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Progress and Plans for a US Laser System for the LISA Mission

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ABSTRACT

NASA Goddard Space Flight Center is developing a master oscillator power amplifier (MOPA) laser transmitter for the ESA-led Laser Interferometer Space Antenna (LISA) mission. Taking advantage of our space laser experience and the emerging telecom laser technology, we are developing a full laser system for the LISA mission. Our research effort has included both master oscillator (MO) and power amplifier (PA) developments, and their environmental testing and reliability for space flight. Our current baseline for the MO is a low-mass, compact micro non-planar ring oscillator (m-NPRO) laser. The amplifier uses a robust mechanical design based on fiber components. We have performed laser system noise tests by amplitude- and frequency-stabilizing the PA output. We will describe our progress and plans to demonstrate a TRL 6 laser system, which is an essential step toward qualifying lasers for space applications, by 2021.

Keywords: LISA, laser noise, interferometry, single-frequency laser, master oscillator power amplifier (MOPA)

1. INTRODUCTION

Gravitational waves (GWs) are ripples of space-time that propagate across the Universe at the speed of light. GWs were derived from the Einstein equations in the general theory of relativity [1]. GW signals are generated by powerful events, such as black hole mergers, in the Universe, and bring the source information directly to us. Their existence was indirectly proved by the observation of the binary pulsar PSR1913+16 in the 1980s [2]. Experimental trials to direct GWs were started in the 1960s. Such direct detection was achieved by the LIGO (Laser Interferometer Gravitational-wave Observatory) [3, 4] on the ground in 2016, opening up a new way to observe the Universe. The field of gravitational-wave astronomy was truly opened up by the recent discovery of GWs generated by the merger of a binary neutron star and follow-up observations of this even using electromagnetic waves [5]. It is the most significant emerging field in astronomy and fundamental physics.

Space-based GW detectors are expected to bring even more information about the Universe through low-frequency GWs. The Laser Interferometer Space Antenna (LISA) mission [6] is a planned space mission designed to detect and accurately measure GWs from astronomical sources. The LISA mission was selected as the third large-class mission in the European Space Agency's (ESA) science program in June 2017. It will have three spacecraft, arranged in a triangle with sides 2.5 million km long. It will use a heterodyne laser interferometer to measure picometer-level-length variations 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 different spacecraft is monitored precisely to observe the passage of the GWs, which are generated, for example, by mergers of super-massive black holes. The LISA Pathfinder mission recently proved that it is possible to achieve drag-free control at the required LISA levels, and to perform picometer-level heterodyne interferometry in space [7]. Originally, LISA was a joint mission between the ESA and NASA. Although NASA announced in 2011 that it would be unable to continue to support its LISA partnership with the ESA, these new results and achievements have led the agency to return to the development of LISA technology.

A highly stable and robust laser system is a key component of the LISA mission, and is one of the candidate component contributions from NASA to the ESA-led LISA mission. The baseline architecture for the LISA laser consists of a low-power, low-noise master oscillator followed by a power amplifier stage with ~2 W output. We are developing such a laser system at NASA GSFC, as well as investigating other laser options. Our research has included the environmental testing and reliability for space flight of these laser systems as well. In the following sections, we will describe the laser requirements for the LISA mission, progress to date, and plans to demonstrate a TRL 6 LISA laser system by 2021, for the planned launch in ~2031. Although the planned launch is still ~13 years away, we are expected to provide the high-

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TRL laser system within a 2-year timeframe, to allow enough time for integration and testing for the extremely challenging mission.

