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Micro-Non-Planar Ring Oscillator Master Oscillator for the NASA LISA Laser Transmitter

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ABSTRACT

This paper describes the technology development of the master oscillator (MO) as part of the NASA laser transmitter for the LISA mission. The MO is based on the non-planar ring oscillator (NPRO) resonator design.

Keywords: Nonplanar ring oscillator, solid state laser, ultra-low noise laser

1. INTRODUCTION

The Laser Interferometer Space Antenna (LISA) is a partnership between the European Space Agency (ESA) and NASA to build a Gravitational Wave (GW) observatory [1]. The observatory, which consists of a three-spacecraft constellation with a nominal separation of 2.5 million km between each spacecraft, provides a tool for scientists to directly detect gravitational waves generated from various astronomical phenomena in a waveband that is not accessible from Earth. NASA is developing laser transmitters as one of the potential US contributions to LISA. The NASA laser design takes on the master oscillator power amplifier (MOPA) architecture [2]. The master oscillator (MO) is based on the monolithic, nonplanar ring oscillator design (NPRO) design with a scaled down crystal from the original size demonstrated by Kane and Byer in 1985 [3], which we designated as the micro-NPRO or, µNPRO.

Since the LISA laser development effort began in late 2017, our team has been evolving the packaging concept of the µNPRO with a goal of space qualifying this package for the LISA mission [4]. The current package offers hundreds of milliwatts of diffraction-limited, single frequency output from a polarization maintaining fiber at a nominal wavelength of 1064.5 nm.

The LISA mission, starting from the on-ground integration phase, requires the laser system to last over 16 years until the end of the extended mission phase. Proper management of redundancy, derating and minimizing risks associated with package induced failure are all strategies employed to meet the lifetime requirement for the µNPRO. We also worked with vendors to understand the failure mechanisms of critical components and performed accelerated lifetest on critical components such as the 808 nm pump diodes to enhance our understanding of their failure mechanism. We also minimized the size, weight, and power (SWaP) of the µNPRO so that two of these units (one hot and one cold spare) can be housed within the allocated volume of the laser optical module (LOM) to meet lifetime requirements.

This paper describes the evolution of the packaging concept from its inception to the current design that will be subjected to environmentally testing to advance the technology readiness level (TRL) to 6, the first step toward space qualification and deployment.

2. TECHNOLOGY READINESS LEVELS

As in all technology development programs, the µNPRO development for LISA follows the progression of advancing the TRL from a breadboard stage (TRL 4) to brassboard (TRL 5) and then fully qualified (TRL 6) meeting form, fit and function with relevant environmental tests (i.e., shock/vibration, thermal vacuum temperature cycling, EMI/EMC, radiation, etc.) to meet the mission requirements. This is a critical step toward space deployment, the TRL 6 design will become the baseline for flight system. Figure 1 shows the path of advancing the TRL from 4 to 6 for the µNPRO. This flow process is applicable for most systems or subsystems toward space applications.

