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Transportable setup for amplifier phase fidelity measurements

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Abstract. One possible laser source for the Laser Interferometer Space Antenna (LISA) consists of an Ytterbium-doped fiber amplifier originally developed for inter-satellite communication, seeded by the laser used for the technology demonstrator mission LISA Pathfinder. LISA needs to transmit clock information between its three spacecraft to correct for phase noise between the clocks on the individual spacecraft. For this purpose phase modulation sidebands at GHz frequencies will be imprinted on the laser beams between spacecraft. Differential phase noise between the carrier and a sideband introduced within the optical chain must be very low. We report on a transportable setup to measure the phase fidelity of optical amplifiers.

1. Introduction

The LISA mission [1, 2] aims to detect gravitational waves by measuring pathlength variations between satellites.

Although the laser concept ten years ago was a single NPRO emitting 1 W of laser power [3], now the baseline is a master-oscillator power-amplifier system with an electro-optical modulator (EOM) between oscillator and amplifier for clock noise transfer [4], ranging, and data communication [5, 6].

On each spacecraft, clock information will be modulated on the laser sent to the distant spacecraft as phase modulation sidebands at GHz frequencies. The phase of the sideband-sideband signals will be measured and used to correct for differential clock noise between the satellites. This requires that the phase of the sidebands is not disturbed by other elements in the transmission chain. This work focuses on the possible effects of the fiber amplifier behind the EOM.

The effect of differential phase noise within the transmission chain $\Delta\phi_{\text{PRO}}$ should affect the phase read out of the carrier-carrier signal by not more than $6 \mu\text{rad}/\sqrt{\text{Hz}}$,

$$\Delta\phi_{\text{PRO}}(f) \leq 6 \mu\text{rad}/\sqrt{\text{Hz}} \cdot u_{\text{PL}}(f) \quad (1)$$

where the shape factor $u_{\text{PL}}(f)$ is given by

$$u_{\text{PL}}(f) = \sqrt{1 + \left(\frac{2.8 \text{ mHz}}{f}\right)^4}. \quad (2)$$

The ancillary modulation error $\Delta\phi_{\text{AME}}$ between a sideband at frequency f_{EOM} and the carrier is given by

$$\Delta\phi_{\text{AME}}(f) \leq \Delta\phi_{\text{PRO}} \cdot \frac{f_{\text{EOM}}}{f_{\text{het}}} \quad (3)$$

where f_{het} is the maximum heterodyne frequency. With $f_{\text{EOM}}=2.4$ GHz and $f_{\text{het}}=24$ MHz we obtain

$$\Delta\phi_{\text{AME}}(f) \leq 0.6 \text{ mrad}/\sqrt{\text{Hz}} \cdot \sqrt{1 + \left(\frac{2.8 \text{ mHz}}{f}\right)^4}. \quad (4)$$

Possible noise sources between carrier and sideband are optical pathlength changes in the amplifier, stimulated Brillouin scattering (SBS), and nonlinear dispersion in combination with seed laser frequency noise. These effects have been discussed previously [7].

2. Flight representative optical amplifier

One option for the LISA laser system is to use the laser developed for the technology demonstrator mission LISA Pathfinder as seed laser in combination with an EOM and optical amplifier originally developed for laser communication terminals [8, 9].

The output power of the amplifier in the desired polarization was measured with an integrating sphere and photo diode and is shown in Fig. 1. The amplifier was seeded by a LISA-like signal (narrowband carrier + two sidebands containing 10% of the total power each). The nominal pump diodes were operated. The redundant pump diodes were not used.

The onset of SBS leads to increased power noise in the amplifier output in a millisecond time scale. The absence of SBS was verified by monitoring the output powers of the individual amplifier stages while slightly tapping on the amplifier using an Allen key. Figure 2 shows relative

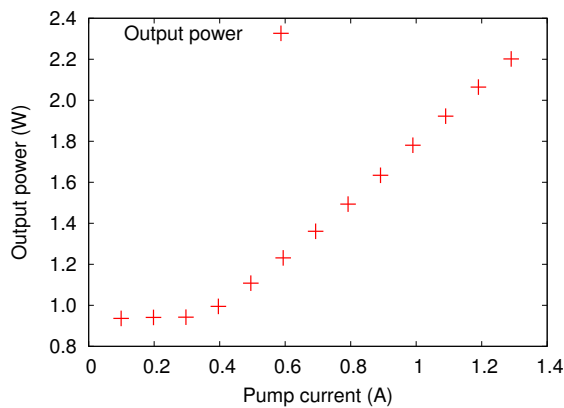


Figure 1. Measured amplifier output power.

