Development of LISA Laser System at NASA

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ABSTRACT

NASA Goddard Space Flight Center (GSFC) is developing a master oscillator power amplifier (MOPA) laser transmitter for the Laser Interferometer Space Antenna (LISA) mission. The laser transmitter is one of the potential contributions to the LISA mission from NASA. Our development effort has included a master oscillator (MO), a power amplifier (PA), a frequency reference system (FRS), a power monitor detector (PMON), and laser electronics module (LEM). We are working on their design, performance evaluation, environmental testing, and reliability testing for space flight. We have built TRL 4 laser optical modules based on the MO and PA, which meets most performance requirements. One of the TRL 4 laser optical modules has been delivered to ESA for independent evaluation. TRL 6 versions of MO and PA are being built and evaluated at GSFC. TRL 5 and 6 versions of laser electronics are under development. In this paper, we will describe our progress to date and plans to demonstrate and deliver a TRL 6 laser demonstrator system to ESA by 2024.
Keywords: LISA, laser, fiber, amplifier

1. INTRODUCTION

LISA is a proposed space mission to measure gravitational waves from astronomical sources in space [1]. The LISA project was originally a joint effort between NASA and ESA. However, due to funding limitations, NASA once terminated the LISA partnership with ESA in 2011. In 2013, ESA selected "the Gravitational Universe" for its L3 mission slot with an expected launch in 2034. After the direct detection of gravitational waves by LIGO in 2015 [2] and the successful operation of the LISA Pathfinder mission in ~2016 [3], NASA expressed interest in rejoining the mission as a junior partner who provides components to ESA. The laser is one of the possible U.S. contributions to the LISA mission. The laser work in the U.S. officially started around 2018. Since then, the Lasers and Electro-Optics Branch at NASA GSFC has been developing and refining the design of the LISA laser. Currently the TRL (technology readiness level) of the NASA LISA laser is transitioning from 4 to 6. By early summer of 2023, NASA plans to deliver a TRL 6 laser optical module (LOM) to ESA for performance evaluation. The ESA mission adoption review (MAR) is set in early 2024.

LISA consists of three spacecrafts forming an equilateral triangle in space with each of the three arms being 2.5 million km in length. LISA uses a heterodyne laser interferometer to detect picometer-level length variation over the arm caused by the gravitational waves. Each spacecraft contains two reference test masses, to which the spacecraft is controlled by the drag-free control system. Each spacecraft also contains 1 laser system (LS), which is composed of 2 laser assemblies (LAs) and 1 frequency reference system (FRS), which is a highly-stable optical cavity that serves as a laser frequency (thereby length) reference (Figure 1). Each arm is illuminated by the LA, which contains two laser heads (LHs) for redundancy purpose. One of the two LHs in one LA is a cold spare. As a result, there will be 12 LHs in the whole constellation, while 6 of them will be active at any given time. There are 3 FRSs in the constellation. Only one of them is used as a frequency reference at a time (2 are cold spares) to which one of the 6 active LHs is frequency-locked. The other five lasers are offset phase-locked to the reference laser as transponder lasers, acting as an amplifying mirror at the far spacecraft. Each LH consists of a LOM and a laser electronics module (LEM).

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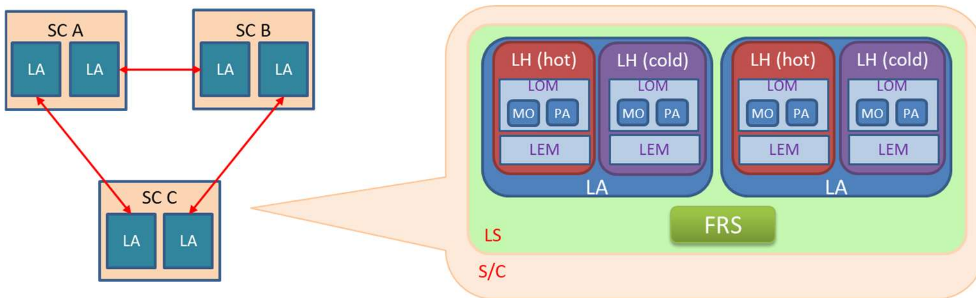


Figure 1: Lasers in the LISA constellation. There will be 12 laser heads (LHs) and 3 frequency reference systems (FRSs) in the whole constellation.