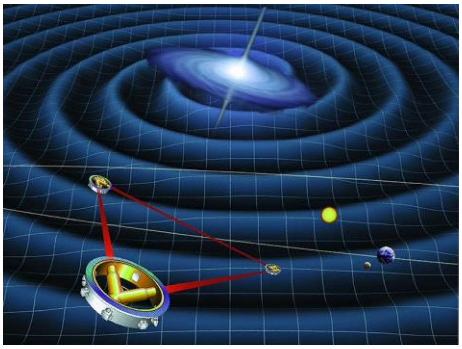

Figure 1. Artist concept of the LISA mission [6]

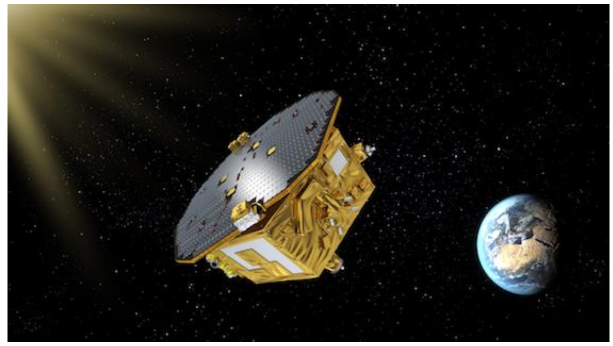

Figure 2. Artist concept of the LISA pathfinder mission [8]

2. OVERVIEW OF THE LISA LASER

2.1 Requirements

Table 1 summarizes the requirements for the LISA laser system. As in other applications of precision interferometry, 1064 nm was chosen as the laser wavelength, due to the availability of high-quality bulk optics and the traditional low-noise Nd:YAG laser source represented by the non-planar ring oscillator (NPRO) [9]. The laser system must deliver ~2 Watt level output power to the optical bench. The available laser power sets a shot-noise limit on the detection sensitivity of the GWs at the high frequency end of the detection band (>~10 mHz). In addition to the standard requirements for mass, power, and radiation hardness as a space laser, the most challenging requirements are set by the low-frequency noise (which requires active stabilization using a high finesse optical cavity), by the low-intensity noise (which requires active stabilization at a low Fourier frequency and shot-noise-limited performance at a high Fourier frequency), and by the long lifetime (~16 years including integration, test, and cruise phases). The LISA laser system has been designed to satisfy those unique requirements.

Table 1. Requirements for the LISA laser system

Item	Value
Operating mode	Continuous wave (CW), single frequency, single longitudinal mode
Wavelength, polarization, spatial mode, beam quality	1064.6 +- 0.8 nm, linearly polarized, TEM00, M^2<1.05
Output power	>2W
Frequency/power controllability	Fine tuning to achieve in-loop noise requirement
Frequency noise	(See Fig. 4 for free-running frequency noise requirement)
Intensity noise	$<10^{-4}/\sqrt{Hz}$ @ 0.03m~10kHz, $<10^{-8}/\sqrt{Hz}$ @ 5~50MHz
Differential phase noise	(See Fig. 9 for differential phase noise requirement)
Modulation	Phase modulation at 2.4+-0.2 GHz
Lifetime	16 years

2.2 Baseline architecture

The LISA laser system requires an electro-optical phase modulator (EOM) within the optical path to transmit reference clock information between spacecraft using a phase-modulation sideband at ~2 GHz. Without the clock noise transfer (or exchange), the tiny 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. Thus, it was a natural course to select a master oscillator power amplifier (MOPA) architecture with a fiber-coupled EOM inserted between the low-power, low-noise master oscillator (MO) and the high-power amplifier (PA). Figure 3 shows the baseline LISA laser system architecture based on such a MOPA concept. Each spacecraft has two sets of full laser systems, excluding cold spares. In a baseline operating mode, one of the six active lasers is frequency-locked to a high finesse cavity as a master laser (as shown in Fig. 3). The other five lasers are offset phase-locked to the master laser as a slave laser, acting as an amplifying mirror at the far spacecraft.

