Lasers for LISA: Overview and phase characteristics

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Lasers for LISA: overview and phase characteristics

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Abstract. We have investigated two alternative laser systems for the Laser Interferometer Space Antenna (LISA). One consisted of the laser of LISA's technology precursor LISA Pathfinder and a fiber amplifier originally designed for a laser communication terminal onboard TerraSar-X. The other consisted of a commercial fiber distributed feedback (DFB) laser seeding a fiber amplifier. We have shown that the TerraSar-X amplifier can emit more than 1 W without the onset of stimulated Brillouin scattering as required by LISA. We have measured power noise and frequency noise of the LISA Pathfinder laser (LPL) and the fiber laser. The fiber laser shows comparable or even lower power noise than the LPL. LISA will use electro-optical modulators (EOMs) between seed laser and amplifier for clock noise comparison between spacecraft. This scheme requires that the excess noise added by the amplifiers be negligible. We have investigated the phase characteristics of two fiber amplifiers emitting 1 W and found them to be compatible with the LISA requirement on amplifier differential phase noise.

1. Introduction

In comparison to LISA Pathfinder [1], the laser system for LISA [2; 3] must emit at least 30 times more power and include an electro-optical modulator for clock noise transfer between spacecraft. The integrated broadband optical modulators we have studied so far can only handle a fraction of the 1 W laser power required for LISA and must hence be followed by an optical amplifier. This amplifier must not change the phase of the sidetones imposed on the light by the EOM for clock noise transfer. In Section 2 we present current options for a LISA laser system and in Section 3 we report on phase characteristics measurements for two optical amplifiers.

2. Laser systems for LISA

LISA requires at least 1 W of laser output power and an electro-optical modulator is needed in the optical path to transmit clock information between spacecraft. The integrated EOMs known to us only handle less than 100 mW of optical power. Hence, a master oscillator power amplifier concept with the EOM before the amplifier seems necessary.

Nonplanar ring oscillators (NPROs) have proven as low-noise master oscillators [4; 5]. One option is to use the LISA Pathfinder laser as master oscillator for LISA. This laser is discussed in Section 2.1. A possible amplifier might be the one flying as part of a laser communication terminal [6; 7] on the TerraSar-X mission, launched on June 15th, 2007. This amplifier was designed for lower output powers than 1 W. We discuss our tests on the engineering model in Section 2.2. Another alternative for the LISA laser is to use an all-fiber system consisting of a distributed feedback (DFB) fiber laser with subsequent amplifier. Measurements on a commercially available fiber laser are presented in Section 2.3.

2.1. LISA technology package laser

The LISA Pathfinder laser (LPL) is a possible candidate for the LISA master oscillator. The LPL weighs 1 kg, has a 12x13 cm^2 footprint, and consumes 12 W of electrical power. The engineering model that was investigated emitted 14 mW of optical power, the flight model will emit 35 mW. The LPL consists of the laser head, a fiber-coupled pump module, and electronics. Power noise and frequency noise measurements are discussed in Section 2.4.

2.2. Space-qualified fiber amplifier

The TerraSar-X mission, launched in June 2007 includes a laser communication terminal [6; 7] with a master oscillator similar to the LPL, a broadband integrated optical modulator, and a two-stage polarization maintaining Ytterbium fiber amplifier.

Onboard TerraSar-X, the amplifier emits 300 mW. At higher output powers, nonlinear effects such as stimulated Brillouin scattering (SBS) might occur which would degrade the noise performance and ultimately limit the output power. We have investigated, if SBS occurs at 1 W of output power when seeded under conditions representative for LISA. We have seeded the amplifier with phase modulated input from an NPRO. Each sideband was spaced by 300 MHz from the carrier and contained 10% of the total power. As indication for the onset of SBS, we have used the amount of backscattered light detected by a monitor photodiode inside the amplifier. Figure 1 shows output power and backscattered light level as function of pump current. The onset of SBS is correlated with a significant slope increase of the backscattered

