-of-principle experiment was carried out at The Australian National University's Centre for Gravitational Physics. To concentrate on the novel aspects of the arm-length stabilisation system, we again examined only a single optical resonator.

Our 1.3 m long cavity was formed from two single-stage piano-wire suspension systems known as 'Tip-Tilts' [20]; it had a g-factor of 0.46 and measured finesses of 300 at 1064 nm and 100 at 532 nm. (For comparison, the Advanced LIGO detectors are expected to have finesses of approximately 450 and 100.) The dichroic cavity mirrors were controlled by coil-magnet actuators via an Advanced LIGO digital control system. The role of the PSL was played by a standard diode-pumped solid-state laser (JDSU NPRO 126); the auxiliary laser was an Innolight Prometheus.

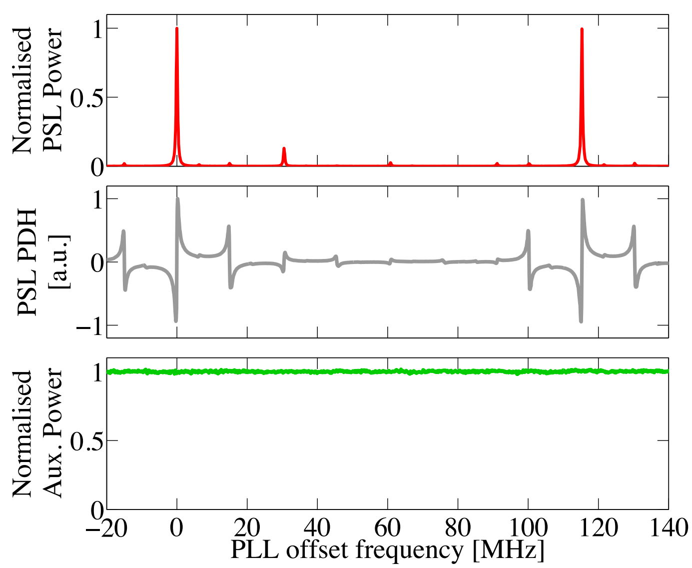

Fig. 3. (Colour online) Systematic cavity detuning over more than one free spectral range using the arm-length stabilisation system. Top – Normalised cavity transmission at the wavelength of the measurement laser (1064 nm); Middle – Pound-Drever-Hall signal generated from the measurement laser alone; Bottom – Normalised cavity transmission at the wavelength of the auxiliary laser (532 nm).

In Fig. 3 we conclusively demonstrate the technique's capacity to explore the full range of arm cavity detunings. With the ALS system active, the offset frequency of the phase-locked loop (item 4 in Fig. 2) was swept linearly over more than one free spectral range. Since the auxiliary laser is securely locked to the arm cavity, this offset frequency directly controls the detuning of the PSL from resonance.

In a gravitational-wave interferometer this capability would permit us to maintain a specified detuning, away from any undesirable resonances, allowing the central degrees of freedom to be easily locked, thus meeting the first ALS goal. The extent to which the specified detuning is 'fixed' will be explored below.

Complete command over arm cavity detuning also allows us to satisfy the implicit goal of manoeuvring the cavity system from a stable off-resonance state to a position where acquisition signals become meaningful. A typical handover from ALS to PSL control signals is shown in Fig. 4.

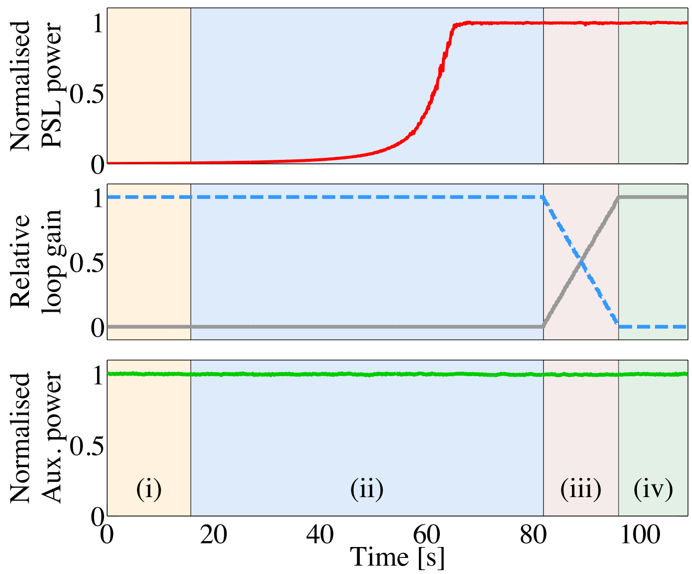

Fig. 4. (Colour online) Transfer of arm cavity length control from the arm-length stabilisation system to signals derived solely from the measurement laser. Top – Normalised cavity transmission at the wavelength of the measurement laser (1064 nm); Middle – Relative gain of arm-length stabilisation (blue dashed) and measurement laser (grey) control signals; Bottom – Normalised cavity transmission at the wavelength of the auxiliary laser (532 nm). The division of the axes into four regions is discussed in the main text. The timescale of this handover does not represent the limit of system performance.

The axes are divided into four shaded regions, representing different stages of the transfer:

(i) The cavity is initially stabilised at a point far from resonance. The detuning is reduced in an orderly fashion by adjusting the offset frequency of the phase-locked loop.

(ii) The cavity approaches resonance, circulating power begins to increase and PSL-based control signals become viable.

