

Laser Development for Gravitational-Wave Interferometry in Space

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Abstract.

We are reporting on our development work on laser (master oscillator) and optical amplifier systems for gravitational-wave interferometry in space. Our system is based on the mature, wave-guided optics technologies, which have advantages over bulk, crystal-based, free-space optics. We are investing in a new type of compact, low-noise master oscillator, called the planar-waveguide external cavity diode laser. We made measurements, including those of noise, and performed space-qualification tests.

1. Introduction

There are two LISA-like gravitational wave mission concepts under consideration, NGO (eLISA) in Europe and SGO-mid and SGO-high in the US. They will use precision interferometry to monitor the motion of freely falling test masses in spacecraft separated by $\sim 10^9$ m. The light source for the interferometer is a highly stable, ~ 1 -2W power laser. Development of such a laser is significant for space gravitational-wave observatories.

The NASA's Goddard Space Flight Center (GSFC) has been producing space-borne lasers for missions, including the Mars Global Surveyor (MGS) [Afzal (1994)], the Ice Cloud and land Elevation Satellite (ICESat) [Afzal et al. (2007)], the MErcury, Surface, Space ENvironment, GEochemistry and Ranging (MESSENGER) [Krebs et al. (2005)], and the Lunar Reconnaissance Orbiter (LRO) [Yu et al. (2008)]. All of these missions were based on diode-pumped solid-state Nd:YAG lasers. For future earth- and space-science missions, including the gravitational-wave missions, 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. This paper gives an overview of our laser development work for space gravitational-wave interferometry.

2. Design

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 pre-amplifier and a power amplifier (Fig. 1). The pump laser diodes (LDs) for the amplifiers are 97x nm, which is more reliable than 808-nm LD for the Nd:YAG lasers in space.

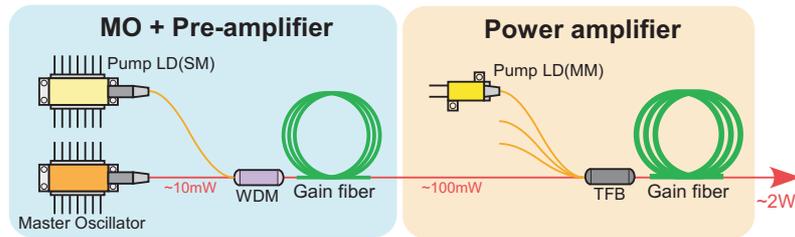


Figure 1. Concept of the MOFA configuration. Optical isolators, modulators, and redundant LDs are not shown. SM: single-mode; MM: multi-mode.

3. Master oscillator

We have developed a fiber ring laser [Numata & Camp (2012b)] 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 have 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 within the telecom C-band (1528~1565 nm). The output power is ~ 15 mW.

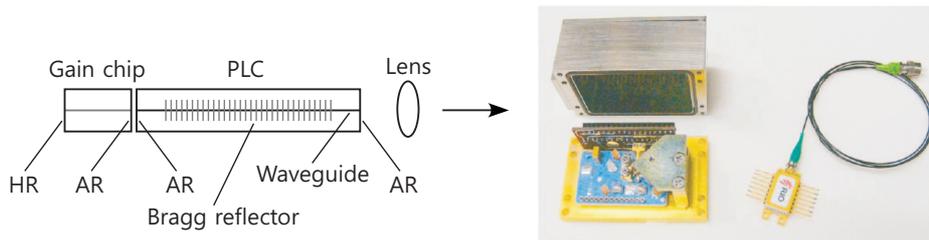


Figure 2. (Left) schematic diagram of the PW-ECL. HR: high-reflector coating; AR: antireflection coating. (Right) size comparison of the NPRO and the PW-ECL.

