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## A New Laser Technology for LISA

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### ABSTRACT

Within the European Space Agency (ESA) activity “Gravitational Wave Observatory Metrology Laser” we designed a laser head to fulfill the LISA laser requirements using a non-NPRO seed laser technology: an external cavity diode laser (ECDL) with resonant optical feedback from an external cavity as master oscillator for further linewidth narrowing. Furthermore, our design features a single-stage fiber amplifier with an amplification factor of about 20 dB. This paper covers the requirements on the laser source for LISA, the design and first results of performance characterization of the laser head breadboard.

**Keywords:** laser, LISA, ECDL, fiber amplifier

### 1. INTRODUCTION

The gravitational-wave detector Laser Interferometer Space Antenna (LISA) [1] has been chosen as the third large-class mission in ESA’s science program to be launched in 2034. The Phase A study of the LISA mission has started in 2018. LISA aims to detect amplitude, frequency, and polarization of low frequency gravitational waves. This will allow to investigate properties of astrophysical objects; e.g. black holes, and to address more general questions, e.g. the state of the universe before the generation of the cosmic micro-wave. The detector will consist of three spacecraft (S/C) forming a triangle with 2.5 million kilometers arm length following the earth around the sun. Each S/C houses two free-falling test masses, two optical benches and two active laser heads. A laser interferometric link is set up between the two optical benches on the opposite S/C and between the optical benches and the assigned test masses on both S/C aiming for the detection of optical displacement variations between the two test masses. Moreover, light is exchanged between the two optical benches on each S/C to reference all three interferometric arms w.r.t. each other. Doing so, all kinds of interferometric combinations of the three interferometer arms can be generated enabling the measurement of the space-time distortion by gravitational waves and analyzing their properties. The displacement requirement on an interferometric arm is

$$S_{\text{link}}^{1/2} < 10 \frac{\text{pm}}{\sqrt{\text{Hz}}} \cdot \sqrt{1 + \left(\frac{2 \text{ mHz}}{f}\right)^4} \quad (1)$$

in the measurement band of  $3 \cdot 10^{-5} \text{ Hz} \leq f \leq 1 \text{ Hz}$  [2].

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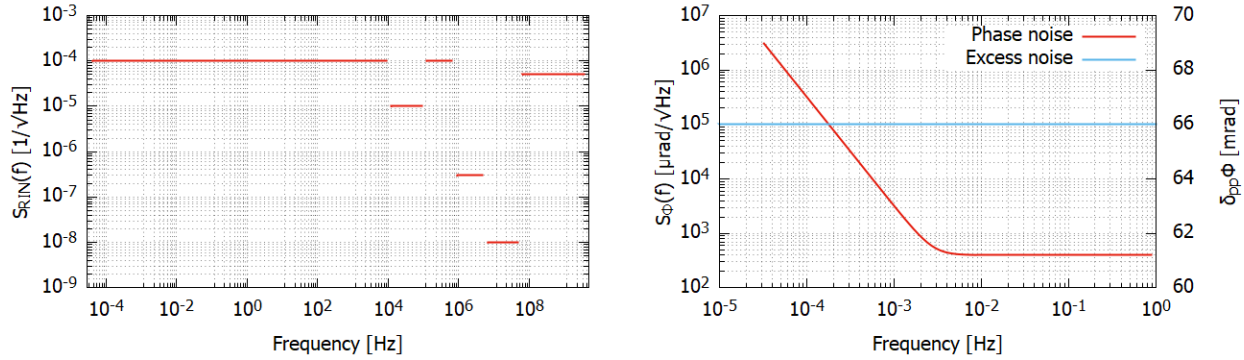


Figure 1 Output power stability requirement (left) and phase sideband noise (right) requirements on the LISA laser.

