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Analog phase lock between two lasers at LISA power levels

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Abstract. This paper presents the implementation of an analog optical phase-locked-loop with an offset frequency of about 20 MHz between two lasers, where the detected light powers were of the order of 31 pW and 200 μW. The goal of this setup was the design and characterization of a photodiode transimpedance amplifier for application in LISA. By application of a transimpedance amplifier designed to have low noise and low power consumption, the phase noise between the two lasers was a factor of two above the shot noise limit down to 60 mHz. The achievable phase sensitivity depends ultimately on the available power of the highly attenuated master laser and on the input current noise of the transimpedance amplifier of the photodetector. The limiting noise source below 60 mHz was the analog phase measurement system that was used in this experiment. A digital phase measurement system that is currently under development at the AEI will be used in the near future. Its application should improve the sensitivity.

1. Introduction

LISA will measure the distance fluctuations on the order of $12\,\mathrm{pm}/\sqrt{\mathrm{Hz}}$ between 5×10^9 m distant free-falling test masses in the frequency range between 1 Hz and 3 mHz, with a decreasing sensitivity below 3 mHz with f^{-2} mainly due to test mass acceleration noise [1].

The length measurements will be done interferometrically and due to the large beam divergence between the satellites only a small fraction of the transmitted power is detected at the remote satellite. The transmitted laser power, the wavelength of the light, the telescope diameter and the losses in the optical chain influence the amount of detected power which finally yield a detectable light power on one of the photodetectors that are used for the science measurement of about 100 pW [2].

The limit for the measurement sensitivity which mainly depends on the detectable power at the remote satellite is approximately $9\,\mathrm{pm}/\sqrt{\mathrm{Hz}}$ and is a consequence from the shot noise introduced by the lasers at the photodiode [2].

The phase information of the incoming light must be transferred to another laser, the so-called slave laser. In the case of LISA this will be done by an optical phase-locked-loop (OPLL) with a maximum offset frequency of 20 MHz which depends on the time-varying Doppler shifts that are induced by the changing velocities of the satellites [3, 4].

The incoming beam interferes with the local laser. Their beat note is detected by a photodetector, which might introduce additional phase noise on one hand due to electronic noise of the photodetector and on the other hand due to the available laser power from the slave laser on the photodiode [3, 5].

The more laser power from the slave laser is used, the lower is the influence of the electronic noise of the transimpedance amplifier (TA). The limits for the usage of slave laser power are set by two facts: The transmitted power to the remote satellite must be as high as possible in order to minimize the shot noise, and the deposed energy on the LISA optical bench must be as small as possible in order to avoid thermal gradients. The amount of power of the slave laser that is used for the OPLL on the LISA optical bench will be 1 mW.

With these constraints given, a suitable photocurrent transimpedance amplifier was designed and characterized in terms of its phase sensitivity.

In Section 2 the experimental setup for characterization of the phase noise performance is described. Section 3 deals with the analytic description of the significant noise sources, their tracing through the phase read-out chain and in Section 4 the experimental results from the analog OPLL are summarized.

2. Experimental setup

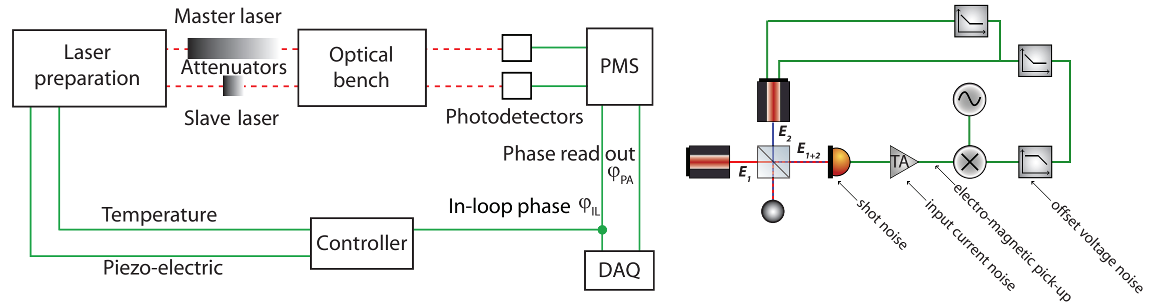
Figure 1a shows a simplified schematic of the experimental setup. For the OPLL two identical Nd:YAG lasers (Innolight Mephisto 500) were used which offer the possibility to control their frequency via piezo-electric and temperature actuators on the laser crystal. Both laser beams were attenuated before they were fed into the interferometer where the phaselock was performed. These attenuators were designed to provide output beams with minimum power fluctuations and to avoid stray light on the beat note that is used for the phase-lock. Thus, out-coupling mirrors were chosen for the attenuators set up separately from the interferometer described below. The attenuated beams were then guided via fibers onto a Zerodur optical bench, where they were brought to interference at a beam splitter. The attenuators were adjusted in such a way that the available power of the lasers at one output of the power beam splitter were approximately 31 pW and 200 μW, respectively. The weak beam power was estimated from the beat note amplitude combined with an estimate for the contrast. The slave laser power was determined from the DC photocurrent. The interference signal at one output was then used to produce the error signal for the OPLL. Photodetectors with dedicated transimpedance amplifiers were used to measure the beat note.