(iii) Control over the cavity length is transferred to the PSL. As both PSL and ALS systems actuate on the cavity's end test mass, this handover is realised simply by tuning the relative gain of the two feedback loops.

(iv) The cavity is under the control of PSL signals alone.

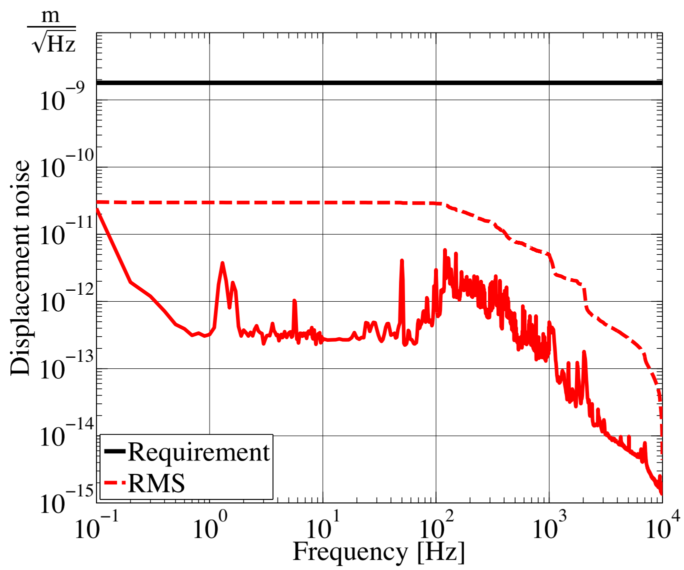

Fig. 5. (Colour online) Residual cavity displacement noise relative to the measurement laser with arm-length stabilisation system active. The integrated rms noise (dashed line) is within one full-width-half-maximum cavity linewidth (solid horizontal line) as required. Data shown in this figure were taken with our optical table's pneumatic vibration isolators activated. The prominent features around 1 Hz are due to the mechanical resonances of this system. All other presented data were recorded with this isolation system turned off.

Recall that the second goal of the arm-length stabilisation system is to reduce the rms displacement noise of the arm cavity, relative to the PSL, to within one linewidth. The full-width-half-maximum-power cavity linewidth is given by

$$\Delta_{\mathrm{FWHM}} = \begin{cases} \lambda/(2\mathscr{F}) & [\mathrm{m}] \\ c/(2L\mathscr{F}) & [\mathrm{Hz}] \end{cases} , \tag{1}$$

where λ is the laser wavelength, $\mathscr{F}$ is the cavity finesse, c is the speed of light and L is the cavity length. For our parameters the cavity linewidth is approximately 1.8 nm, comparable to the Advanced LIGO value of 1.2 nm.

This specification was tested by tuning the cavity onto resonance using the arm-length stabilisation system and employing the PSL PDH measurement as an out-of-loop sensor. The resulting amplitude spectral density is shown in Fig. 5. The integrated rms motion (dashed line) was found to be 30.2 pm, comfortably meeting the cavity-linewidth requirement (solid horizontal line).

Figure 5 also describes the stability of *any* offset from resonance (e.g. that introduced when locking the central degrees of freedom) as the performance of the ALS system does not vary as a function of arm cavity detuning.

Combined, the above findings demonstrate the validity of arm-length stabilisation approaches based on frequency-doubled auxiliary lasers. This positive result should, nevertheless, be considered in context. Any extrapolation of the work presented here to a kilometre-scale interferometer will require the differences in environment, test mass actuation and optical configuration to be addressed. However, recent simulation work predicts that, taking these differences into account, the linewidth specification can still be met [19].

5. Discussion

The results presented in Fig. 5 reveal an increase in noise at low frequencies ($<$1 Hz). It is suspected that this roll-up is due to a combination of spurious amplitude modulation introduced by our electro-optic modulators and mirror alignment fluctuations (our cavity was not instrumented with any auto-alignment systems). Both effects can be mitigated should it be found necessary; however, the measured noise is a factor of 60 below the linewidth requirement and smooth cavity tuning and efficient control transfer were achievable at all times.

For ideal operation, the arm-length stabilisation strategy described herein demands that both the PSL and the auxiliary laser sense identical cavity lengths. In practice, a number of wavelength-dependent effects limit the extent to which this is possible. For example, the two beams have different spot sizes on the mirrors, field penetrations into the dichroic coatings and susceptibilities to cavity misalignment. In our (bench-top) experiment air turbulence was identified as a significant noise source. This effect may have been exacerbated by the different mode volumes occupied by the two lasers within the cavity.

6. Conclusions

In this investigation we have developed the general method of arm-length stabilisation based on auxiliary lasers. We have demonstrated the viability of this approach using a single cavity, stabilising its residual motion to within one cavity linewidth.

Our method is described as a series of key measurements. Each of these measurements can be made using several proven techniques, allowing the scheme to be easily modified without reducing capability.

A conceptually identical arm-length stabilisation system, based on frequency-doubled auxiliary lasers, has now been selected as a baseline technology for Advanced LIGO. Testing of this scheme on a fully-suspended, dual-recycled interferometer is underway at the California Institute of Technology.

The integration of the ideas introduced here into the Advanced LIGO length sensing and control architecture will not be without challenges. However, an effective arm-length stabilisation system would, for the first time, decouple the arm cavities from the central degrees of freedom and enable global control to be achieved from the start of a repeatable and diagnosable lock acquisition sequence.

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