Our current development effort is focused to achieve the TRL 6 laser demonstrator requirements defined by ESA [6]. Table 1 summarizes the TRL 6 LISA laser requirements. There are general requirements, such as size, mass, dissipated power, operating and non-operating temperature ranges, vibration, shock, and radiation. The laser output power shall be over 2 Watt at the optical bench (OB), to which the laser power is provided through a single-mode polarization-maintaining fiber, at the end of life. It is a continuous-wave laser with 1064.5 nm wavelength. Unlike other space lasers, it must have very low frequency noise, low intensity noise, and low RF (radio frequency) sideband phase noise at the same time, not to add length measurement errors through interferometric sensing noise, force noise on the test mass, and clock synchronization noise, respectively. Another unique requirement is the long lifetime. Including testing and integration phase on the ground, cruise phase, nominal science operation phase, and extended science operation phase, 10~16 years of lifetime is required for the LISA laser. Each of the laser subsystems, especially the pump laser diodes, must have high enough reliability or redundancy to meet the unique lifetime requirement.

Table 1: Summary of the key TRL 6 LISA laser requirements [4]. Some values are still not finalized. Noise requirements are shown for a particular Fourier frequency range only for simplicity.

General requirements		**Optical requirements**	
Dimensions	330 x 330 x 250 mm^3	Output power	>2 W on OB at end of life
Mass	12 kg	Operating mode	Continuous wave
Operating temperature	20±5 ºC	Wavelength	1064.50 -0.05/+0.10 nm
Non-operating temperature	-20 ºC to +40 ºC	Polarization extinction ratio	>20 dB
Random vibration (RMS)	Lateral 8.4g Vertical 13.0g	Frequency noise	$S_\nu(f) \leq 30 \frac{Hz}{\sqrt{Hz}} \sqrt{1+\left(\frac{2\,mHz}{f}\right)^4}$ @ 0.1mHz~1Hz
Shock	20g@100Hz 1000g@1kHz 700g@10kHz	Intensity noise	$S_{RIN}(f) \leq 10^{-4} \times \sqrt{1+\left(\frac{2\,mHz}{f}\right)^4}$ @ 0.1mHz~100Hz
Radiation	40krad total ionizing dose	RF phase noise	$S_\phi(f) < 400 \frac{\mu rad}{\sqrt{Hz}} \sqrt{1+\left(\frac{2\,mHz}{f}\right)^4}$ @ 0.1mHz~1Hz

2. LASER OPTICAL MODULE

The baseline optical configuration of TRL 6 LISA laser is shown in Figure 2. It is based on a master oscillator power amplifier (MOPA) architecture with a fiber-coupled EOM inserted between the low-power, low-noise MO and the PA. The electro-optical phase modulator (PM) is required to transmit reference clock information between spacecraft using a phase-modulation sideband at ~2.4 GHz. Without the clock noise exchange, the tiny gravitational wave signal would be buried in the clock noise on the three spacecraft. Such GHz-level phase-modulation can be added only by a waveguide-based EOM, which has an input power limitation of ~400 mW at best with current technology. The fiber-based MOPA laser system naturally overcomes this limitation.

For the LH's internal redundancy, there are two MOs and phase modulators which are cold redundant. One of them is selected by the low power switch (denoted as LPSwich in Figure 2). The "seed" light is amplified by a forward-pumped fiber amplifier. The amplified light goes through the high-power isolator and the high-power tap coupler. The high-power optical switch (denoted as HPSwich) was introduced to turn on and off the laser light quickly without affecting the thermal condition of the spacecraft during the constellation acquisition. The polarizer is needed to compensate for PER (polarization extinction ratio) degradation introduced by the high-power optical switch. These two components may not be installed, because they introduce additional losses and complications to the system and different constellation acquisition schemes are getting more promising.