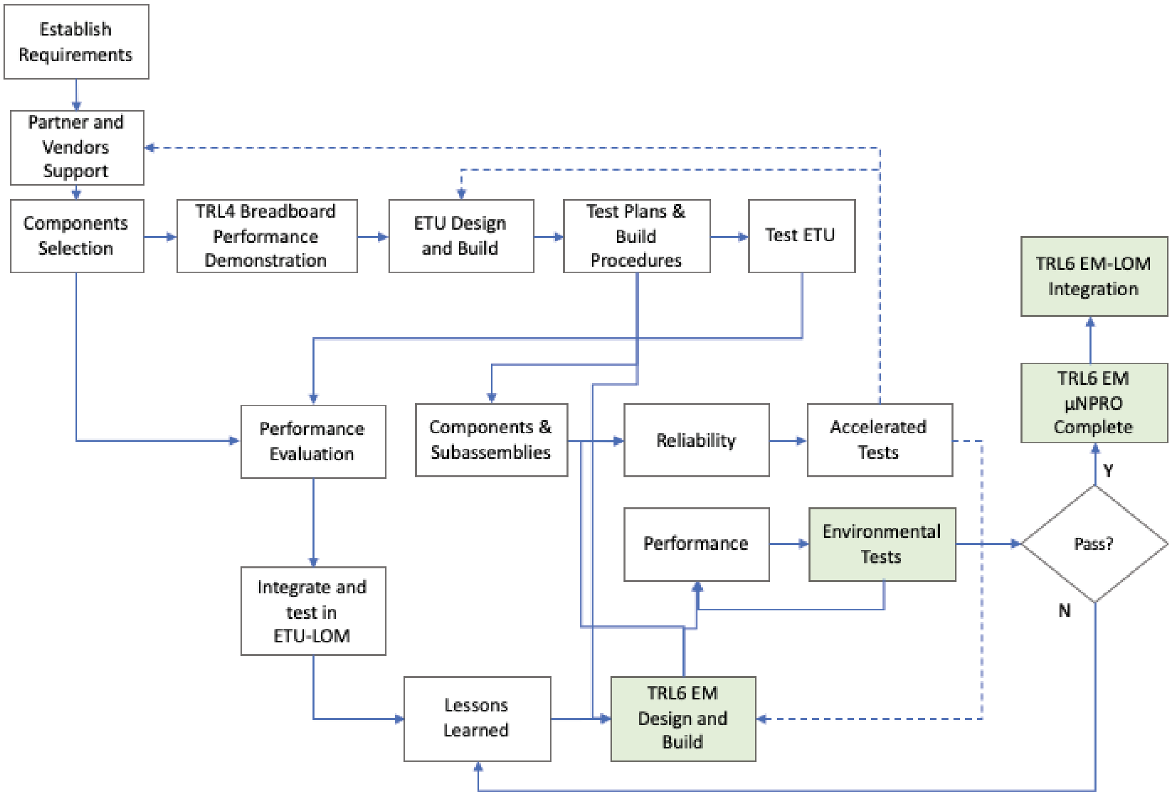


Figure 1. Flow chart of the evolution of TRL4 to TRL6 maturation for the µNPRO. The green shaded boxes are specific to TRL6 qualification process.

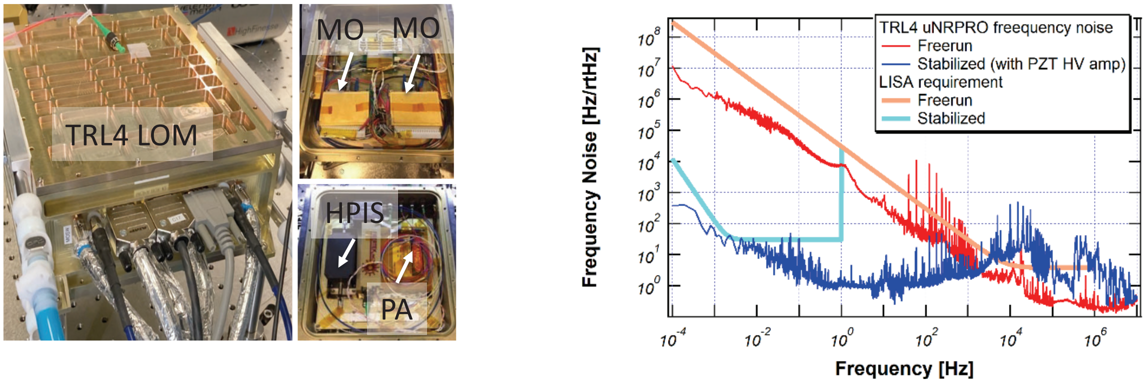
The overall LISA laser requirements [5] from ESA provided the baseline for establishing the requirements for subsystems within the LOM, which comprises of the MO and the power amplifier (PA). For the MO, we have identified the NPRO resonator design as the most promising architecture for its lowest noise and simplicity. Prior to arriving at this decision, we have investigated other technologies, including a semiconductor laser architecture [6]. The µNPRO provides the stable, low-noise oscillator for the system and it was selected based on the existence of a prototype that provides required performance with minimal changes to design. The smaller NPRO crystal also allows for smaller overall MO form factor, thus provides the possibility of a cold redundant MO within the LOM to meet the LISA lifetime requirement. Other key factors and availability of matured components for the µNPRO laser, such as the monolithic µNPRO resonator; the 808-nm pump lasers; micro-optics for beam shaping and coupling of pump beams into the crystal and coupling optics for single-mode polarization maintaining (PM) delivery fiber; as well as the high heat-load laser housing that leverages matured photonic packaging helped to advance the final form factor for the MO. Other details that were extensively investigated includes thermal management, hermetic sealing, mechanical structure, and electrical feedthroughs all contributed to the final form factor of the current design.

