Weak-light phase-locking for LISA

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Abstract. The long armlengths of the LISA interferometer, and the finite aperture of the telescope, leads to an optical power attenuation of $\sim 10^{-10}$ of the transmitted to received light. Simple reflection at the end of the arm is therefore not an optimum interferometric design. Instead, a local laser is offset phase-locked to the weak incoming beam, transferring the phase information of the incoming to the outgoing light. This paper reports on an experiment to characterise a weak light phase-locking scheme suitable for LISA in which a diode-pumped, Nd:YAG, non-planar ring oscillator (NPRO) is offset phase-locked to a low power (13 pW) frequency stabilised master NPRO. Preliminary results of the relative phase noise of the slave laser shows shot noise limited performance above 0.4 Hz. Excess noise is observed at lower frequencies, most probably due to thermal effects in the optical arrangement and phase sensing electronics.

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1. Introduction

The need for phase-locked lasers in interferometric gravitational wave detectors is unique to spaceborne interferometers. In the case of LISA [1], phase-locked lasers enter into the interferometric design in two ways: the two lasers on-board each spacecraft (s/c) must be phase locked to form an effective single light source (equivalent to one laser and a beamsplitter in conventional interferometers); and, the local laser at the end of the interferometer arm must be phase locked to the weak incoming beam [2, 3, 4]. This paper focusses on the latter case. Other missions requiring weak-light phase-locking include BBO (Big Bang Observer) [5], ASTROD (Astrodynamical Space Test of Relativity using Optical Devices) [6], and a proposed lunar laser ranging instrument [7].

In conventional ground based Michelson interferometers, the light at the far end of the arm is simply reflected back; in the case of LISA, the extremely long armlength would make simple reflection grossly inefficient. The armlength, coupled with the diffraction of the laser beam (a diffraction limited 1 W beam of $\lambda = 1064$ nm, through a 30 cm telescope gives a beam diameter ~ 24.5 km at the receiving s/c), means only ~ 100 pW of light is detected on the photodiode of the far s/c. If this were to be simply reflected, the detected signal back at the original s/c would be completely swamped by photon counting noise. For this reason, the received light at the end of the arm is amplified before being transponded back. This is achieved by phase locking a local laser to the received beam, and transponding the phase locked, higher power beam back along the arm.

The length of the interferometer arm also affects the phase-locking in a more subtle way. Due to the chosen orbits of the s/c, and the finite speed of light, the transmitting spacecraft must *point-ahead* of the receiving spacecraft. This leads to the received and transmitted beams being at an angle with respect to each other on the optical bench. [1]. The angle is removed by sensing the wavefront misalignment on the main quadrant photodiode, and compensating by feeding back to the tilt of the proof mass. However, this necessarily leads to a lateral shift of the received beam position with respect to the local beam, thereby reducing the mixing efficiency (fringe contrast) of the beams, and hence increasing the shot noise limit to the measurement.

Recent developments in the interferometric measurement system of LISA requires the laser to be locked to the length of the interferometer arm (*arm-locking*). In this case, the feedback loop is very different from the more simple laser transponder. However, even with arm-locking as the baseline design of the interferometer, phase-locking of the lasers in the *non-master* arm is still a necessary ingredient of the mission.

2. Experimental Description

The final goal of these experiments is to demonstrate shot noise limited performance of a phase-locking scheme suitable for LISA, using LISA-like parameters (*e.g.* low-power master laser, "top-hat" intensity profile), and LISA-like equipment (*e.g.* digital phase-meter and digital feedback). The current experiments are designed to test one aspect of the above list; namely weak-light phase-locking using Gaussian intensity profiles.

Two separate Nd:YAG non-planar ring oscillators [8] (Lightwave model 126), operating at $\lambda = 1064\,\mathrm{nm}$ are used as the laser sources. This laser design is similar to the master oscillator in the baseline LISA laser design (the current baseline LISA laser consists of a master oscillator followed by a fibre amplifier) [9]. One of the lasers (the *master*) is frequency stabilised to a rigid ULE reference cavity (Figure 1). This reference cavity is housed in a thermally stable environment consisting of five layers of gold coated stainless steel cylinders inside a cylindrical vacuum tank. The thermal stability of the ULE spacer is of the order of $\mu\mathrm{K}/\sqrt{\mathrm{Hz}}$ at 1 mHz, leading to a laser frequency stability of $\sim 30\,\mathrm{Hz}/\sqrt{\mathrm{Hz}}$ at 1 mHz. Details of the frequency stabilisation can be found elsewhere [10].