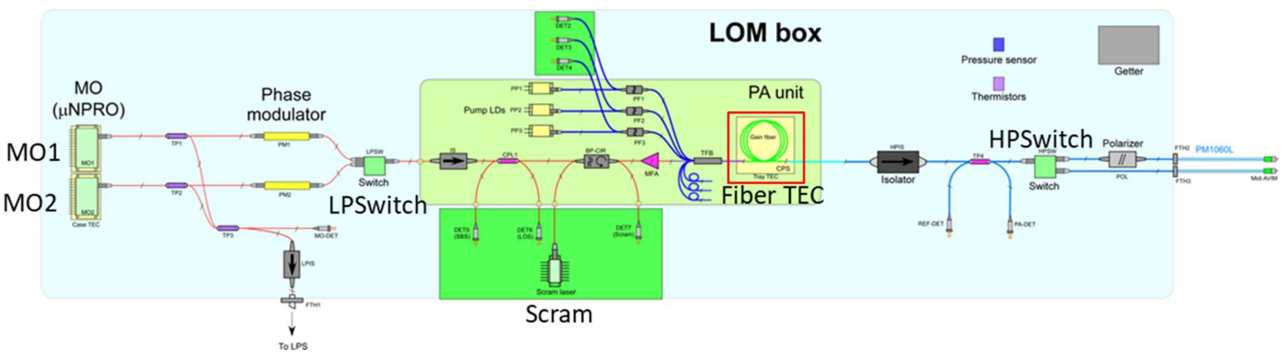


Figure 2: LISA TRL6 laser optical module optical layout.

To prevent the amplifier from catastrophic damages, especially unexpected lasing, multiple protection mechanism will be installed. They include the "scram" laser which quickly turns on and extracts any excess optical gain from the gain fiber when the seed power is lost, and the fast pump shutdown mechanisms when the loss of seed or the backward lasing is detected by the monitor photodiodes.

To extend the lifetime, each MO has two 808-nm pump single-mode diodes which are hot redundant. They are both operated at ~1/3 of their maximum operating current for derating. The PA uses three 976-nm multimode fiber-coupled pump diodes which are cold redundant. They are operated at ~1/4 of their maximum operating current. Each PA pump laser diode has three internal emitters.

Since the MO has enough output power to seed the single-stage PA, this design does not involve a "pre-amplifier" stage. While the single-stage design reduces numbers of electro-optical components and the overall system complexity, we are keeping an option to split the PA stage into two as a back-up option, in case unexpected issues arise over the long term. The typical input power to the amplifier is 80 mW in the current single-stage design. The MO needs to emit ~160 mW of optical power in this case, and the phase modulator must withstand against such high input power level over long term (~10 years) operation with minimal degradation.

Figure 3 shows the TRL 6 LOM mechanical design. We adopted a "clamshell" design where two slices are built separately and put together at the end of the build. The MO slice and the PA slice can be built separately, allowing for a streamlined build process. The LOM enclosure is pressurized by double O-rings and hermetic connectors. This is because most of fiber optics components, especially the PA's pump diode and high-power components, are not hermetically sealed. The LOM enclosure will be purged and positively pressurized slightly above the atmospheric pressure with clean dry air during the build. The internal pressure will be monitored continuously during the environmental tests and long-term life aging tests. These procedures have been adopted in other space lasers we have built and flown.

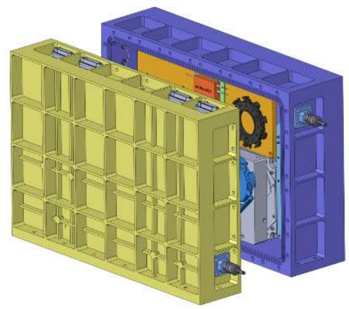


Figure 3: LISA TRL6 LOM mechanical design. Left: MO slice, right: PA slice.

2.1 Master oscillator

As for the MO, we have identified a NPRO (non-planar ring oscillator) [5] as the most promising architecture for its lowest noise and simplicity, while we also looked into semiconductor laser architecture initially [6]. We have invested in a small NPRO design, denoted as micro NPRO (µNPRO), to satisfy the stringent LISA MO requirements. The µNPRO is designed and built by AVO Photoncis under supervision from GSFC and Tom Kane, the original inventor of NPRO laser.