## 2. LASER REQUIREMENTS

The key specifications of the laser head are an optical output power delivered by a single-mode polarization-maintaining optical fiber onto the LISA Optical Bench of  $\geq 2$  W at a wavelength of 1064 nm, a high frequency stability of the free-running laser of

$$S_v(f) \leq 3.75 \frac{\text{Hz}}{\sqrt{\text{Hz}}} \cdot \sqrt{1 + \left(\frac{8 \text{ kHz}}{f}\right)^2} \quad (2)$$

for  $3 \cdot 10^{-5} \text{ Hz} \leq f \leq 1 \text{ MHz}$ , and for the pre-stabilized laser of

$$S_v(f) \leq 300 \frac{\text{Hz}}{\sqrt{\text{Hz}}} \cdot \sqrt{1 + \left(\frac{2.8 \text{ kHz}}{f}\right)^4} \quad (3)$$

for  $3 \cdot 10^{-5} \text{ Hz} \leq f \leq 1 \text{ Hz}$  and for  $1 \text{ Hz} \leq f \leq 1 \text{ MHz}$  of

$$S_v(f) \leq 3.75 \frac{\text{Hz}}{\sqrt{\text{Hz}}} \cdot \sqrt{1 + \left(\frac{8 \text{ kHz}}{f}\right)^2}, \quad (4)$$

a low relative intensity noise and a phase sideband noise as depicted in Figure 1.

## 3. LASER DESIGN

The main building blocks of the laser head are the seed laser source, an amplifier, light modulation and power stabilization technologies including associated electronics; see Figure 2. Redundant elements are highlighted by dashed lines. The laser is based on a master oscillator power amplifier (MOPA) design with a seed laser as MO and a fiber amplifier as PA. We investigate an extended cavity diode laser (ECDL) with resonant optical feedback by an external cavity as a seed laser and a semiconductor optical amplifier (SOA) providing an optical output power out of the fiber of 300 mW (with 50% derating); see Section a. Various laser types have been investigated as a seed laser source for LISA [3, 4]. To date a non-planar ring oscillator (NPRO) is the baseline for the LISA seed laser. However, an ECDL offers some advantages over the NPRO: a better electro-optical efficiency and – comparing the only NPRO with space heritage to our proposed ECDL – a by an order of magnitude higher optical output power.

A fraction of the seed laser light is tapped off to the laser pre-stabilization system (LPS) to stabilize the laser light in frequency utilizing a reference cavity and the Pound-Drever-Hall locking scheme. An electro-optical modulator (EOM) is located between the seed laser and the amplifier to imprint sidebands to the carrier for inter-satellite ranging, data transfer, and clock-tone transfer via phase modulation. The optical power of the laser light after the EOM is amplified by a fiber amplifier with an amplification factor of 80 (best case) to 154 (worst case) to deliver an optical output power of 2100 mW onto the optical bench; see Section b for details on the fiber amplifier.

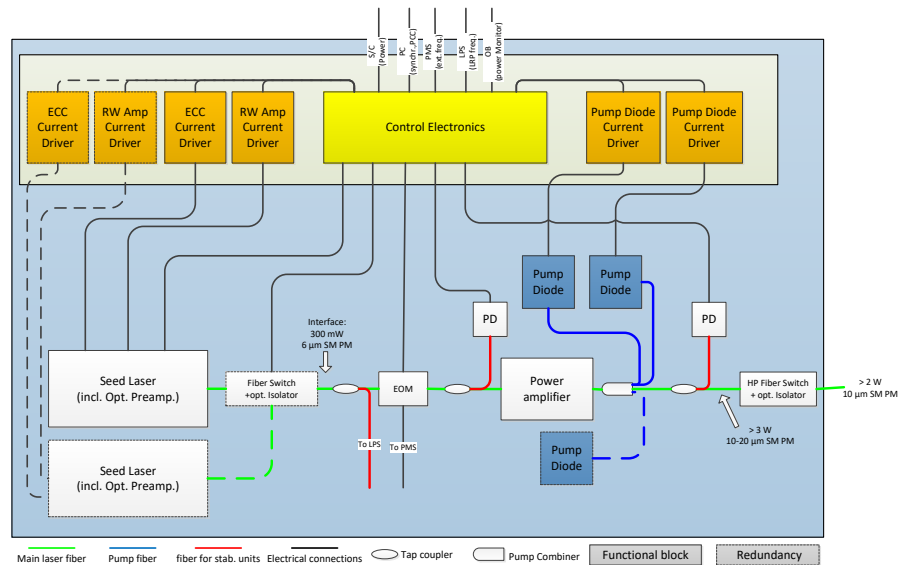


Figure 2 Block diagram of a LISA laser.