A small fraction of the light from the master laser is split off from the main beam and used as the weak light source for the phase locking. This light undergoes a two-stage attenuation; first by using the light transmitted through a highly reflecting mirror ($\mathrm{T} = 10\,\mathrm{ppm}$) followed by using the leakage field through a polarising beamsplitter ($\mathrm{T} = 500\,\mathrm{ppm}$), giving a total attenuation of $\sim 5 \times 10^{-9}$. The weak light is then mixed with approx 1mW of light from the slave laser. Stray light is reduced by use of polarisation techniques, details of which can be found in [2].

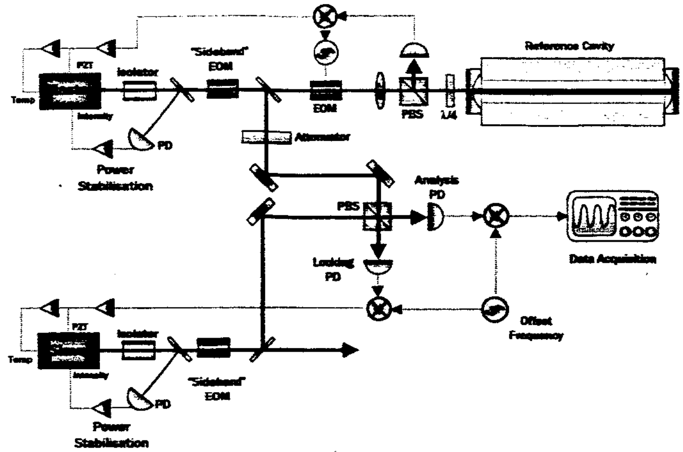

Figure 1. Schematic diagram of the optical layout of the phase locking experiment. Solid lines represent optical paths, dotted lines represent electrical paths. PD = photo-detector, PBS = polarising beam splitter, EOM = electro-optic modulator.

The signal from the locking photodetector is demodulated at the desired offset frequency, in this case 21 MHz, and fed back to the laser via suitable gain and filtering.

The second port of the beamsplitter is used as an out-of-loop monitor of the relative phase of the slave laser with respect to the master. At this port, most of the master laser's light is reflected by the beam splitter, and is again mixed mixed with approximately 1 mW of light from the slave laser. By increasing the master laser power by three orders of magnitude compared with the in-loop signal, the shot noise limit of the out-of-loop measurement is ~ 30 times lower, and hence will not limit the measured performance.

3. Results

The experiment was conducted with master and slave laser powers of 13 pW and 1 mW respectively at the locking photodiode. The power of the interfering beams is calculated by firstly measuring the calibrated DC photocurrent from the locking photo-detector. If the master laser power is significantly lower than the slave laser power (as is the case in this experiment) then the DC photocurrent gives a direct measure of the slave laser power. Now, by measuring the *rf* component of the interference signal, and knowing the slave laser power, the master laser power can be calculated. In this way, the power measured is the actual power interfering with the slave laser, *i.e.* reduces the effect of mis-alignment of the beams when calculating the shot noise limit to the measurement. The calculated shot noise limit to the achievable relative phase noise of the slave is given by Equation 1 [3]:

$$\widetilde{\delta\phi} = \sqrt{e\left[\frac{1}{i_2} + \frac{1}{i_1}\right]} \approx \sqrt{\frac{e}{i_1}} \;\; \mathrm{rads}/\sqrt{\mathrm{Hz}} \qquad \text{for } i_1 \ll i_2 \qquad (1)$$