2.1 µNPRO requirements and design approach

The µNPRO requires to have a minimum 150 mW output power exiting the PM fiber to eliminate the use of a pre-amplifier stage prior to seeding the PA subsystem. This minimizes the number of components inside the LOM and simplified the system complexity. The dual pump subassembly provides hot redundancy for the MO, each of the 808 nm chip-on-submount (CoS) pump laser also supports lone operation in case of a failure. The redundant CoS pairs are chosen for similarity in performance and are integrated on a pump subassembly thus allowing for a single thermoelectric cooler (TEC) to regulate the temperature of the subassembly.

The two pump beams are combined and propagate on a common path with beam shaping optics to pump the µNPRO crystal with optimal overlap between the pump and lasing modes.

The NPRO crystal is installed as part of a compact stack assembly that contains a TEC for regulating the crystal temperature, a piezoelectric transducer (PZT) is bonded to the crystal allowing frequency tuning of the laser emission frequency with an applied voltage. The NPRO operates unidirectionally with a magnet straddled above the compact stack assembly. The emitted 1064 nm light is then routed to the enclosure exit port with coupling optics to efficiently coupled to the PM fiber.



(a) (b)

Figure 2. (a) TRL4 MO integrated into a TRL4 LOM enclosure with the PA and a high-power isolator (HPIS) and (b) Frequency noise performance of the TRL4 MO ETU under free run operation and stabilized with a GSE optical cavity. The stabilized performance of the MO is limited by the GSE optical cavity, not by the MO performance.

In our TRL4 effort during 2019-2021, we successfully demonstrated a very small form factor, based on modern photonics packaging technologies. Ten ETUs have been assembled and carefully assessed. Lessons learned from this phase have been captured and incorporated into the TRL6 design phase. We also work closely with component vendors (i.e. for 808 nm pump diodes, pump laser optics, Cr:Nd:YAG crystal material, thermoelectric coolers, etc. and fabrication shops) during all phases of the development program. The objectives are to understand the performance and reliability risks for each component and subassembly and to design test programs that are tailored specifically to understand performance margins and properly derate the operating conditions, so the LISA laser meets the lifetime and performance requirements.

The TRL4 units were integrated into the TRL4 LOM enclosure as shown in Figure 2 and frequency noise performance in free-running and stabilized with a ground support equipment (GSE) optical cavity. The TRL4 LOM was tested and fully evaluated by CSEM [7].

After the completion of the TRL4 µNPRO phase of the program, we captured lessons learned and proceeded to revise the design for the next phase of the program in advancing the design with a goal of reaching TRL6 by end of 2022.

2.2 TRL6 Design

Since our earlier TRL4 work, the TRL6 design has been significantly improved. The TRL6 µNPRO package is hermetically sealed with internal getter, similar to 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].

Figure 3 shows the changes made to the µNPRO internal and enclosure design between TRL4 and TRL6. Table 1 captures the TRL6 µNPRO requirements.

We are currently beginning to build several TRL6 engineering model qualifying (EMQ) units for evaluation and process refinement. Once EMQs are done with satisfctory performance, we will proceed to build 20 EM units for TRL6 LOM assemblies. Figure 4a shows the internal design of the TRL 6 µNPRO package. Following the updated build procedures and materials, about 7 EMQ µNPRO packages have been built and tested (Figure 4b) so far.

