Development of a US Gravitational Wave Laser System for LISA

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Abstract. A highly stable and robust laser system is a key component of the space-based LISA mission architecture. We will describe our plans to demonstrate a TRL 5 LISA laser system at Goddard Space Flight Center by 2016. The laser system includes a low-noise oscillator followed by a power amplifier. The oscillator is a low-mass, compact external cavity laser, consisting of a semiconductor laser coupled to an optical cavity, built by the laser vendor Redfern Integrated Optics. The amplifier is a diode-pumped Yb fiber with 2 W output, built at Goddard. We show noise and reliability data for the full laser system, and describe our plans to reach TRL 5 by 2016.

1. Introduction

The NASA's Goddard Space Flight Center (GSFC) has been producing space-borne lasers for various missions (See, for example, [1, 2]). These space instruments were based on diode-pumped solid-state Nd:YAG lasers. For future earth- and space-science missions, including the gravitational-wave missions like LISA, we are making transition to a new generation of space-based lasers. These lasers use the emerging telecom laser technology, such as fiber laser/amplifier, waveguide devices, and semiconductor lasers. These components naturally fit into the precision laser systems for the interferometric missions because of their high mechanical robustness, excellent reliability, compact form factor, and high wall-plug efficiency. We are targeting to provide TRL (technology readiness level) 5 laser for the LISA-like missions by 2016. We have invested approximately $3.5 million over the past six years on laser development for the LISA-type missions. Our research has included development of 1064 nm Planar-Waveguide external cavity laser (PW-ECL), PW-ECL reliability tests, and amplifier development, including its noise measurements and reliability studies. These are funded through multiple funding sources, such as NASA's SBIR (Small Business Innovative Research) and SAT (Strategic Astrophysics Technology) awards.

For the LISA-like missions, we are pursuing an all-fiber/waveguide space laser solution based on the MOFA (master oscillator fiber amplifier) configuration, which is a waveguide-based oscillator followed by a preamplifier and a power amplifier (Fig. 1).

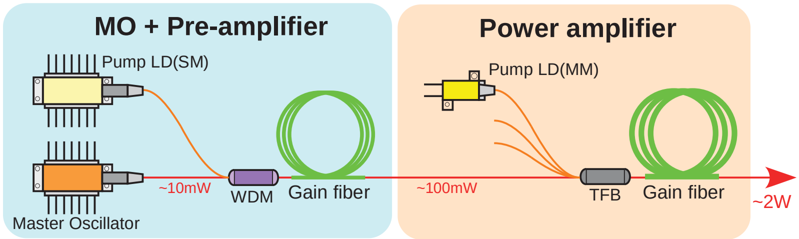

Figure 1. Concept of the MOFA configuration. Optical isolators, modulators, and redundant LDs are not shown. SM: single-mode; MM: multi-mode.

2. Master Oscillator

We have developed a fiber ring laser [3] and a fiber DBR laser for space interferometry. Although these lasers perform like the non-planar ring oscillator (NPRO) at low (<10 kHz) frequency, they have larger relaxation oscillation peak, around 1 MHz, which could affect the heterodyne interferometry typically operated near this frequency. Therefore, we shifted our focus to the development of the planar-waveguide external-cavity diode laser (PW-ECL). The Telecordia-qualified PW-ECL, built by Redfern Integrated Optics, offers advantages over solid-state lasers, including simpler design, more compact size, lower mass, and less consumption of electrical power. The narrow reflection peak of the Bragg reflector in the planar lightwave circuit (PLC) enables stable, low-noise, single-mode lasing at a selected wavelength. Originally, the PW-ECL was only available at the telecom C-band (1528~1565 nm). Based on the experience on the C-band PW-ECL, we have successfully built 1064 nm version of PW-ECL by changing the gain chip and the PLC design. The maximum output power of PW-ECL is 15 mW.

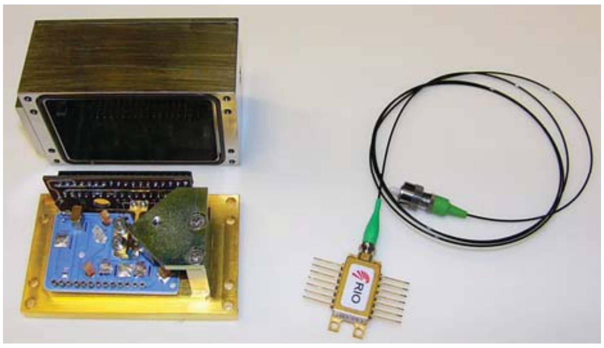

Figure 2. Size comparison of the NPRO (left) and the PW-ECL (right).