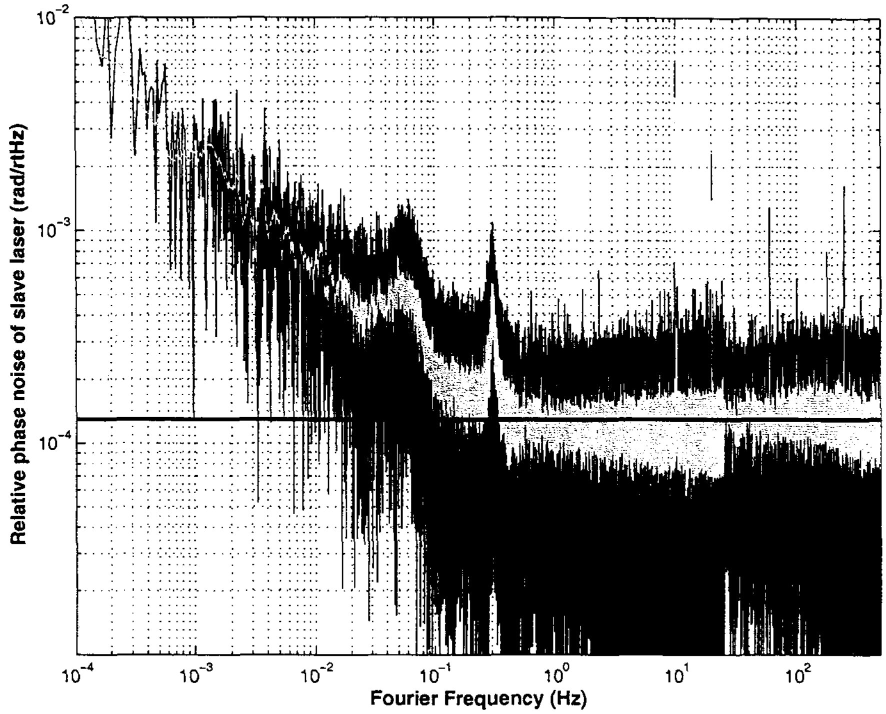

Figure 2. Power spectral density of relative phase noise of slave laser with respect to weak-light master laser. The dark gray shows the raw power spectrum of the data, the light gray shows a 20-point running average of the dark gray line, and the solid black line represents the shot noise limit to the measurement (1.3×10^{-4} rad/$\sqrt{\text{Hz}}$).

where $\widetilde{\delta\phi}$ is the linear spectral density of the relative phase noise, $i_{1/2}$ are the photocurrents of the master and slave laser respectively, and e is the electronic charge.

As expected the shot noise limit is dominated by the photocurrent of the master laser. For the calculated 13 pW of the master, the shot noise limit to the relative phase stability is set at 1.3×10^{-4} rad/$\sqrt{\text{Hz}}$.

Figure 2 shows the power spectral density of the relative phase noise of the slave laser. The data presented is obtained from the independent, out-of-loop photodetector shown in Figure 1. The signal from this detector is demodulated via an analogue mixer (Mini-circuits SRA-1), using the same local oscillator used to demodulate the locking signal. The solid line on the graph shows the shot noise limit to the phase noise of the slave laser.

As can be seen, the relative phase noise of the slave laser is shot noise limited above 0.4 Hz, however, the noise increases significantly beneath this frequency, although is still less than two orders of magnitude above the shot noise limit over the LISA bandwidth. Possible contributors to this excess noise include: room temperature fluctuations - neither the beamsplitter nor photo-detectors are in vacuum; and differential drift in feedback and analysis mixers - the mixers are not currently temperature stabilised.

Further investigations are needed to isolate and remove the limiting noise sources.

4. Discussion

The results presented here represent a significant step forward in demonstrating a phase-locking scheme suitable for LISA. The power levels used are significantly lower than the actual powers to be used in LISA, however, these experiments show that phase-locking to lower powers is possible. This could be significant during the LISA initial acquisition.

One caveat remains. The out-of-loop monitor photodiode effectively samples the same light as the in-loop detector, and thereby there may be a degree of common-mode noise rejection limiting the effectiveness of the independent measurement.

Future experiments will include moving the critical optical components into a thermally stable vacuum system, thermal isolation and stabilisation of the analogue mixers, and increase master laser power to levels appropriate to the LISA mission.

Further work will involve replacing the analogue mixers with a digital, LISA-like phase-meter, and will also include mixing LISA-like wavefronts (Gaussian intensity profile with a Top-Hat intensity profile), along with the effect of mis-alignments and beam offsets. Finally, the effects of the phase modulation sidebands on the master laser and slave laser will also be investigated.

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