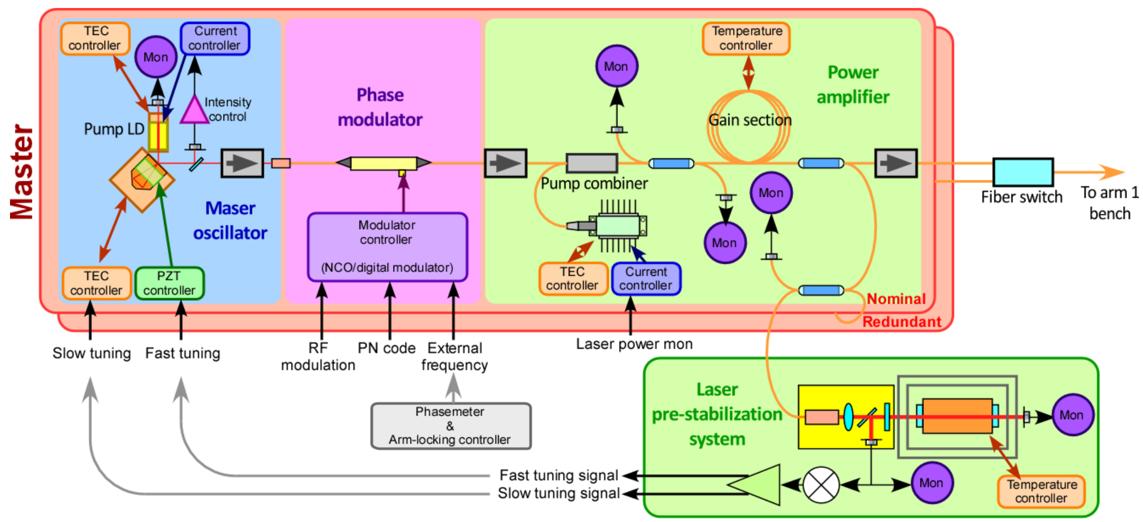

Figure 3. LISA laser system conceptual figure. In this figure, the laser is frequency-locked to a frequency reference (optical cavity), serving as a master laser for the other 5 slave lasers. The MO and PA are assumed to be NPRO and fiber amplifier, respectively, in this conceptual figure. Design details are still under discussion and will be modified during the course of development.

3. MASTER OSCILLATOR

3.1 Overview

We have performed wide experimental and industrial surveys to identify the best MO architecture. We have identified NPRO as the most-promising MO architectures, and have invested in micro NPRO (m-NPRO) design to satisfy the stringent LISA MO requirements.

3.2 Frequency and relative intensity noise

Figure 4 compares free-running frequency noises of single-frequency lasers near 1 µm. Commercially available NPRO and our newly designed m-NPRO show the lowest level of frequency noise of the entire frequency band, compared to other lasers, such as Littman ECL, a distributed feedback (DFB) laser diode, fiber lasers, and planar-wave external cavity lasers (PW-ECL by RIO [10]). Some lasers are claimed to have lower frequency noise than NPRO between 1 and 10 kHz. However, they do not satisfy the frequency noise requirement at high Fourier frequency (> 10 kHz), which is very important for precision phase locking and affects the phasemeter design.

As for the relative intensity noise (RIN), fiber lasers have a larger and broader relaxation oscillation peak at around 1 MHz, failing to satisfy the $10^{-8}/\sqrt{\text{Hz}}$ RIN requirement at the LISA's heterodyne frequency (5~50 MHz range). NPROs have a sharp relaxation oscillation peak around ~600 kHz in free running condition. An active control loop (often called a "noise eater") to suppress this peak would be desirable to avoid any noise couplings.