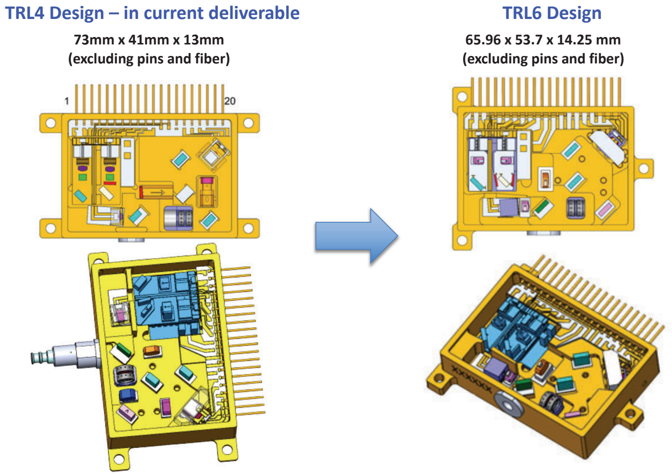


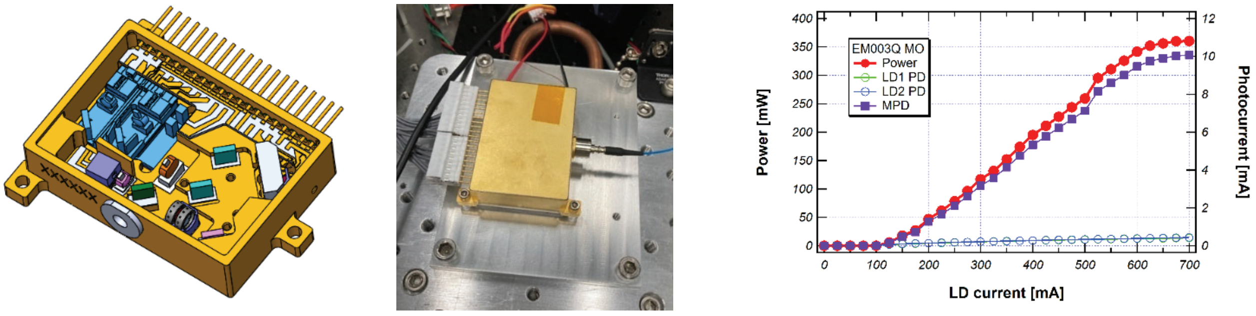
Figure 3. (left) TRL4 and (right) TRL6 (right) μNPRO designs.

Table 1. TRL 6 μNPRO requirements.

Specification	Requirement
Output Optical Power	>300 mW (no internal isolator)
Spatial Mode	TEM_{00}
Optical-to-Optical Efficiency	>50%
Center Wavelength	1064nm
Pump Lasers	Two 808 nm Single Mode Pumps
Pump Wavelength Matching	Two pumps center wavelength 808 nm ± 1 nm
Pump Powers	500 mW typical from each
PER	>15 dB
Fiber Coupling Efficiency	>50%
Magnetic Field on μNPRO	H-vector along crystal length
PZT Thickness	0.5 mm, nominal thickness
PZT Voltage	<100 V
Fiber Length & Terminator	1 m; FC/APC
Package size	73mm x 41mm x 13mm (excluding pins and fiber)
Monitor photodiode	for 808 nm pumps and for 1064 nm output power
Temperature Controls	for two 808 nm pumps and μNPRO crystal
Crystal Temperature Control	± 1mK
Pump Lasers Temperature Control	± 10mK

It has passed all space qualification tests, such as radiation, shock, vibration, and temperature cycling.

In addition, the 808-nm pump laser diode has been life-aging tested at the vendor (Eagleyard/TOPTICA optics) at CoS level, and at GSFC at the pump-subassembly level. Figure 4c shows the μNPRO EMQ output power. It emits >300 mW output power in fiber with low frequency noise and drift. They are realized by the small crystal design and the precise package temperature control.



(a) (b) (c)

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.

Some notable improvements between the TRL4 and TRL6 μNPRO designs are –

- hermetically sealed with internal getter,
- use of flux-free solders wherever possible to minimize slow drift of components.
- package is mechanically stiffened to avoid misalignment due to package distortion – moving from a 4 point mount to a 3-point mechanically mounting feet
- μNPRO crystal has been redesigned to have a lower threshold, stable beam size, higher fiber coupling efficiency, and higher PZT frequency tuning efficiency [8]

3. CONCLUSIONS

NASA GSFC is developing the laser transmitter for the LISA project. The LOM is configured as master oscillator power amplifier. The MO is based on a monolithic NPRO design. The µNPRO takes on a small form factor, on order of 66 mm x 54 mm x 14 mm, allowing a cold redundant MO inside the LOM to meet the LISA lifetime requirement. We have successfully completed a TRL4 phase development and proceeding toward a TRL6 qualification by early 2023 to meet the project milestones.

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