Figure 4 A) shows the internal design of the TRL 6 µNPRO package. Since our earlier TRL ~4 work, the TRL 6 design has been significantly improved. The TRL 6 µNPRO package is hermetically sealed with internal getter, similar to a commercial hermetically sealed butterfly laser package. We use two types of flux-free solders wherever possible to minimize slow drift of components. The package is mechanically stiffened to avoid misalignment due to package distortion. The µNPRO crystal has been redesigned to have a lower threshold, stable beam size, higher fiber coupling efficiency, and higher PZT (piezoelectric transducer) frequency tuning efficiency [7].

Following the updated build procedure and material, about 7 EMQ (engineering model, qualification) µNPRO packages have been built and tested (Figure 4, B) so far. It has passed all space qualification tests, such as radiation, shock, vibration, and temperature cycling. The 808-nm pump laser diode has been life-aging tested at the vendor (Eagleyard/TOPTICA optics) at CoS (chip on submount) level, and at GSFC at the pump-subassembly level. Figure 4 C) shows the output power of the µNPRO EMQ model. It emits >300 mW output power in fiber with low frequency noise and drift. This are realized by the small crystal design and the precise package temperature control.

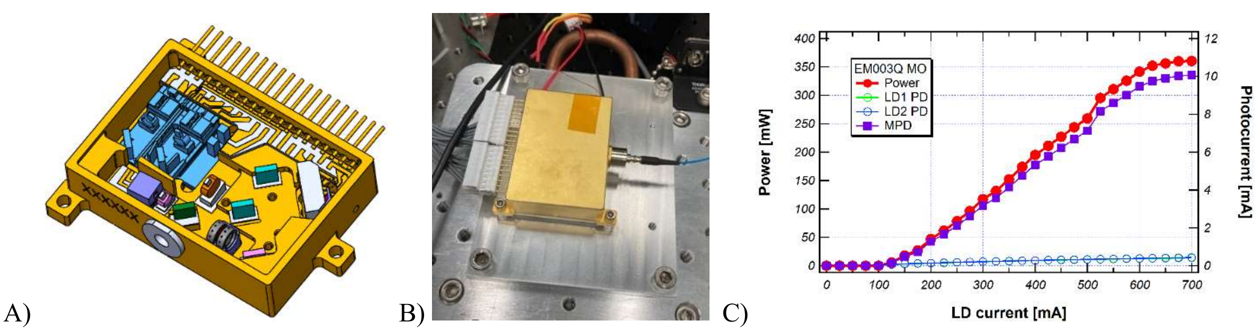


Figure 4 A) Internal design of the TRL 6 µNPRO package. The fiber coupling assembly is not shown. B) Completed EMQ µNPRO package under test. C) Output power of EMQ µNPRO package. Photocurrents of internal photodiodes are also shown on the right axis.

2.2 Power amplifier

The PA is a forward-pumped fiber amplifier with 10-µm double-clad Yb gain fiber. The PA module is built by Fibertek. Figure 5 A) shows the mechanical design of the TRL 6 PA. It is based on a spaceborne laser communication terminal for 1-U Cubesat. Compared to the earlier TRL ~4 units delivered by 2021, the new design has been improved both mechanically and optically. For example, the scram laser is coupled into the core of the gain fiber for more efficient gain extraction. Seven additional optical monitoring channels were added for better characterization and to prevent the amplifier from damages. The 976-nm pump laser diode vendor was changed to Coherent/DILAS. The same pump laser diode has been adopted for other space missions and qualified from multiple perspectives. An EMQ-version of the PA unit has been built and tested at Fibertek and at GSFC. All components in the amplifier have been tested and characterized before and after thermal cycle and vibration. The EMQ PA unit has also passed vibration test at 18.5g rms, storage and operational temperature tests, and basic performance tests. Long-term testing of the amplifier is starting both at the component level and at the unit level.