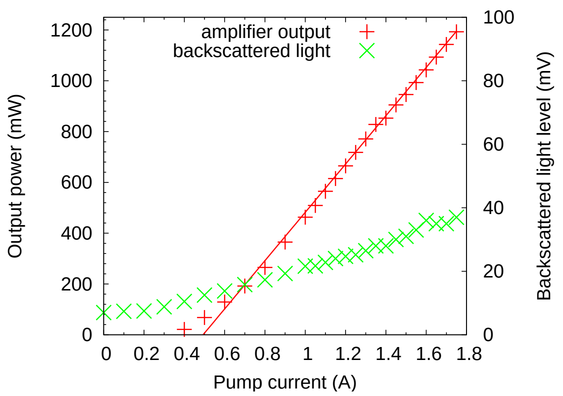

Figure 1. Measured output power and backscattered light level as function of pump current of amplifier with space heritage.

light signal. We have not observed such a slope increase. We have extracted 1.2 W of output power without the onset of SBS. The measurements were performed in one of our laboratories where no special care was taken to minimize acoustic noise. The air conditioning was active during the measurements as well as fans from laboratory equipment such as laser diode drivers.

2.3. Master fiber oscillator with amplifier

As an alternative for the LISA laser we have investigated an Ytterbium-doped distributed-feedback fiber master oscillator power amplifier system (BoostiK by Koheras) emitting 1 W at

1064 nm. A fiber DFB laser was used as master oscillator followed by a polarization-maintaining two-stage fiber amplifier. The laser system had actuators for power and frequency tuning and a control loop was implemented to suppress the relaxation oscillation of the DFB laser. Power noise and frequency noise measurements are discussed in Section 2.4.

2.4. Power and frequency noise

Figure 2 shows measured relative power noise of the LPL and the fiber laser with amplifier. The output of the LPL was detected by a photodiode with transimpedance amplifier. For frequencies up to 200 Hz the photodiode signal was digitized using a computer, and the program lpsd [8; 9] was used to calculate spectral densities. For higher frequencies the photodiode signal was measured with a spectrum analyzer (Agilent 4396B). For the fiber laser a fraction of the output power was detected and for frequencies up to 2 Hz a computer and lpsd were used to produce the graph. For higher frequencies, the spectrum analyzer was used. None of the traces was limited by the measurement sensitivity. The relaxation oscillation of the LPL is visible at 600 kHz while the fiber laser used an internal control loop to suppress its relaxation oscillation.

Figure 3 shows the free-running frequency noise of the LPL and the fiber laser with amplifier. For comparison, the frequency noise of a commercial NPRO (Mephisto 500 by Innolight) emitting 300 mW is also shown. For frequencies up to 1 Hz the traces were obtained from beat measurements of the free-running lasers with a frequency-stabilized laser [10, pp. 71]. For higher frequencies, the lasers were frequency-locked to a stable Fabry-Perot cavity while actuator and error signals were recorded [10, pp. 111].

For Fourier frequencies below 0.2 Hz the frequency noise of the fiber laser is up to a factor of 10 above the frequency noise of the LPL. Between 0.2 Hz and 1 kHz, the frequency noise of the LPL is up to a factor of 30 above the noise of the fiber laser, and above 1 kHz the frequency noise of the fiber laser is up to three orders of magnitude higher than the noise of the LPL. Compared to the 300 mW NPRO, the LPL shows up to a factor of 20 higher frequency noise for Fourier frequencies above 10 mHz.

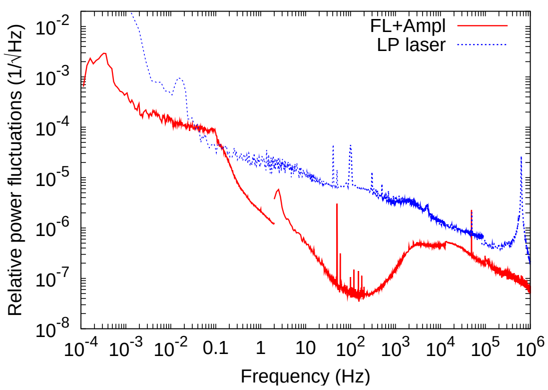

Figure 2. Measured power noise of fiber laser with amplifier and LISA Pathfinder laser.