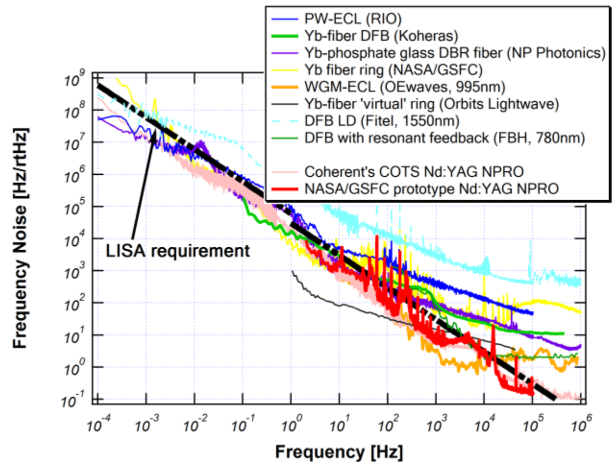

Figure 4. Free-running frequency noise spectrum of various single-frequency lasers near 1um.

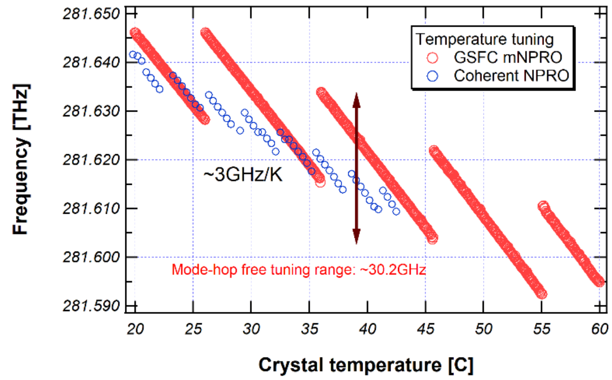

Figure 5. Thermal frequency tuning of standard commercial NPRO design and the micro NPRO design.

3.3 Micro NPRO features

We are currently investing on the development and packaging of m-NPRO. Since our MO is intended for low output power with low noise (as a seed laser for the MO), it is possible to use a lower-power pump diode that has single-mode or low-order multimode laser diode. The short round-trip length of the micro-NPRO cavity makes the free-spectral-range (FSR) larger. This makes the mode-hop-free tuning range wider as shown in Figure 5, and thus makes it more robust against tuning operations and external disturbances. It also makes easier to have frequency overlap between the 6 lasers used during the operation of LISA. The larger FSR also minimizes the coupling from the neighboring longitudinal oscillation mode. The small size makes the thermal volume of the system smaller, and thus makes the temperature control of the crystal more robust, maximizing the control bandwidth of the slow loop. Its temperature sensitivity is identical to the traditional design (~3GHz/K, Fig. 5). More importantly, the micro-NPRO can be packaged into a much smaller form factor, such as a telecom-standard butterfly package, using micro-optics used to package semiconductor lasers. We are designing a laser system package that has two m-NPRO packages to have full MO redundancy, and to satisfy the lifetime requirement. The m-NPRO package has two pump diodes inside, which are simultaneously driven at low injection current, to further extend the lifetime.

3.4 Development history and status

The compactness of the PW-ECL package, low cost, and simple design were attractive for space use, and we invested in it to investigate the source of excess frequency noise (relative to the NPRO), and to empirically study gain chip leakage current and side modes, spurious optical reflections, etc. The 1.5-µm PW-ECL [11] was adopted as the metrology laser for the OpTIIX mission [12] on the International Space Station for its low noise and compatibility with space environments. However, the frequency noise level of 1-µm PW-ECL is still higher than the LISA requirement (and NPRO) by a factor of ~200 at 100 kHz as shown in Figure 4. No clear path was identified to improve this situation within the given time-frame of two years allocated for the MO qualification. It would also require an extra preamplifier stage to seed the PA, adding extra complexity and cost. Therefore, we are now focusing only on the development of m-NPRO. We have designed the new structure based on the considerations specially sought for the LISA mission. This activity has been very successful, and the new m-NPRO design is achieving all the fundamental LISA requirements. We are packaging it into a very small form factor, based on modern photonics packaging technologies, as well as seeking to establish partnerships with a commercial NPRO vendor in order to ruggedize the traditional NPRO design as a backup. We are building working prototypes and will space-qualify their engineering model by 2019, after some necessary modifications.