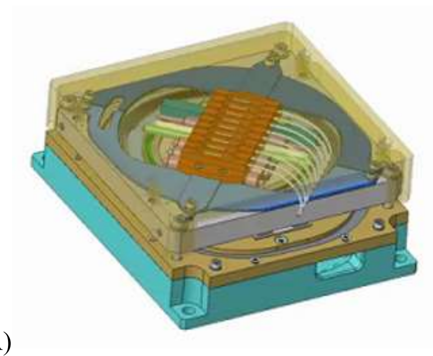
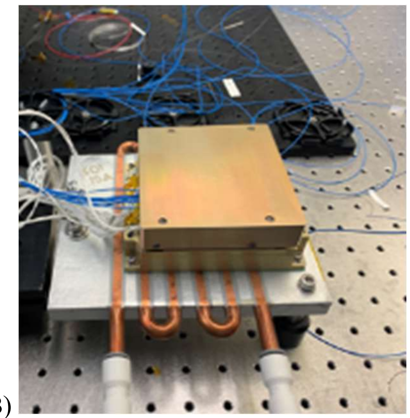
A) 
B) 

Figure 5 A) TRL 6 PA package mechanical design, B) delivered EMQ PA unit.

RF sideband phase noise added by the PA is a key parameter for the LISA laser. It directly affects the LISA's science performance since the phase noise limits the ability to synchronize reference clocks in the three spacecrafts. Because the exact origin of this noise is not well understood, we have started a dedicated experimental work at GSFC and a theoretical investigation at University of Illinois Urbana-Champaign. Figure 6 A) shows the GSFC setup to measure the RF sideband phase noise of the PA and/or MOPA. The noise floor of the measurement system has been improved by temperature stabilizing all components, including RF electronics, and by thermally isolating everything from the room temperature fluctuation. Figure 6 B) shows example measurement results of different fiber amplifier modules. We realized that it may be difficult to achieve the original phase noise requirement, which is simply allocated from 1 pm/√Hz length noise, and that slight uncontrolled differences can contribute to the excess phase noise. To capture the excess phase noise at as early a stage as possible during the build process, we are duplicating the measurement setup for use at multiple locations, including Fibertek and the SLAC (Space Laser Assembly Cleanroom, a GSFC's clean room dedicated for space laser assembly). At the same time, we are exploring different optical configurations to reduce the excess phase noise level. We are also investigating the possibility of re-allocating the requirement in the system-level noise budget with a different frequency dependence to better accommodate the measured laser system's performance.

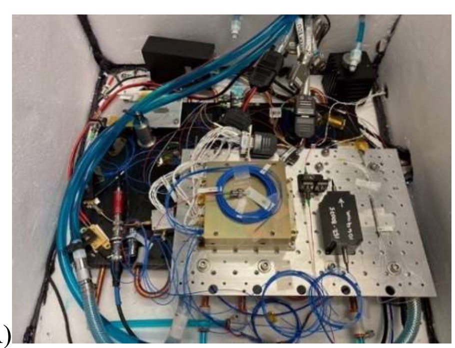
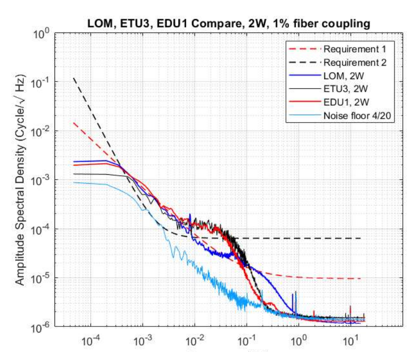
A) 
B) 

Figure 5 A) RF sideband phase noise measurement setup at GSFC, B) Measured RF sideband phase noise of different amplifier units.

2.3 Other MOPA components

We selected other MOPA components with previous space flight heritages as possible. They included fused fiber couplers, monitor photodiodes, pressure sensor, and getters. Some other components do not have enough qualification data, are subjected to appropriate qualification processes at GSFC for LISA and future space applications.

For example, the high-power isolator at the output end is a custom product with higher magnetic shielding to achieve the magnetic cleanness requirement. Our DPA (destructive package analysis) shows some concerns with its internal structure. We are thus looking into other designs with low residual magnetic field. We have worked with a different vendor and achieved very low magnetic field leakage by arranging magnets around it to cancel the far magnetic field. For the TRL 6 LOM box, we plan to use a ~5 GHz phase modulator that has been tested at high optical power and at high temperature and qualified for space use. A similar modulator with narrower bandwidth has been used in the GRACE Follow-on reference cavity and will be used for the LISA FRS as well (mentioned later). The low power switch is unique to our design with the redundant MO. We are working with a vendor to address issues identified by our DPA, to test different switch types, and to develop a hermetic version of it for higher reliability and robustness. At this moment there is no commercial high-power switch that meets all LISA requirements. While we are working with ESA to develop a custom space-qualifiable high-power switch, involving multiple vendors, we are hoping to remove this switch as it introduces too many complications for the entire LH.

