Independent Reliability Assessment and Progress Review of the NASA GSFC Laser Transmitter for the LISA Program

Anthony W. Yu, Kenji Numata
NASA Goddard Space Flight Center, Greenbelt, MD USA

Upendra Singh
NASA Engineering and Safety Center, Hampton, VA USA

ABSTRACT

NASA Goddard Space Flight Center (GSFC) has been actively developing the laser transmitter for the Laser Interferometer Space Antenna (LISA) program since the late 2017. In 2021 we delivered a prototype laser transmitter to the LISA program for performance evaluation as well as performed an independent technology assessment on the laser design supported by the NASA Engineering and Safety Center (NESC). We continued to further develop the LISA laser with a goal of advancing the technology readiness level (TRL) of the laser to 6 by the end of 2023. In this paper, we report on the progress we made on the laser development for the LISA program as well as the technology assessment findings by the NESC.

Index Terms— space instrument, laser interferometer, gravitational wave observatory, solid state lasers, fiber amplifier, ultra-stable laser, space laser

1. INTRODUCTION AND LASER REQUIREMENTS

The Laser Interferometer Space Antenna (LISA) observatory was selected to be the ESA third large-class mission and will be the first space-based 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 2037 [1]. NASA is developing laser transmitters as one of the potential US contributions to LISA. The NASA laser design leverages latest technologies in photonics packaging and reliability engineering to ensure a laser lifetime of >16 years covering integration and test through a possible extended mission phase.

The LISA observatory consists of three spacecraft (S/C) as shown schematically in Figure 1. Each S/C carries one laser system (LS). The LS is made up of two laser assemblies (LA) and each LA has two laser heads (LH) as shown in Figure 1. Only one of the two LHs in an LA will be on at any one time for the mission. The other LH is a cold spare to meet the mission lifetime. Each LH includes a laser optical module (LOM) and a laser electronics module (LEM). The LH enables the interferometric sources for the LISA mission. LISA will use a heterodyne laser interferometer to measure picometer-level length variation between the spacecraft 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.

Figure 1. LISA Observatory.
The GSFC baseline LOM takes on the master oscillator power amplifier (MOPA) architecture that comprises a low-power, low-noise master oscillator (MO) followed by a power amplifier (PA) stage with a nominal output power of ~2 W throughout the mission. Our effort includes advancing the laser from the breadboard concept to space qualified demonstrator in preparation for the LISA mission. In the following sections, we describe the progress on the laser development effort for the LISA mission and plans to demonstrate a TRL 6 [2] LISA laser demonstrator system by 2024. The top-level requirements for the LISA LH are shown in Table 1. [3]

Table 1. Top-level LISA laser requirements.

- Dimensions 330 × 330 × 250 mm³
- Mass 12kg
- LH dissipated power <75W (TBR)
- LH operating temperature 20±5°C (TBR)
- LH non-operating temperature -20°C to +40°C (TBR)
- LOM Output Power >2W on optical bench (OB) at end of life (EoL)
- Wavelength 1064.50, -0.05/+0.10 nm
- Polarization extinction ratio (PER) >20dB (TBC)
- Lifetime >16 years
  - 6 years - 1 year for on-ground integration and testing, plus 5 years (TBC) of storage
  - 1.5 years TBC OFF state in operational environment (cruise phase)
  - 5 (TBC) years continuous operation in nominal science mode (nominal mission lifetime)
  - 11 (Goal) years continuous operation in nominal science mode (extended mission lifetime)

The wavelength selected for the precision interferometer is 1064 nm due to availability of high-quality bulk and fiber optic components with extensive flight heritage and the traditional low-noise Nd:YAG laser source implemented as an NPRO (non-planar ring oscillator) [4]. The available laser power sets a shot noise limit on the detection sensitivity of the gravitational waves at the high frequency end of the detection band (>~10 mHz). In addition to the standard requirements for mass, power, radiation hardness, and other requirements as a space laser, the most challenging requirements are set by the low frequency noise (that requires active stabilization using a high finesse optical cavity), by the low intensity noise (that requires active stabilization at low Fourier frequency and shot-noise-limited performance at high Fourier frequency), and by the long lifetime (~16 years including integration, test, and cruise phases). The GSFC LISA laser has been designed to satisfy these unique requirements.

