Technology Readiness Advancement of the Laser Transmitter for the LISA Mission

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Abstract: We report on the design philosophy, technology readiness level advancement for space application, laser performance verification, and independent assessment of a single frequency, ultra-low noise master oscillator power amplifier laser transmitter for the LISA mission.

1. The LISA Mission

Since 2017, NASA Goddard Space Flight Center (GSFC) has been actively developing and refining the design of a master oscillator power amplifier (MOPA) laser architecture to meet the stringent performance and packaging requirements for the Laser Interferometer Space Antenna (LISA) mission. A highly stable and robust laser design is a key subsystem to the LISA observatory. LISA was selected to be the European Space Agency's (ESA) third large-class mission and will be the first space-based gravitational wave (GW) observatory to address the science theme of the Gravitational Universe. The LISA observatory consists of three spacecraft separated by 2.5 million km in a triangular formation, following Earth in its orbit around the Sun. Launch is expected in 2035 [1].

LISA consists of three spacecrafts (S/C) forming an equilateral triangle in space where the sides of the triangle, also called LISA's "arms" are ~2.5 million km. LISA uses a heterodyne laser interferometer to measure picometer-level length variation along each arm at 1000-sec timescales. Each spacecraft contains two drag-free test masses, to which the spacecraft follows in drag-free mode. The length variation between the free-floating test masses in each spacecraft is monitored precisely to observe the passage of the GWs, which are generated, for example, by mergers of super-massive black holes. NASA continues to collaborate with ESA, with the laser transmitter being one of the potential contributions to the LISA mission.

2. Laser Architecture

A metric used by NASA to evaluate the space worthiness of a system is by assessing the technology readiness level (TRL) at different technology development phases [2]. We followed a similar approach for the laser transmitter we designed for the LISA mission. We selected a MOPA architecture based on the ESA performance requirements for the laser transmitter. Figure 1 shows the MOPA laser schematic.

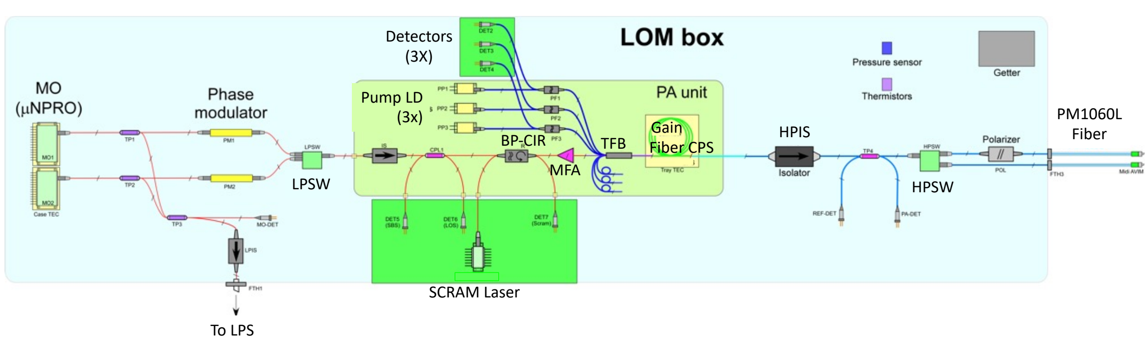

Figure 1. Schematic of the GSFC LISA laser LOM.

The MOPA laser, which also is known as the laser optical module (LOM), consists of a master oscillator (MO) laser source (the 'seed'), a power amplifier (PA) for power scaling, and a phase modulator (PM) for imprinting clock noise transfer, ranging, and data information on the main laser carrier. Two MOs are in our design for full redundancy to meet the lifetime requirement. Each MO has a PM, which is an electro-optical phase modulator (EOM) within the optical path to transmit reference clock information between spacecrafts using the phase-modulation sideband at ~GHz. Without the clock noise transfer (exchange), the small gravitational wave signal would be buried in the clock noise on the three spacecrafts.

The MO is based on the monolithic, Nd:YAG nonplanar ring oscillator (NPRO) crystal design demonstrated by Kane and Byer in 1985 [3], and scaled down from the original size which we designated as the µNPRO.

The power amplifier is a single frequency, forward-pumped Ytterbium-doped fiber amplifier. The MOPA laser is required to deliver a 2-Watt optical power to the optical bench (OB) on the LISA observatory throughout the mission [4].

The LOM is driven by the laser electronics module (LEM) and also interfaces with a Frequency Reference System (FRS). The FRS consists of a high finesse optical cavity that has space flight heritage and will be used in concert with the MOPA laser to achieve the low frequency noise requirement. A power monitor detector (PMON) located on the OB will be used to reduce the relative intensity noise (RIN) of the MOPA laser.

We have built TRL 4/5 LOM modules based on the MO and PA, which meet most of the performance requirements. We have completed the design of a TRL 6 demonstrator LOM and LEM and are prepared to build the engineering model to go through environmental qualification tests to advance the TRL to 6, a critical step toward the LISA launch in 2035.

3. Independent Assessment of the LISA Laser Design

As part of the laser development process, we requested support from the NASA Engineering and Safety Center (NESC) to independently assess the technical approach of the GSFC laser system (LS) design. The independent assessment included the following tasks: (a) assess the LS design for weaknesses and suggest improvements to mitigate risks, (b) assess the LS reliability plan for weaknesses and suggest improvements to mitigate risks and improve effectiveness, and (c) assess the current redundancy plan on LS subsystems for weaknesses and suggest improvements to mitigate risks and improve effectiveness. The NESC team comprised of a team of subject matter experts (SMEs) and performed a 12-month review of every aspect of the LS design.

In summary, the overall NESC team's assessment conclusion is that there is no fundamental problem or major design issue that will prevent the GSFC LISA team from meeting the ESA requirements for the TRL 6 demonstrator. The findings showed the GSFC LISA team has established a technically sound risk mitigation plan, but recommended a few areas that will need further consideration, including: (1) several design alternatives to improve performance and reliability; (2) improve tracking of requirements and hardware configuration in the LS subsystems to ensure that the design closes; (3) testing protocols for components and subsystems needs to be developed (e.g., functionality, aging, thermal, radiation, etc.) to ensure required measurements are made and that the design is not affected; and (4) flight components lead times and obsolescence may affect the design's viability in the future. All these are being considered as the laser team continues the maturation of the laser for the LISA mission.

4. Conclusions

GSFC has been developing the laser transmitter for the LISA mission since late 2017. We are working on advancing the LISA laser system to TRL6 by mid 2023. The NESC assessment on our technical approach was mostly positive. We acknowledge the review team's recommendations and have incorporated them into the flight laser development effort.

5. References

[1] https://sci.esa.int/web/lisa; https://lisa.nasa.gov/.
[2] https://www.nasa.gov/seh/appendix-g-technology-assessmentinsertion.
[3] Kane, T.J. and R.L. Byer, Opt. Lett, Vol.10, (1985) p.65.
[4] Numata, K., et al., to present at the International Conference on Space Optics (ICSO) 2022, 03-07 Oct 2022, Dubrovnik, Croatia.