2.4 TRL 4 Prototype LOM at CSEM

On May 2021, we shipped a TRL 4 prototype LOM to CSEM (the Centre Suisse d'Electronique et de Microtechnique), an independent laboratory chosen to evaluate the laser for ESA. Figure 6 shows the TRL 4 LOM system sent to CSEM. The LOM was driven by commercial electronics and custom software written in LabVIEW. While the CSEM group successfully confirmed many of the performance parameters, they observed larger RF sideband phase noise, which was overlooked by GSFC due to an inappropriate pre-ship measurement. They also experienced a total loss of power event after ~6000 hours of operation. The root cause of this is thought to be a degraded seed power, which resulted from a long-term photorefractive damage within the phase modulator. It resulted in an eventual unexpected lasing of the PA leading to a PA damage. The phase modulator used in this TRL 4 had never been evaluated for a long term under the high (~160 mW) optical input power. To analyze the damage mechanism, and to repair the LOM back to a fully functioning unit, the TRL 4 laser was sent back to GSFC recently. Our current plan is to send it to CSEM again with a different phase modulator (same as TRL 6 design) installed. Some other upgrades will be performed to improve the performance, especially the RF sideband phase noise, and to prevent this kind of catastrophic damage. The details of the TRL 4 LOM system and the evaluation results are presented by the CSEM team in this Journal [8].

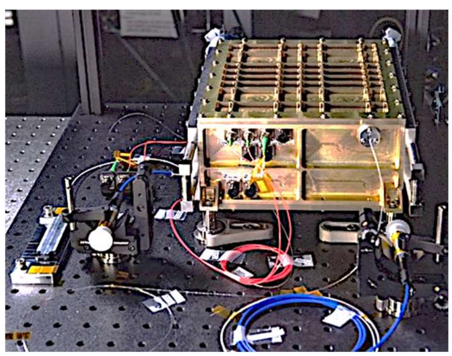


Figure 6: TRL 4 LISA laser LOM sent to CSEM. The unit came back to GSFC from CSEM for failure analysis and repair operation.

3. LASER ELECTRONICS MODULE (LEM)

The GSFC's Electrical Engineering Division is taking a lead in LISA TRL 6 LEM development. Each LH has 1 LEM, which consists of 5 cards: LPDC (laser power distribution card), LFPDC (laser FRS power distribution card), CTC (command and telemetry card), MOCC (master oscillator control card), and PACC (power amplifier control card) (Figure 7). The PDCs and CTC are being designed based on previous space electronics. The PDCs convert the spacecraft's 50V DC input to other required DC voltages for the other cards. In our design, the FPGA on the CTC will not require much computational power, since most controllers are based on low-noise analog circuits instead of digital signal processing. A radiation-hardened FPGA with moderate size has been selected for this reason. We have multiple versions of TRL 4 MOCC and PACC. A TRL 5 version of them is being designed based on the laboratory prototype circuits, considering direct flight parts replacements and parts availability. Redundancy of each connection to the spacecraft, LOM, and PMON, is an important topic for the system reliability. We are having active discussions with ESA and other partners to finalize the interfaces between subsystems. Our current plan is to have a TRL 5 breadboard LEM by the end of 2022, and a TRL 6 demonstrator LEM by the end of 2023.