Figure 2 shows a comparison of its size with the non-planar ring oscillator (NPRO). The PW-ECL's package is much more compact than that of the NPRO, in which a strong magnet limits the size. We based our choice of the PW-ECL on an investigation of number of lasers [4]. The ECL can be locked to either a hyperfine absorption line of acetylene at 1542 nm [4], that of iodine at frequency doubled 1064 nm [5], or an optical cavity of finesse 10^5 [6] with low-residual frequency noise.

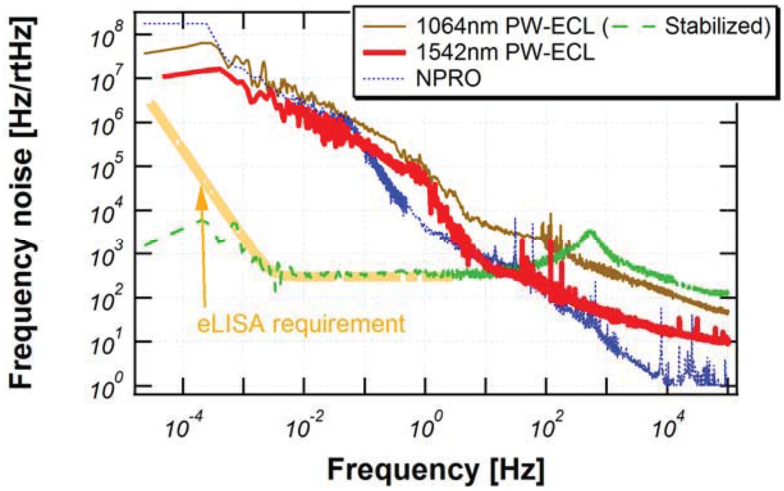

Figure 3. Frequency noise of NPRO, 1542 nm PW-ECL, and 1064 nm PW-ECL.

Figure 3 compares frequency noise of NPRO, 1542 nm PW-ECL, and 1064 nm PW-ECL. Below 0.1 Hz, the PW-ECLs make frequency noise comparable to the NPRO. Above 10 Hz, the noise drops by $1/\sqrt{f}$ and $1/f$ for the PW-ECL and NPRO, respectively; therefore their difference becomes larger at a higher frequency. At 10 kHz, the PW-ECL produces approximately 5 and 40 times higher frequency noise than the NPRO at 1542 nm and 1064 nm, respectively. When stabilized to the iodine reference, after amplified by the two stage Yb fiber amplifier and frequency-doubled by a MgO:PPLN crystal, the 1064 nm PW-ECL achieved the frequency noise requirement of eLISA [7] at low frequency. However, the high frequency noise at high Fourier frequency may still be problematic from the viewpoint of phase locking. We estimate that the RMS phase noise must be suppressed by a factor of about 100. Therefore, we are trying to improve the frequency noise performance by optimizing the gain chip and PLC designs. We are also looking into a possibility to implement a 100 MHz bandwidth intra-cavity phase modulation section within the gain chip, so that we can use it as a widely-tunable, fast frequency tuning actuator. By the time these implementations are completed, we will try to use external acousto-optic modulator in order to suppress the excess noise.

We made a detailed study of the mechanical, thermal, and radiation robustness of the PW-ECL, and found it to be qualified for use in space. Lucent Government Solutions (LGS) planned and oversaw the tests, which involved vacuum thermal cycling, hermiticity, radiation, and accelerating aging [8]. For these reasons, the 1550-nm PW-ECL was adopted as the metrology laser for the OpTIIX mission [9] on the International Space Station (ISS). We will revisit some of these reliability studies for the 1064 nm PW-ECL in FY15. We think the risk of failing the reliability test is low, since it is using the same packaging as the 1550 nm PW-ECL and the gain-chip vendor (Eagleyard) data indicates high reliability.

3. Fiber amplifiers

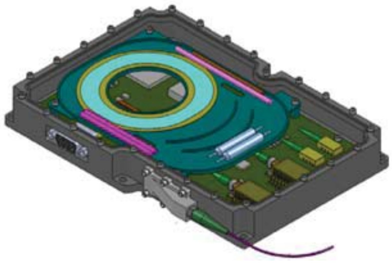

Figure 4. Package design of the seed laser and the pre-amplifier system.