Due to time and budget constraints not a single breadboard including all building blocks is set up, but three breadboards: the seed laser consisting of the two breadboards ECDL and semiconductor optical amplifier, and the third breadboard being the fiber amplifier breadboard. All three breadboards were set up independently, but for some test they were operated together. All three breadboards are or will be characterized w.r.t to the requirements. The characterization phase is ongoing. In the following first results are presented.

#### a. Seed laser – design & first measurements

The seed laser schematics is depicted on the left hand-side of Figure 3. The design is based on the concept of resonant optical feedback [5, 6, 7] using diode lasers.

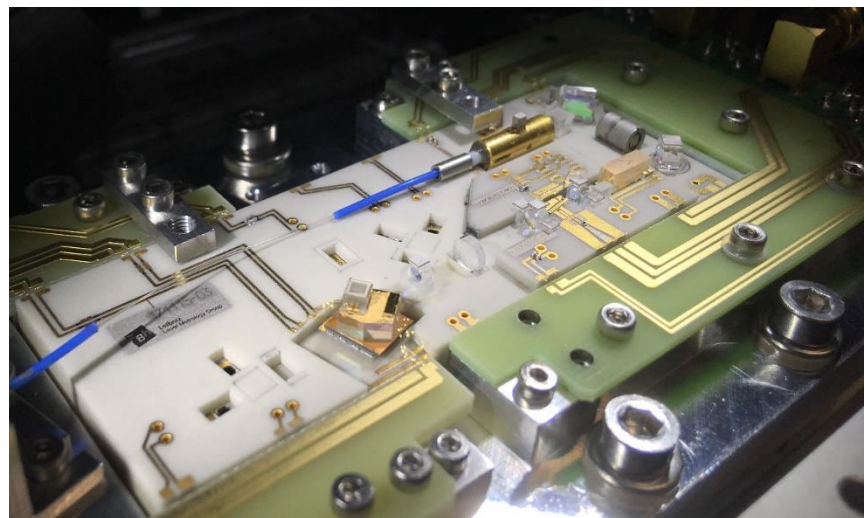
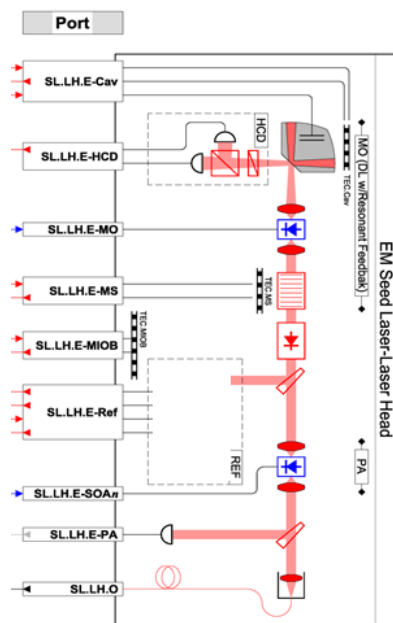


Figure 3 Left: schematic layout of the seed laser, an ECDL with resonant optical feedback. Right: a photograph of the micro-integrated seed laser breadboard during integration.



Diode lasers with resonant optical feedback utilize optical feedback from a separate, external cavity for linewidth narrowing. As the light travels back and forth inside the external cavity before feeding back to the laser chip, this setup effectively implements a very long cavity, but at the same time it avoids problems related to very long ECDL setups. The seed laser uses a volume holographic Bragg grating (VHBG) in conjunction with an unstructured laser diode and an external cavity. Furthermore, it is foreseen to implement a MOPA concept also for the seed laser, where the output of the ECDL with resonant optical feedback, the MO, is (pre-) amplified by means of a power amplifier (PA), a semiconductor optical amplifier (SOA). In this way several hundreds of milli watts of output power will be realized.