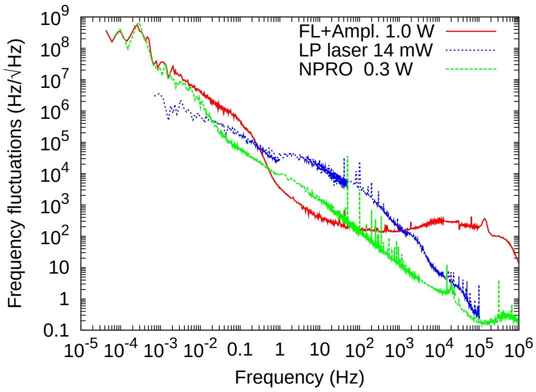

Figure 3. Measured free-running frequency noise of fiber laser with amplifier, LISA Pathfinder laser, and a commercial NPRO.

Due to the control loop suppressing the relaxation oscillation of the fiber laser, the measured relative power noise is not directly comparable to the noise of the LPL. However, for frequencies in the LISA measurement band from 0.1 mHz to 1 Hz the fiber laser shows comparable or lower noise than the LPL and is already within a factor of 20 within the stabilized power noise requirement for LISA. Using its power modulation input an external stabilization can be built to further reduce its power noise.

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For Fourier frequencies below 1 kHz the free-running frequency noise of the fiber laser is comparable to or better than the free-running frequency noise of the LPL. For frequencies above 1 kHz the frequency noise of the fiber laser was significantly higher than the LPL frequency noise. This high-frequency frequency noise can impact the performance of the LISA phase measurement system due to aliasing. Its impact on the phase measurement system will need to be investigated in future work.

3. Clock noise transfer in optical amplifiers

We have investigated differential phase noise between carrier and sideband in two fiber amplifiers.

3.1. Potential noise sources

There are at least two possible sources of differential phase noise in fiber amplifiers:

(i) Nonlinear dispersion leads to differential phase noise when the seed laser frequency changes with respect to the amplifier gain profile. First measurements have been performed (not shown) that show a tiny effect, which is negligible for LISA.

(ii) Optical length changes in the amplifier, ΔL, due to e. g. changes in ambient temperature, pump power, or seed power lead to differential phase changes, $\Delta\phi$, of sidebands at f_{EOM} with respect to the carrier of

$$\Delta\phi = \frac{2\pi f_{\mathrm{EOM}}}{c}\Delta L, \tag{1}$$

where c is the speed of light. We have measured the combined effect and discuss it in Section 3.4.

3.2. Optical amplifiers under test

We have investigated two amplifiers built at Laser Zentrum Hannover. Both used Ytterbium-doped fibers as gain medium pumped by laser diodes at 976 nm and emitted 1 W of optical power. One amplifier was pumped directly into the fiber core and consisted of two idential stages using 0.4 m of doped fiber each. The second amplifier used 3 m of polarization-maintaining double-clad fiber in a single stage and was pumped in the multi-mode cladding.

3.3. Differential phase noise measurements

Figure 4 shows the (simplified) schematic setup for measuring fiber amplifier differential phase noise. Light from two lasers (Mephisto 500 by Innolight) was superimposed and used to seed the fiber amplifier under test. Before and behind the amplifier, a fraction of the light was detected by fiber-coupled photodiodes (SIR5-FC by Thorlabs). The signal before the amplifier was split and one half used to offset-phase-lock both lasers to a difference frequency of 2 GHz+1.6 kHz. This was performed by an analog mixer with subsequent low-pass filter and loop filter. The other half of the photodiode signal and the signal behind the amplifier were mixed with a local oscillator at a slightly different frequency, namely 2 GHz. Both signals at 1.6 kHz were digitized by a computer and a phasemeter [11] implemented in software was used to determine the phase difference between both signals. The amplitudes of both 1.6 kHz signals were kept constant by control loops (not shown) acting on piezo-mounted tilt-mirrors in front of the fiber-coupled photodiodes.