The 15 mW maximum output power of PW-ECL may not be sufficient for a seed laser of the 2-W power amplifier in LISA-type missions, when the optical loss in phase modulator and instability caused by too high gain in the power amplifier are taken into account. Therefore, in order to have a power margin, and to have flexibility in changing mission requirements, we are developing fiber pre-amplifiers with output power of ~100 mW at 1064 nm. Figure 4 shows the design of the seed laser and the pre-amplifier system. The laser unit will house two PW-ECLs and two pump laser diodes for redundancy, as well as their control circuits.

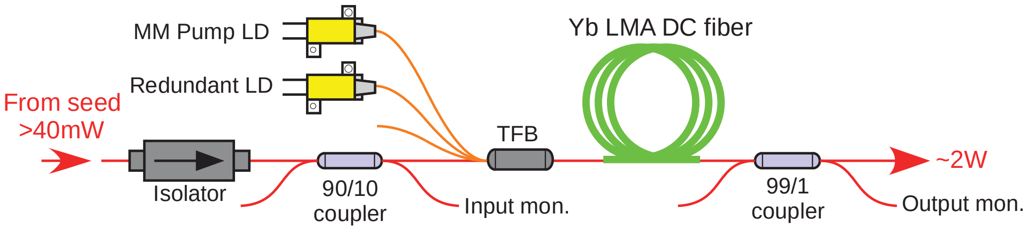

Figure 5. Architecture of the power amplifier

We worked with LGS to develop a Yb fiber power amplifier for the LISA-type missions. After trade studies and simulations, we adopted the 1064 nm amplifier architecture shown in Fig. 5. A 10-μm core, double-clad (DC), large-mode area (LMA) fiber was selected as a gain media to elevate the SBS (stimulated Brillouin scattering) threshold. It is forward, clad-pumped through a tapered fiber bundle (TFB). The forward-pumping design minimizes potential sources of feedback (e.g. from the TFB). Such feedback could result in lasing and in catastrophic damage, which we found to occur in our prototype backward-pumped amplifiers.

Using a commercial NPRO as a seed source, we evaluated the noise performance of the power amplifier, such as the frequency noise, the differential phase noise, and the intensity noise [10]. We also performed vacuum thermal cycling and gain fiber irradiation in order to look at the amplifier reliability. We have learned that the amplifier performance is not degraded by thermal cycling, but is degraded by gamma irradiation if improper gain fiber is used. The combined performance of the PW-ECL, the pre-amplifier, and the power amplifier has been in part proven in the frequency-stabilization experiment using iodine [5] mentioned above.

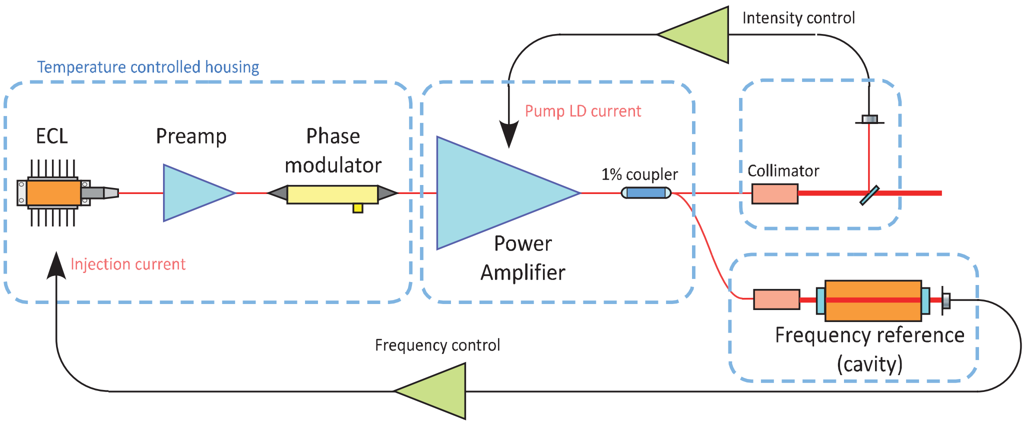

Figure 6. Planned system testing setup for FY15 and FY16.

By 2016, we will rebuild amplifiers using more realistic components, combine them with the low-noise 1064 nm PW-ECL, and perform system and environmental tests (Fig. 6). The system test will include locking the power amplifier output to an optical reference cavity, and phase-locking two laser systems, in order to show applicability of our system to the LISA-like missions.

4. Summary

NASA/GSFC has been involved in research on spaceborne lasers since the 1990s. Taking advantages of the space laser experience and the emerging telecom laser technology, we are developing laser system for the LISA-type missions. Our research has included both master laser and amplifier developments. We plan to finish to lowering PW-ECL's frequency noise and laser system testing by the end of FY15, and to perform reliability testing by the end of FY16 to achieve TRL 5.

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