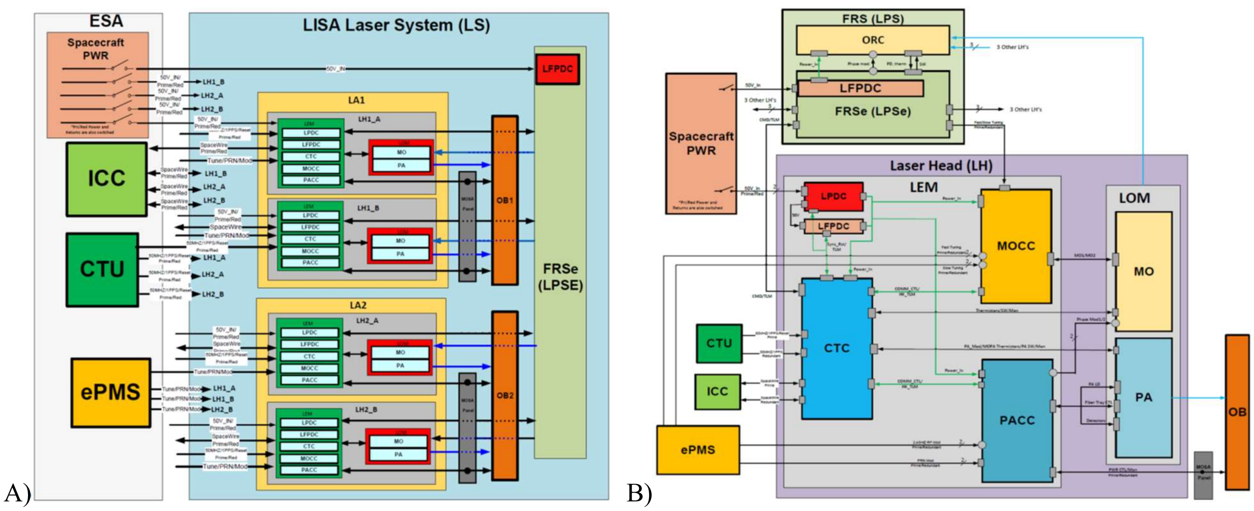


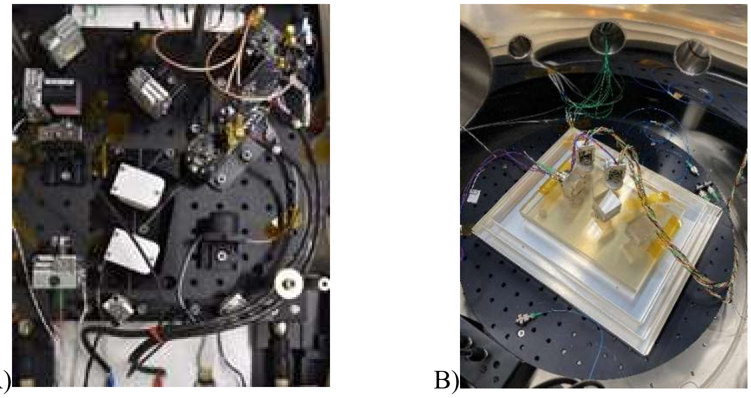
Figure 7 A) LS LEM connection diagram. B) LH LEM connection diagram. ICC: instrument control computer (or on-board computer, OBC), CTU: central timing unit, ePMS: enhanced phase measurement system, OB: optical bench. These figures represent how each subsystem is connected and how their redundancies have been treated.

4. FREQUENCY REFERENCE SYSTEM (FRS)

The FRS, which consists of a high finesse optical reference cavity (ORC) and electronics (FRS-E), will be used in concert with the MOPA laser to achieve low frequency noise requirement. The ORC will be an improved version of the GRACE-Follow-On's cavity, which is in orbit and is working at thermal-noise limited performance [9]. It was built by Ball Aerospace under JPL management. The LISA study office funded Ball Aerospace to improve the ORC design, especially the robustness against thermal drift. GSFC will be working with Ball Aerospace to develop a TRL 5 and TRL 6 LISA FRS (including FRS-E). The improved opto-mechanical design will be used for the LISA FRS. A TRL 6 version of FRS will be tested at GSFC and be sent to ESA for performance evaluation in 2024.