In contrast to the LISA photodetectors, single element photodiodes were used instead of quadrant photodiodes. Therefore, the available power from both lasers had to be adjusted. For the photodetector characterization the power of the master laser was chosen to be slightly higher compared to LISA which results in a lower limit for the achievable phase noise. Thus, other noise sources like the TA input current noise could be seen more clearly.

The phase read-out is done via a DC read-out scheme. The beat note was mixed with a reference frequency using a mixer (Mini Circuits TUF-3H). When both signals have approximately the same frequency, the output signal of the mixer contains information about the phase difference between both signals and an additional signal at the sum of both frequencies. The sum frequency was suppressed by an active low-pass filter, consisting of two second order Tschebyscheff low-pass filters which were implemented using an LT1028 operational amplifier. The input offset voltage of the operational amplifier was compensated using a composite amplifier design with an AD8628 in the feedback chain [6]. The mixer, the low-pass and the Data acquisition system (DAQ) used to sample the low-pass output signals represent the phase measurement system (PMS).

The error signal was passed through a PI controller before being fed back to the slave laser via its piezo and temperature tuning inputs. Thereby, the phase difference between the beat note and the reference signal is kept close to zero. Further information on the setup can be found in [5].

Figure 1b shows a schematic of the OPLL where the significant sources and their coupling nodes have been highlighted. The important noise sources for the development of the photodetectors



(a) Experimental setup of weak light OPLL (b) OPLL noise sources

Figure 1: Analog OPLL with offset frequency - Experimental setup and possible noise sources

are the input current noise of the transimpedance amplifier and the electro-magnetic pick-up of the electrical components of the OPLL [3].

The input current noise can be kept as low as possible by an optimized TA design. Due to the limited gain-bandwidth product, this design is a trade-off between high gain that reduces the effect of additional noises introduced by the following stages and the photodetector transimpedance bandwidth.

3. Photodetector design

In Figure 1b the electro-magnetic field E at the output of the power beam splitter is a interference signal of the electro-magnetic fields $E_{\mathrm{ML,SL}}$ at the inputs of the power beam splitter [7]. This interference signal E can simply be converted into a power

$$P = P_{\mathrm{ML}} + P_{\mathrm{SL}} + 2C\sqrt{P_{\mathrm{ML}}P_{\mathrm{SL}}}\cos\left(\Delta\omega t + \Delta\phi\right). \tag{1}$$

$P_{\mathrm{ML,SL}}$ denotes the regarding power from the master and the slave laser after the beam splitter, $\Delta\omega$ and $\Delta\phi$ describe the frequency and the phase difference between both laser beams and C the contrast of the beat note. The current i_{P} produced by the photodiode can be calculated by multiplication of Eq. 1 with the photodiode efficiency, ρ. The Perkin Elmer C30619G photodiode that was used in our experiment had an efficiency specified to be 0.68A/W [8].