4. POWER AMPLIFIER

4.1 Overview

The low-power, low-noise laser light from the MO passes through a fiber-coupled waveguide EOM, and then subsequently is amplified by the PA stage to the 2-Watt level. We have mainly pursued an all-fiber PA solution due to its high compatibility with the phase modulator and its high robustness against environmental disturbances and contaminations. In addition to standard power and space readiness requirements, one of the most LISA-specific requirements is set by the differential phase noise [13]. If the phase noise is differentially introduced between the carrier and the clock-transfer sideband, the clock noise cancellation algorithm fails to reveal the tiny GW signal. This differential radio frequency (RF) phase noise is not usually considered in any other amplifier systems, and its origin hasn't been well identified. In addition to the stringent frequency noise and the intensity noise requirement, this noise is making the amplifier selection and development process more complicated. Nevertheless, we have established a baseline fiber amplifier design, which satisfies the LISA requirements, based solely on commercial off the shelf components as discussed in the next section. We are also seeking different PA architectures to further improve performance.

4.2 Baseline fiber amplifier

Our baseline 2.5 W fiber amplifier is shown in Figure 6. It includes a pump diode to provide power, a tapered fiber bundle to allow redundant power input, and a 2.3-m-length, 10-µm core, double-clad, large-mode-area gain fiber. The same package contains an MO and a phase modulator, making it a complete opto-mechanical package of the LISA laser system, excluding the frequency reference optical cavity. The gain fiber is forward-pumped by 976-nm multimode laser diodes. This forward-pump design was adopted to minimize potential sources of feedback and catastrophic damages. The amplifier uses a robust mechanical design and temperature stabilization to suppress fiber-length variations. Output power of our latest prototype is shown in Figure 7.

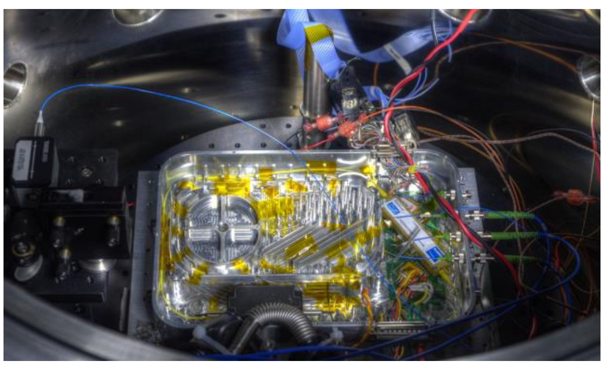

Figure 6. Photo of the baseline fiber amplifier built at NASA/GSFC. It is set in a thermal vacuum chamber for environmental testing.

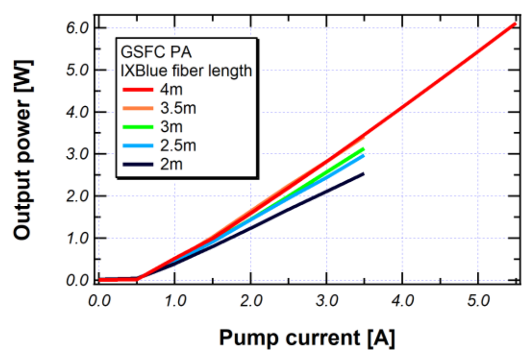

Figure 7. Output of the baseline fiber amplifier. Left axis (circle markers) represents main output power. Right axis (square markers) represents backward monitor power.

We have performed laser system noise tests by amplitude- and frequency-stabilizing the PA output. By stabilizing the amplifier pump-diode current, an amplitude noise attenuation of ~30 was achieved at a frequency of 0.1 mHz. The laser system was also frequency-stabilized by locking a small fraction of the amplifier's output to a hyperfine absorption line of iodine molecule as shown in Figure 8. Figure 9 shows that the differential phase noise between the carrier and a 2.4-GHz sideband transmitted through the PA meets the LISA requirement.