5. POWER MONITOR DETECTOR (PMON)

The PMON is used to achieve the relative intensity noise requirement of ~100 ppm/√Hz at the LISA's main observation frequency band. The PMON is located on the Optical Bench (OB), and it measures the optical power illuminating the LISA's test mass precisely. The information is used to control the laser output power through a low-noise servo loop and the amplifier's pump current driver. While the PMON is located on the OB, far from the LH, it is now part of the GSFC deliverables. In the latest OB design, there are two PMONs per OB, which serve as in-loop and out-of-loop detectors to control and monitor the laser power, respectively. A TRL 3/4 PMON system was built (Figure 8, A), and has been sent to CSEM for performance evaluation. For the TRL 6 PMON development, the performance test setup was upgraded (shown in Figure 8, B). The setup uses a Zerodur mockup optical bench and multi-layer thermal shields in vacuum to minimize long-term power measurement errors as possible. The setup is confirmed to have enough stability to achieve the 100 ppm/√Hz requirement at the LISA's frequency band. We are in discussions with ESA and the OB group to define the requirements and specifications, and also meeting with multiple possible vendors to acquire space-qualifiable large area photodiodes. A device test bench has been designed and is being set up at GSFC, based on our experiences with previous photodiode qualification activities for other space missions.



A) B)

Figure 8: A) TRL 4 PA intensity stabilization setup with TRL 4 PMON. B) Mock-up Zerodur optical bench for TRL 6 PMON development.

6. RELIABILITY

As a reliability activity, we are performing component-level analysis and testing, and theoretical analyses. They include functional testing, environmental testing (radiation, vibration, temperature cycle), magnetic field testing, DPA, and life aging tests. Special attentions have been paid for the long-term life aging tests of pump laser diodes in the MO and PA.

The MO’s pump diodes went through two sets of 5000-hour tests at a high stress level. Each sample size was 20. The pumps are also tested at the pump submount level at low-to-mid stress level. Our conclusion so far is that there will be no failure due to the gradual degradation (1 dB power loss) during the mission as long as the diode is de-rated as planned. Since we need more data to evaluate the lifetime, especially sudden death, and wafer dependencies, more tests are being planned and will be performed in an improved setup to remove any ambiguity existing in our previous test setups.

The PA’s pump laser diode has been tested for other space missions. We are repeating the tests at relevant operating conditions for LISA. At the same time, the same pump laser diode is being tested by ESA at a high stress level under vacuum, and the reliability information have been actively exchanged. Our upcoming activities include LOM-, LEM-level life aging, additional component testing, especially under high power for the phase modulator and PA’s output optics, and long-term non-operating condition tests.

7. DEVELOPMENT SCHEDULE

Currently the TRL 6 demonstrator LOM is on target to be delivered to ESA early summer 2023. The first EMQ LOM will be built by the end of 2022 and environmentally tested by early 2023 for TRL 6 qualification. The LEM development faced some contractual delays initially and is now catching up under the direct GSFC management. The first set of TRL 6 LEMs is scheduled to be built late summer of 2023, and to be sent to ESA early 2024 after functional and environmental tests. The FRS development was also delayed due to contractual delays with Ball Aerospace, which have since been resolved. We expect to receive the first ORC by the end of 2023 and FRS-E by mid 2024. The design and development of flight models (FMs) will be conducted in parallel to these activities.

8. SUMMARY

Our on-going LISA laser development activities are designed to meet the requirements per ESA’s TRL 6 laser demonstrator requirements document. Our near-term goal is to deliver a TRL 6 LH which meets form, fit, and functionalities to ESA by mid 2024. Since 2018, we have continued the LISA laser development and have made key advancements to improve performance and reliability. The μNPRO MO is the most innovative component within the overall LH design. It has been improved significantly and has passed all environmental tests with improved optical performance. The lessons learned from the TRL 4 LOM module, especially the issues identified by CSEM independently during long-term operation, will be fully incorporated into the TRL 6 LOM LEM designs. We are performing performance and environmental tests, paying special care to some performance areas, such as RF sideband phase noise and relative intensity noise. The LISA mission is unique and most challenging in terms of laser performance, which requires ultra-low noise laser systems, and long life-time. We chose the MOPA architecture and have been developing technologies to meet these challenges. Our laser design was also independently assessed by the NASA Engineering and Safety Center [10]. We continue to perform and monitor life aging tests of components, subsystems, and laser system. Multiple reliability analyses are ongoing to demonstrate lifetime of the laser using available test data as possible. The NASA laser team continues to expand to meet growing challenges and expanded responsibilities to deliver the LISA laser as a U.S. contribution.

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