3.4. Amplifier phase characteristics

Figure 5 shows measured differential phase noise between 2 GHz sideband and carrier at 1 W of amplifier output power for the core-pumped and the cladding-pumped fiber amplifiers. Both amplifiers meet the LISA requirements. The cladding-pumped amplifier showed slightly higher differential phase noise than the core-pumped amplifier. In an independent experiment, the

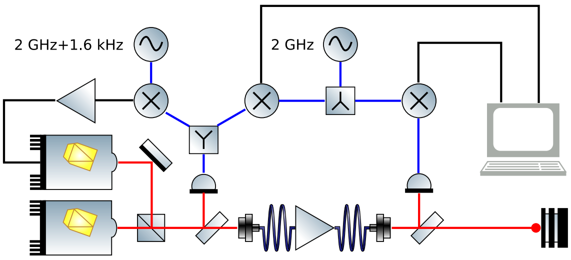

Figure 4. Schematic setup for fiber amplifier differential phase noise measurements.

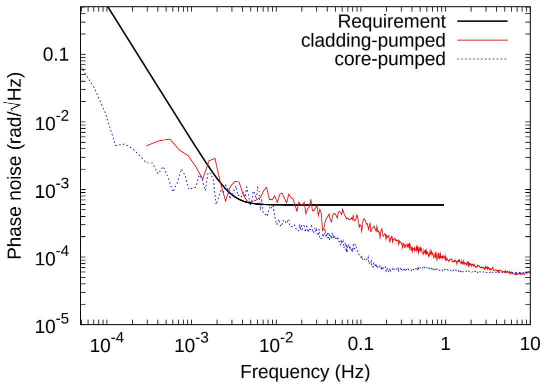

Figure 5. Measured differential phase noise of core-pumped and cladding-pumped fiber amplifier.

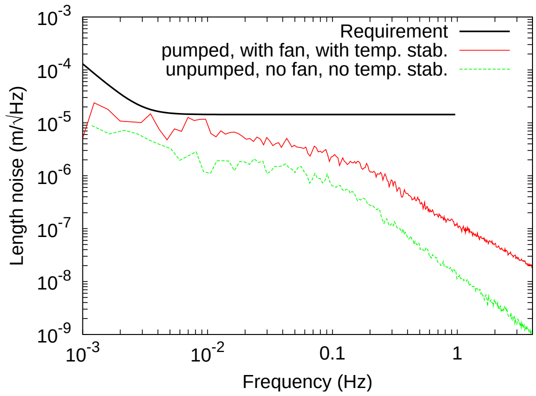

Figure 6. Measured length noise of cladding-pumped fiber amplifier.

cladding-pumped amplifier was seeded by a single laser and placed in one arm of a homodyne Mach-Zehnder interferometer with balanced detection. A mirror mounted on a piezo actuator was used to stabilize the interferometer armlength difference to mid-fringe. By reading the actuator signal the length fluctuations of the amplifier were measured. They are shown in Figure 6. The trace with the pumped amplifier shows higher noise than the trace of the unpumped amplifier, which proves that the measurement setup was sensitive enough. Length noise below the trace labelled “Requirement” leads to differential phase noise below the respective requirement. For Fourier frequencies around 10 mHz, the length fluctuations of the amplifier limit the differential phase noise. If lower differential phase noise shall be achieved, lower length fluctuations are required.

4. Conclusions

We have investigated two alternative laser systems for the Laser Interferometer Space Antenna (LISA) and we have measured the phase characteristics of two fiber amplifiers for clock noise comparison between spacecraft.

The laser of LISA’s precursor LISA Pathfinder in combination with a fiber amplifier originally designed for a communication terminal and a commercial fiber distributed feedback (DFB) laser both delivered 1 W output power as required by LISA. Within the LISA measurement band from 0.1 mHz to 1 Hz the fiber laser showed power noise up to a factor of 20 above the requirement for the stabilized laser. Using the power actuator of the fiber laser further suppression of power noise should be possible to reach the stabilized LISA requirement.

In comparison to the LISA Pathfinder laser, the fiber laser showed significantly higher frequency noise for Fourier frequencies above 1 kHz, that can possibly impact the LISA phase measurement system. The impact of this frequency noise needs to be analysed in future work.

We have investigated differential phase noise between a carrier and a 2 GHz sideband in two different fiber amplifiers. Both amplifiers used Ytterbium-doped fibers as gain medium and emitted 1 W of output power. The amplifiers showed sufficiently low differential phase noise for clock-noise comparison between LISA spacecraft.

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