2. BASELINE LASER ARCHITECTURE

The main optical output of the MOPA laser is a linearly polarized, continuous wave (CW) laser beam. This beam is sent to the optical bench (OB) of the instrument via a PM1060L polarization maintaining optical fiber (PMF). In a baseline operating mode, one of the 6 active lasers is frequency-locked to a high finesse cavity, which is designed as the Frequency Reference System (FRS) shown in Figure 1, as a master laser for the rest of the system, while the other five active lasers are offset phase-locked to the master laser as transponder lasers, acting as an amplifying mirror at far spacecraft. The laser is frequency-locked to an optical reference cavity that is the main function of the FRS. In each of the MO path inside the LH, a tap coupler is used to provide input to the FRS for frequency locking. The LOM also includes a high-power optical switch (HPSW) after the high-power output isolator (HPIS) for turning the laser output either to the distant S/C for normal operation or to deep space during the S/C acquisition. This allows the laser to remain in a constant thermal state throughout the mission life. The functionalities and key features of key subsystems within the LOM and nominal power levels are shown in Figure 2 [5,6].
The MOPA laser consists of a MO laser source (the ‘seed’), a PA for power scaling, and a Phase Modulator (PM) for imprinting clock noise transfer, ranging, and data information on the main laser carrier. Each MO has a PM, which is an electro-optical phase modulator (EOM) within the optical path to transmit reference clock information between spacecraft 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 spacecraft. Practically, GHz-level phase-modulation can be added only by a waveguide-based EOM, which is known to handle less than ~200 mW of optical power.

The LEM interfaces with the LOM and the payload computer as shown schematically in Figure 3: (a) LH drive electronics (LHDE) provides the main control of the laser system, e.g., coarse setting of the laser power and frequency, as well as health monitoring; (b) LH frequency control electronics (LHFC) processes the control signal for coarse frequency setting signal and the external/pre-stabilization frequency change commands; (c) LH laser modulation control electronics (LHMC) accepts modulation waveforms from the frequency distribution system (FDS), and applies them with appropriate modulation index (amplitude) to the laser light. The LHMC may also accept phase modulation required for the Pound-Drever-Hall (PDH) locking to FRS, depending on the frequency noise reduction scheme chosen; (d) LH Power Control electronics (LHPC) is responsible for the relative intensity noise (RIN) suppression at ~10-kHz bandwidth, by acting on the PA.

3. PACKAGED LASER DESIGN EVOLUTION

The TRL4 packaged LOM is designed to be a two-sided enclosure where an optical bench in the middle of the enclosure serves as the common mounting surface for either side, as seen in Figure 4 (left). In this approach, the two MO’s, PA and the high-power isolator (HPIS) are assembled on one side of the box and the PA, HPIS and HPSW are on the other side. We have done extensive finite element analysis (FEA) on this enclosure design based on the LISA environmental requirements. The FEA results showed potentially damaging amplification of the random shock and vibration levels on critical components on the PA. We, therefore, updated our TRL6 LOM design as well as the LEM enclosure to that shown in Figure 4 (right). Initial FEA shows promise, and we are in the process of finalizing this TRL6 design and proceed to build this demonstrator for full environmental testing.
4. **NESC INDEPENDENT TECHNOLOGY ASSESSMENT**

As part of the laser development process, we requested support from the NASA Engineering and Safety Center (NESC) to independently assess the technical approaches of the GSFC LS design. The independent assessment included the following tasks: (a) assess the design for weaknesses and suggest improvements to mitigate risks, (b) assess the laser reliability plan for weaknesses and suggest improvements to mitigate risks and improve effectiveness, and (c) assess the current redundancy plan on laser 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 laser design.

In summary, the overall SME team’s assessment conclusion is that there is no fundamental problem or major design issue that will prevent the LISA team from meeting the ESA requirements for the TRL 6 demonstrator. The findings showed the 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.

5. **CONCLUSIONS**

GSFC has been developing the laser transmitter for the LISA mission since late 2017. We are working toward delivering a TRL6 LH and FRS to ESA for evaluation in late 2023. The NESC assessment is mostly positive, and we acknowledge the review team’s recommendations and incorporate them for the flight laser development effort. This laser, once launched, will be one of the most stable lasers ever flown in space to realize the LISA GW observatory as noted by the recently released 2020 Astrophysics decadal survey [7].

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7. **REFERENCES**