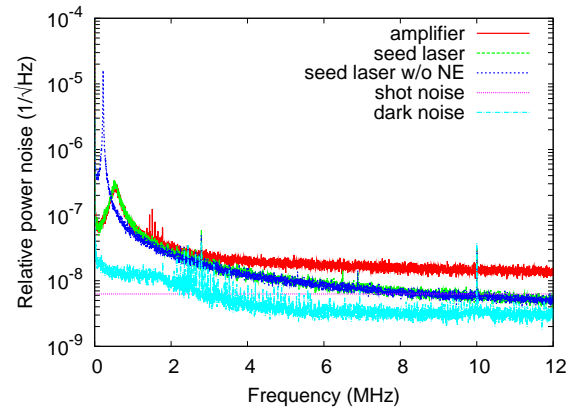


Figure 2. Relative power noise.

power noise (RPN). It is compatible with LISA requirements [10]. It was measured using an in-house photo detector by Tesat-Spacecom GmbH & Co. KG. Dark noise consists of electronic noise of the photo detector, preamplifier and spectrum analyzer. The relative power noise of the seed laser was measured without and with active noise eater. The amplifier was seeded only with active noise eater. It was operated at 2.2 W output power. The trace “shot noise” was plotted as consistency check. Approx. 8 mA photocurrent were detected. The measured noise of the seed laser shows only the same noise as the shot noise of the photocurrent at high frequencies. The finite bandwidth of the detector causes the slight reduction of the measured noise below the shot noise.

3. Test setup

Figure 3 shows the simplified setup to measure differential phase noise of a fiber amplifier. Light from two lasers is interfered and used to seed the amplifier under test. One of the lasers acts as carrier, the other mimicks a single phase modulation sideband. A fraction of the light is detected by photo diodes before and behind the amplifier. A control loop is used to offset-phase lock the difference frequency of both lasers to 2.4 GHz. The signals from both photo diodes are digitized, mixed with a slightly different frequency ($2.4 \text{ GHz} + 1.6 \text{ kHz}$), and low-pass filtered. A phasemeter implemented in software [11] was used to determine the phase difference between both signals. Differential phase noise between carrier and phase modulation sideband is visible as phase noise in this difference signal.

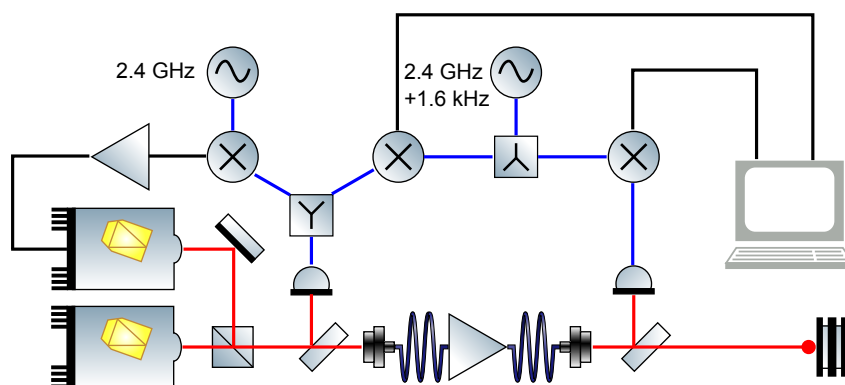


Figure 3. Simplified setup to measure fiber amplifier differential phase noise.

Figure 4 shows the planned setup for differential phase noise measurements. It differs in some details from the simplified setup shown in Fig. 3. The planned setup is implemented using three breadboards to ensure transportability. The first breadboard houses the two lasers, the second the actual interferometric measurement setup, and the third is the interface to the fiber amplifier under test with a mode-matching telescope and a power-attenuation stage consisting of two polarising beam splitters and a half-wave plate in between.

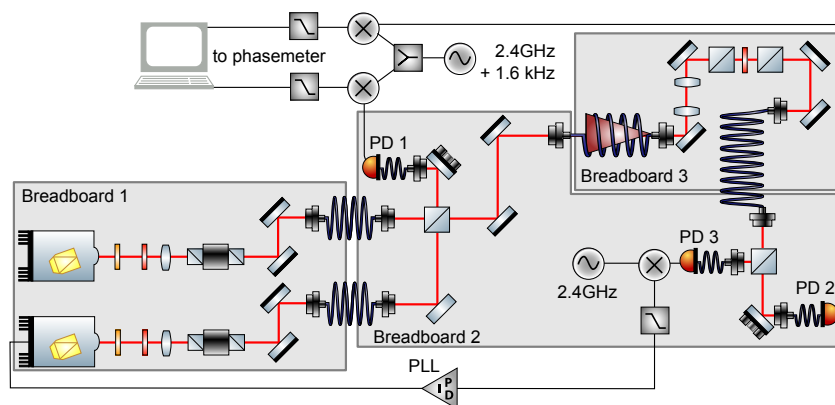


Figure 4. Planned setup for differential phase noise measurements.

A third photo diode (labelled PD3) is used for the offset-phase lock of the lasers. With only two photo diodes, the local oscillator of the offset-phase lock coupled into the respective phasemeter channel leading to a parasitic signal that is present even in the absence of laser light.