$$\begin{aligned} i_{\mathrm{P}} &= \rho\left(P_{\mathrm{ML}} + P_{\mathrm{SL}} + 2C\sqrt{P_{\mathrm{ML}}P_{\mathrm{SL}}}\cos\left(\Delta\omega t + \Delta\phi\right)\right) && (2)\\ &= 0.14\,\mathrm{mA} + 21.7\,\mathrm{pA} + 0.1\,\mu\mathrm{A}\cos\left(\Delta\omega \mathrm{t} + \Delta\phi\right) && (3)\end{aligned}$$

For the next processing steps this photocurrent must be converted by a transimpedance amplifier into a voltage [9, 10]. When both the AC and the DC photocurrent are amplified, the DC term limits the amplification to a factor of about 10^5 when an operational amplifier with a typical output voltage range of $\pm 15\,\mathrm{V}$ is used. In this case the amplitude of the beat note would only be 10 mV which is not desirable because electro-magnetic pick-up and the noise contributions from following stages become more significant. In addition to this the mixer in the PMS needs a higher beat note amplitude to function properly. For this reasons the AC and the DC part of the photocurrent are decoupled to maximize the amplification in the first stage.

One major noise source is the input current noise of the TA. The shot noise i_{SN} at the output of the photodiode is dominated by the slave laser power because it is much higher than the master laser power [11]:

$$i_{\mathrm{SN}} \cong= \sqrt{2\mathrm{e}\rho\mathrm{P}_{\mathrm{SL}}}, \tag{4}$$

where e is the elementary charge. In our case the slave laser power received by the photodiode is $200\,\mu$W and, therefore, the shot noise spectral density of the photocurrent is $6.69\,\mathrm{pA}/\sqrt{\mathrm{Hz}}$. This current noise is amplified and converted into a voltage by the transimpedance amplifier. In the analog PMS, the voltage noise is multiplied as well as the beat note with the reference frequency. Thus the shot noise from the photodiode leads to a voltage noise at the output of the analog PMS which finally will limit the phase measurement.

The achievable phase sensitivity at the output of the PMS can be derived by knowing the properties of an analog PMS and tracing the noise from the photodetector through the phase read-out chain [12]. If the input current noise of the transimpedance is neglected and only the shot noise of the photodiode is taken into account, this assumption leads to the following equation for the observed phase noise

$$\delta\widetilde{\phi}_{\mathrm{SN}} = \sqrt{\frac{\mathrm{e}}{C^2 \rho P_{\mathrm{ML}}}}. \tag{5}$$

The achievable phase noise depends in the ideal case only on the available power P_{ML} of the master laser.

Now a closer look at the input current noise of the transimpedance amplifier is taken. An ordinary transimpedance amplifier consists of an operational amplifier and a resistor [9]. The input current noise of an operational amplifier like the low noise amplifier LMH6624 is approximately $2\,\mathrm{pA}/\sqrt{\mathrm{Hz}}$ at 20 MHz plus the current noise from the transimpedance resistor, the so-called Johnson noise. The current noise for a resistor, i_{JN}, with resistance, R, is given by

$$i_{\mathrm{JN}} = \sqrt{\frac{4\mathrm{k_B T}}{R}} \tag{6}$$

where $\mathrm{k_B}$ denotes the Boltzmann factor and T the temperature. For a $2\,\mathrm{k}\Omega$ resistor Eq. 6 yields approximately $2.8\,\mathrm{pA}/\sqrt{\mathrm{Hz}}$.

The equivalent input current noise for the transimpedance amplifier is of the same order as the shot noise from the slave laser and hence, cannot be neglected when designing a dedicated photodetector.

The two noise source of the TA are quadratically added and yield the additional input current noise, i_{dn}. The input current noise is uncorrelated to the shot noise of the slave laser and if both noise sources are kept in mind the calculations yield the following equation for the achievable phase noise:

$$\delta\widehat{\phi}_{\mathrm{SN}} = \sqrt{\frac{\mathrm{e}}{C^2 \rho P_{\mathrm{ML}}} + \frac{i_{\mathrm{dn}}^2}{2C^2 \rho^2 P_{\mathrm{ML}} P_{\mathrm{SL}}}}. \tag{7}$$

Assuming realistic values for the parameters one can calculate the achievable phase noise for a TA. If the detectable power from the master laser is 31 pW and the power from the slave laser is $200\,\mu$W, this yields a phase noise of $8.28 \times 10^{-5}\,\mathrm{rad}/\sqrt{\mathrm{Hz}}$ in the ideal case. If one additionally takes the unavoidable input current noise (i_{dn}) of about $3\,\mathrm{pA}/\sqrt{\mathrm{Hz}}$ into account, the phase noise increases to $9.4 \times 10^{-5}\,\mathrm{rad}/\sqrt{\mathrm{Hz}}$.