In a later implementation all components of the seed laser MOPA are micro-integrated on a common bench. This increases the thermal and mechanical stability of the setup. The current breadboard of the seed laser described in this paper only contains the “ECDL with resonant optical feedback” as micro-integrated part because it uses existing hardware. The SOA breadboard is implemented on a separate breadboard using standard opto-mechanics, see top left in Figure 4. The left graph of Figure 5 shows the optical output power of the SOA delivering up to 550 mW with an injection current of 1 A. The SOA breadboard is operated to deliver an output power 300 mW of at the fiber output as foreseen for later implementation.

### b. Fiber amplifier – design & first measurements

The fiber amplifier basically consists of a gain fiber contra-directionally pumped by three wavelength-stabilized pump diodes to achieve 2.1 W of output power, ensuring proper derating of the diodes. At the fiber exit of the amplified signal a combination of fiber-coupled Faraday isolator and bandpass filter is implemented prior to beam collimation and a tap coupler for power stabilization.

Figure 4 depicts the fiber amplifier breadboard including SOA breadboard and an NPRO ground support equipment (GSE) laser. Its design was optimized for low stimulated Brillouin scattering (SBS) and amplified spontaneous emission (ASE) resulting in a single-stage fiber amplifier with the advantage of limited number of devices and limited complexity.

The right inset of Figure 5 shows the optical output power of the fiber amplifier measured before the final Faraday isolator. The output power is limited by the available optical power of the pump diodes. Taking into account the losses by subsequent optical components; e.g. combined Faraday isolator / bandpass, beam collimator; the output power is well sufficient to deliver the required  $\geq 2$  W onto the optical bench. The beam quality in the vertical axis is  $M^2 = 1.09$  and  $M^2 = 1.18$  in the horizontal axis. A polarization extinction ratio of 24.7 dB was detected after the isolator/bandpass filter. The left graph in Figure 6 shows a first measurement of the relative intensity noise (RIN), also called output power stability.