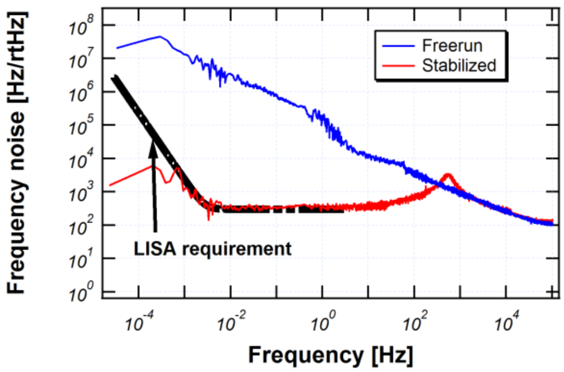

Figure 8. Frequency noise of the baseline PA with and without frequency stabilization. Molecular iodine and PW-ECL were used as frequency reference and MO, respectively, in this demonstration.

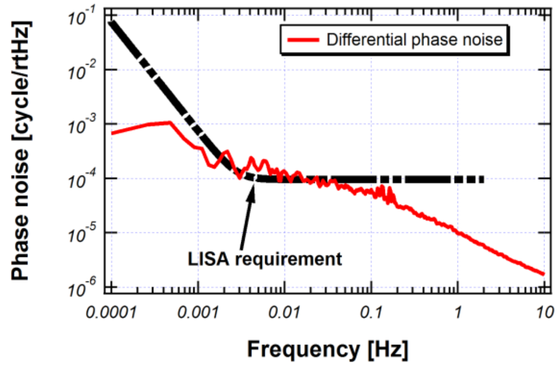

Figure 9. Differential phase noise of the baseline fiber amplifier with 2-GHz frequency offset at 1.4-W output power.

4.3 Alternative architecture

Although the baseline architecture satisfies the fundamental requirements for LISA, we are still seeking for even better PA architectures. We are aware that there are many other 1-µm laser amplifiers that can deliver 2-W level output based on specialty technologies, such as highly doped gain fibers and crystalline fibers. The differential phase noise is expected to be smaller, when the SBS threshold is high (i.e., any smaller nonlinear effect) and when the gain section is shorter and thermally more uniform. The amplifier architecture is not limited to fiber-based designs, since efficiency and cooling are not the primary concerns in this case. Because the measurement and evaluation of the noise (especially the differential phase noise) are very difficult, requiring a stable environment and precision optical phase-lock and measurement systems, we are establishing a noise measurement station, and have started evaluating commercial amplifier products. We have issued a request for proposal (RFP) to solicit a proposal to build test amplifiers for the GSFC LISA laser group, and selected ~2 vendors to deliver their fiber amplifiers. We will down-select the PA architecture by the end of 2018 after careful performance evaluations at GSFC, and will attempt to qualify it by mid-2019.

5. SUMMARY

NASA/GSFC has been involved in research on space-borne lasers since the 1990s. Taking advantage of its space laser experience and the emerging telecom laser technology, we are developing a full laser system for the LISA mission. The laser system can be one of the most important component contributions from NASA to the ESA-led LISA mission. Importantly, NASA has recently received input from the 2016 Mid Decadal Review [14] emphasizing the need for increased US technology funding to allow the Agency to play an important role in LISA. The recent events of the opening of the GW astronomy and the successful completion of the LISA pathfinder mission are pushing our efforts for LISA to the next level.

Our research has included both MO and PA developments, and their environmental testing and reliability for space flight. Remaining work on the US/NASA laser system for LISA includes the following: 1) packaging and full performance testing of the new m-NPRO designs; 2) PA architecture evaluation and selection; 3) reliability testing of the laser system to show compliance with the 16-year lifetime requirement; and 4) demonstration of noise and locking performance combined with other subsystems such as the frequency reference cavity and the phasemeter. We believe these tasks are achievable by 2021 provided sufficient funding is allocated to the laser system development.

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