That is why the development of a fast and low noise TA design was one major issue for the LISA interferometry. The TA consisted of a cascode plus a common collector stage offers a high gain-bandwidth product [9][13][14]. It simultaneously decreases the Johnson noise of the feedback resistor since a higher resistance value can be used. Another advantage of the transistor design is the lower power consumption in comparison to operational amplifiers.

The AC part of the photodetector shown in Figure 2 has a transimpedance gain for the first stage of $30\,\mathrm{k}\Omega$ ($2 \times 15\mathrm{k}\Omega$) and a voltage amplifier with a gain of 20 dB in the second stage. This

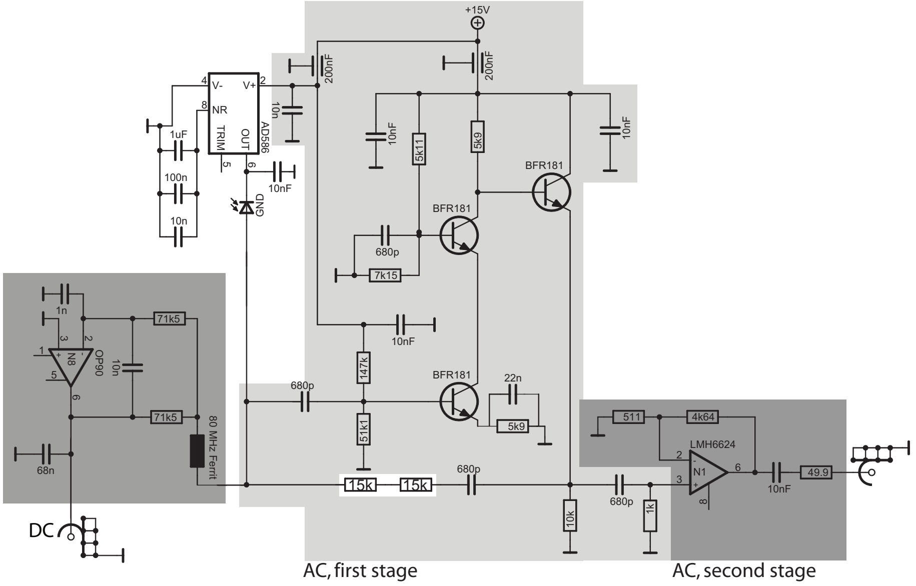


Figure 2: Schematic of the transimpedance amplifier. The AC amplifier uses only discrete transistor stages

yields an amplification factor of 1.5×10^5 [V/A] which includes the attenuation due to impedance matching between photodetector output and PMS input. The amplitude of the 20 MHz beat note at this stage was 15 mV. The amplitude was still too small for the analog PMS, which requires 0.5 and 2 $\mathrm{V_{pp}}$ input signals in order to achieve a sufficiently low phase noise. For this reason an additional amplifier with a gain of 50 was added, yielding an amplitude of 0.75 V at the input of the PMS. The introduced photodetector design was finally used for the OPLL at LISA power levels.