This parasitic signal can disturb the phase measurement. Similar parasitic signals have been observed and investigated previously [12].

The kilohertz signal produced from photo diode 2 is split and the two nominally identical signals are digitized and processed by two phasemeter channels. The difference between these two signals is used to measure the phasemeter sensitivity.

The mixers that convert the GHz signals to kilohertz are known to show a signal amplitude-dependent phase shift [7]. Hence, the amplitudes of the phasemeter input signals could be stabilized by control loops that acted on piezo-driven tilt mirrors in front of fiber couplings before the (fiber-coupled) photo diodes.

Half-wave plates and polarizing beam splitters are used before and after fiber couplings for polarization control. Room temperature fluctuations are suppressed by passive thermal isolations.

4. Sensitivity

Figure 5 shows the current status of the transportable setup. Most electronics are integrated in the rack. Breadboards one and two from Figure 4 are placed on top of the rack and a simple passive fiber is used instead of the amplifier under test and breadboard three. Photo diode three for the laser offset phase lock and the mixer are placed in the smaller of the boxed on-top of breadboard one. The larger box contains the photo diodes and mixers that feed the phasemeter. Figure 6 shows the sensitivity of the setup, measured with a passive polarization-

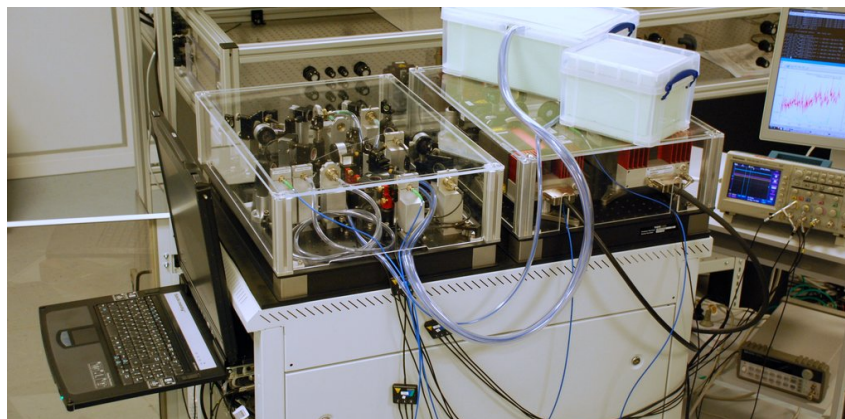


Figure 5. Current status of the transportable setup.

maintaining single-mode fiber instead of breadboard 3 and the fiber amplifier under test. The trace labelled “phasemeter” shows the difference of two nominally identical phasemeter channels. The trace labelled “fiber” shows the difference between the signals before and behind the fiber. Although a sufficient sensitivity has been shown, it is not yet reliably reproducible. Currently, noise investigations are in progress to ensure a constant and reliable performance.

5. Conclusions

A laser system candidate for LISA with space-qualified hardware is available. It consists of the seed laser for the LISA Technology Package as well as an electro-optical modulator and Ytterbium-doped fiber amplifier originally developed for optical communication. A transportable test setup to measure the phase fidelity of the amplifier has shown sufficient sensitivity. Noise hunting is in progress to ensure a constant noise level of the setup.

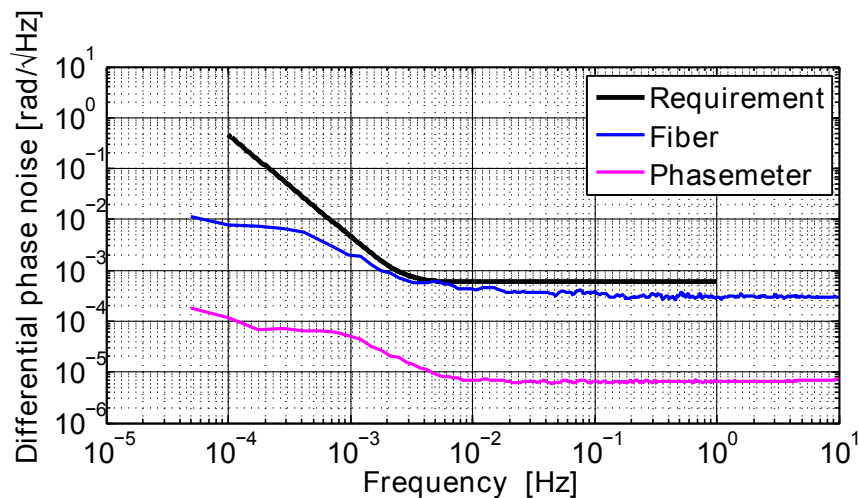


Figure 6. Sensitivity of the setup, measured with a passive polarization-maintaining single-mode fiber instead of breadboard 3 and fiber amplifier under test.

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