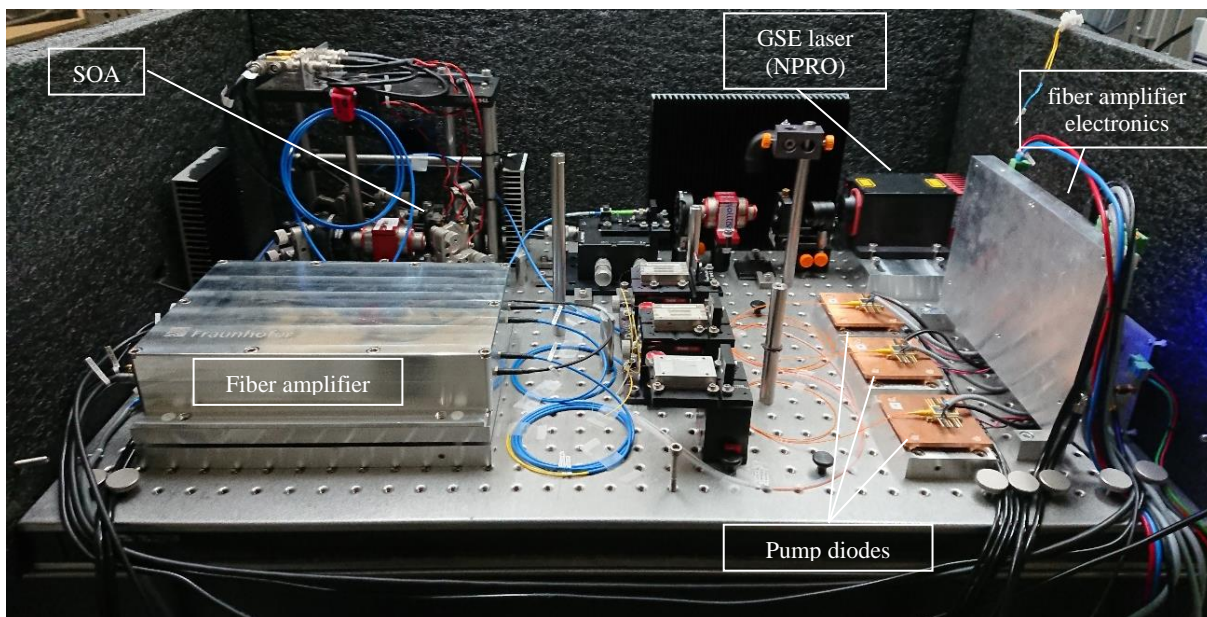


Figure 4 Fiber amplifier breadboard including SOA, fiber components, three pump modules, fiber amplifier electronics, and GSE laser (NPRO).

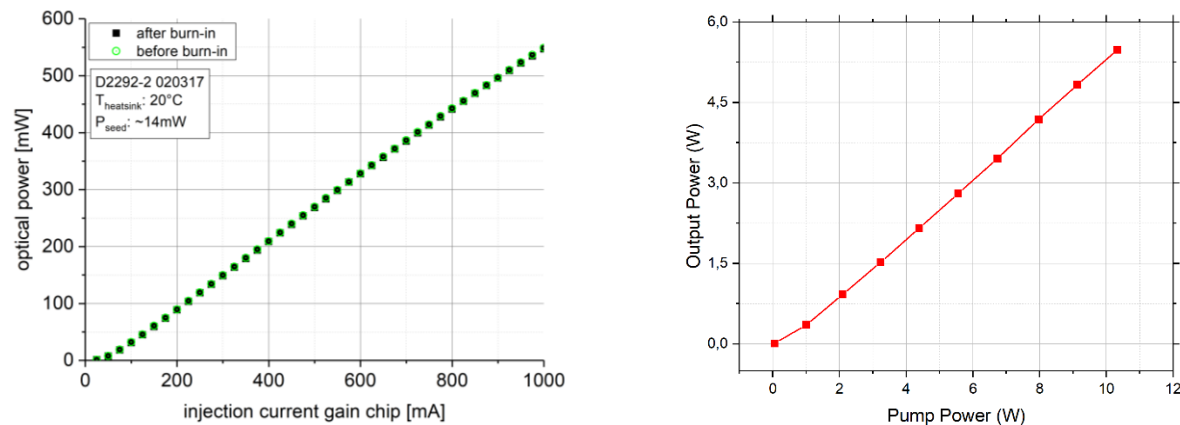


Figure 5 Left: optical output power of the semi-conductor optical amplifier before (green) and after (black) burn-in over injection current of the gain chip. Right: optical output power of the fiber amplifier over optical pump power.

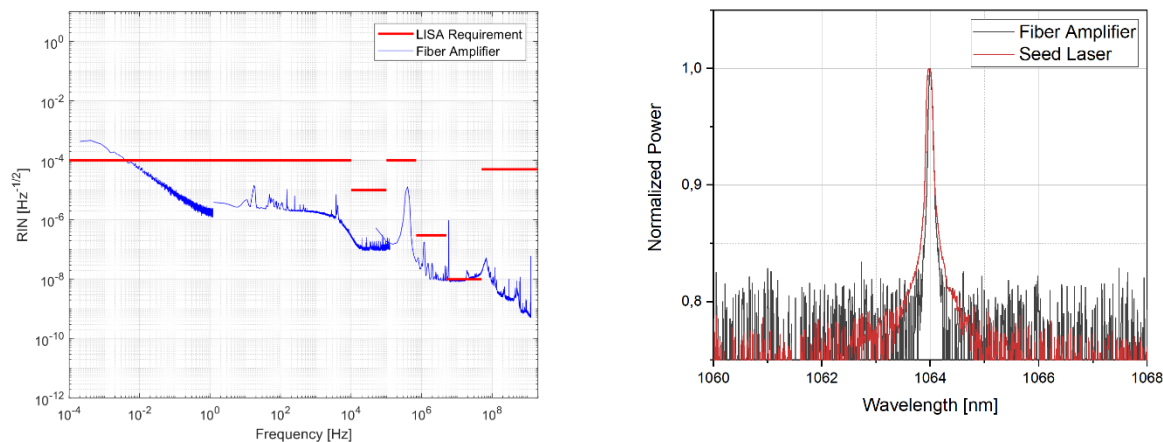


Figure 6 Measurement data of the fiber amplifier. Left: relative intensity noise of the fiber amplifier. Right: spectral linewidth of output light (black) in comparison to input light (red).