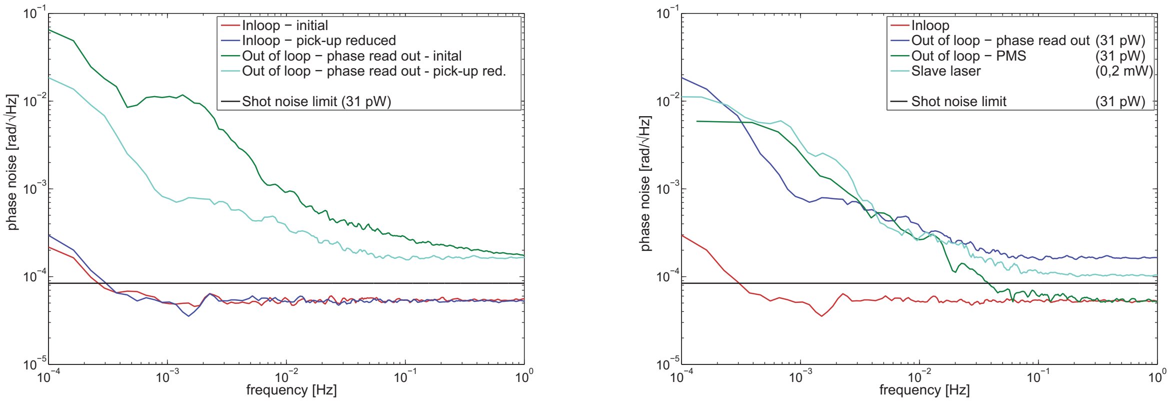
4. Results

The phase read-out sensitivity was measured by placing identical photodetectors at both outputs of one recombination beam splitter. One photodetector was used for the OPLL and the other was used to measure the out-of-loop phase noise of the photodetector plus the PMS. Figure 3a shows a comparison of two measurements of the phase read-out.

One important noise source was identified to be electro-magnetic pick-up. Its effect could be reduced by including better shielding of the photodetectors and the PMS and by using high frequency transformers (Mini Circuits T1-6T+) in the high frequency chains. Figure 3a shows that with these improvements a shot noise limited phase read-out could be achieved down to 60 mHz. The spectra were calculated using an improved FFT algorithm, called LPSD[15].

In order to identify the impact of the PMS on the noise performance, one photodetector signal was used as input for both the in-loop and the out-of-loop measurement paths. Thus, one output channel of the PMS was used for locking the two lasers and the other output of the PMS was measured by the DAQ. The spectrum of this measurement is shown as the green curve in Figure 3b indicates that the noise of the PMS is limiting the phase read-out below 60 mHz.

The light blue noise curve shows the noise of the phase read-out without any beat note for comparison. For this measurement only the slave laser beam was directed onto the photodiode. The shot noise introduced by the second laser on the photodiode can be calculated and converted into phase noise at the output of the PMS. The theoretical value is $1.1 \times 10^{-4}\,\mathrm{rad}/\sqrt{\mathrm{Hz}}$ and is almost identical with the measured value. A comparison of the measurement to the theoretical



(a) Improved electro-magnetic shielding (b) Current phase noise sensitivity

Figure 3: Phase measurements with analog OPLL at LISA power levels

value gives information about residual unknown noise sources in the experiment which are still under investigation.

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Bibliography

[1] Danzmann K and Rüdiger A 2003 *Classical Quantum Gravity* **20** 1–9
[2] McNamara P W 2005 *Classical Quantum Gravity* **22** 243–247
[3] Huntington E 2005 *Optics Communications* **250** 178–190
[4] Dhurandhar S 2005 *Classical Quantum Gravity* **22** 481–487
[5] Steier F 2008 *Interferometry techniques for spaceborne gravitational wave detectors* Ph.D. thesis Institute for gravitational physics, University of Hannover
[6] Williams J 1986 Technical note 21 - composite amplifier Tech. rep. Linear Technology
[7] Bergmann and Schfer 2002 *Optik - Wellen- und Teilchenoptik* (de Gruyter)
[8] Datasheet http://optoelectronics.perkinelmer.com/content/datasheets/dts_c30619.pdf [date: 2008/10/29]
[9] Horowitz P and Hill W 1989 *The art of electronics - second edition* (Cambridge University Press)
[10] Mancini R 2002 *Op Amps For Everyone - Design Reference* (Elsevier LTD)
[11] Schottky W 1918 *Annalen der Physik* **57**
[12] Diekmann C 2008 *Phasenstabilisierung und -auslesung für LISA* Dipl. thesis Institute for gravitational physics, University of Hannover
[13] El-Diwany M 1981 *IEE Proc.* **128** 299–305
[14] Hobbs P 2000 *Building electro-optical systems - making it all work* (John Wiley and Sons,Inc.)
[15] Troebs M and Heinzel G 2006 *Measurement* **39** 120–129