Except for frequencies below 3 mHz and for frequencies of a few tens of MHz it is well within the requirement. The right inset of Figure 6 depicts the optical power over wavelength showing that the input wavelength (the one of the seed laser) is not shifted or broadened and that the amplifier runs at a single wavelength.

A measurement of the laser frequency noise is presented in Figure 7. The fiber amplifier does not introduce additional frequency noise. The violation of the requirement around 8 kHz is due to the resonance frequency of the NPRO GSE laser, and the system is shot noise limited for frequencies higher than  $10^5$  Hz.

#### 4. SUMMARY

We presented a design of a laser system for the inter-satellite gravitational-wave interferometer LISA whose general layout is based on previous work and existing specifications [3, 5, 8, 9]. New and different of our approach is the choice of an ECDL concept with resonant optical feedback from an external cavity as a seed laser and the use of a single-stage fiber amplifier instead of a double-stage amplifier. Currently all breadboards are assembled and integrated, the characterization test campaign has started and is ongoing. First preliminary results are shown and demonstrate that the chosen concept can achieve more than sufficient performance for the LISA mission.

#### ACKNOWLEDGMENTS

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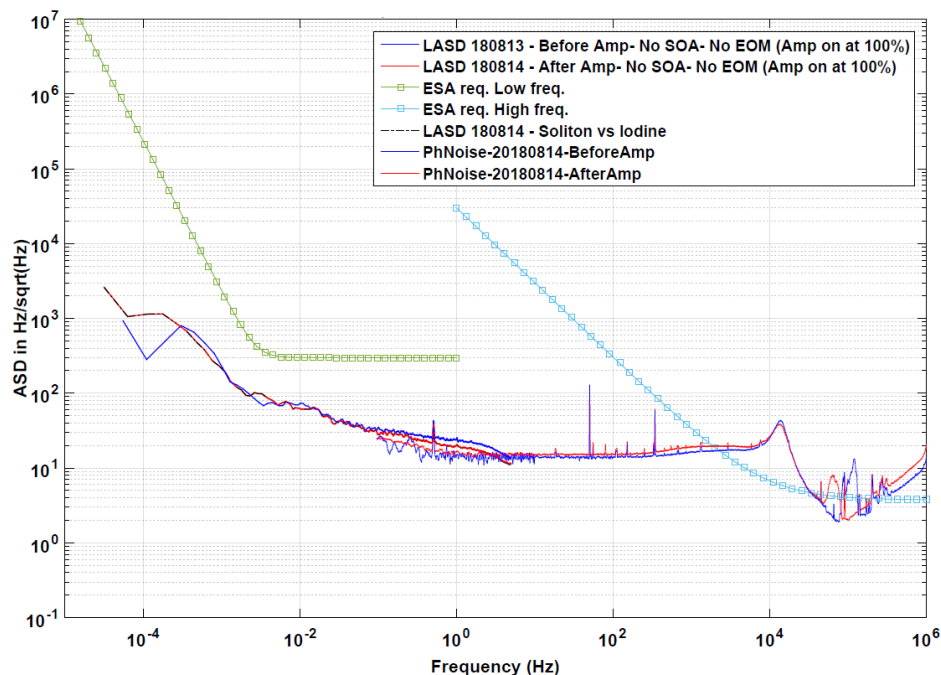


Figure 7 Laser frequency stability measured before (blue lines) and after (red lines) the fiber amplifier. Lines with squares refer to the laser frequency requirement.

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