Figure 2 shows a schematic the PW-ECL, and a comparison of its size with the non-planar ring oscillator (NPRO). All components are integrated into a standard 14-pin butterfly package on top of a thermoelectric cooler. As a result, the 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 [Numata et al. (2010)]. We compared the frequency and amplitude noise of these lasers, and identified the PW-ECL as having the second-lowest frequency noise and the lowest-amplitude noise. Recent experiments showed that the ECL can be locked to either a hyperfine absorption line of acetylene [Numata et al. (2010)] or an optical cavity of finesse 10^5 [Clivati et al. (2011)] with low-residual frequency noise. Two PW-ECLs can be phase-locked with unity-gain frequency of ~ 100 kHz by controlling the injection current.

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, hermeticity, radiation, and accelerating aging [Numata & Camp (2012a)]. For these reasons, the 1550-nm PW-ECL

has recently been adopted as the metrology laser for the OpTIIX mission [Burdick et al. (2012)] on the International Space Station (ISS). Using the PW-ECL for the GW laser would require changing its wavelength to 1064 nm. A SBIR contract is already under way to enable the wavelength change, and we are optimistic that a space-qualified 1064-nm PW-ECL will be available in fiscal year (FY) 2014.

4. Pre-amplifier

The ~ 15 mW output of PW-ECL may be sufficient for a seed laser of the ~ 2 -W power amplifier in LISA-type missions. However, in order to have a power margin, to have flexibility in changing mission requirements, and to have a reference design for the missions that does not require power amplifier (such as OpTIIX), we are developing fiber pre-amplifiers with output power of >100 mW both at $1.06 \mu\text{m}$ and at $1.55 \mu\text{m}$.

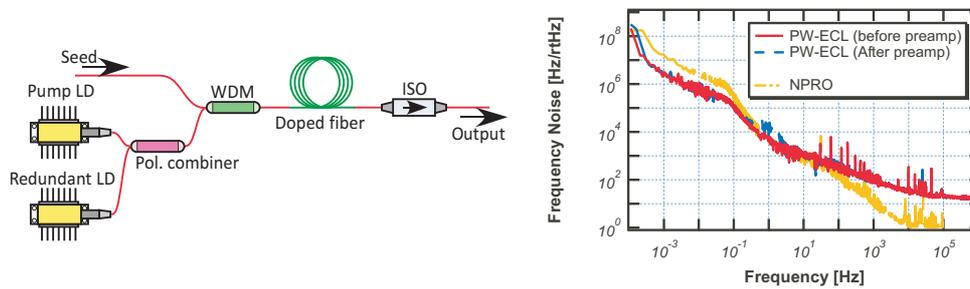


Figure 3. (Left) schematic diagram of the pre-amplifier. (Right) frequency noise of amplifier, as comparison of the PW-ECL (seed) and the NPRO.

Figure 3 (left) shows the design of the seed laser and the pre-amplifier system. The laser unit will house two seed lasers (PW-ECLs) and two pump laser diodes for redundancy, as well as their control circuits. The gain fiber is core-pumped.

Using a 1542-nm PW-ECL seed and an Er-doped gain fiber, we built a test pre-amplifier. Figure 3 (right) shows noise performance of the 1542-nm preamplifier, where the 9-mW PW-ECL input is amplified to 180 mW. The preamplifier adds negligible frequency noise (Fig. 3 (right)). The preamplifier adds intensity noise, especially at low frequency. This excess noise can be suppressed by controlling the pump power. For the 1064-nm system, we are using Yb-doped gain fiber and seed NPRO, which will be eventually replaced by the 1064-nm PW-ECL.

The fiber-based preamplifier power level is low, and, thus, the system components are not expected to present a flight risk; however, radiation hardness is an important remaining factor in qualifying pre-amplifier components. We have performed gamma irradiation tests on $1.06\text{-}\mu\text{m}$ Yb amplifier components, which are less mature than the $1.55\text{-}\mu\text{m}$ components. They showed a level of radiation damage compatible with mission requirements.

5. Power amplifier

We worked with LGS to develop a Yb fiber amplifier for the NGO/SGO missions. After trade studies and simulations, we constructed the $1.06 \mu\text{m}$ fiber amplifier shown in Fig. 4 (left).

A $10\text{-}\mu\text{m}$ 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, 6:1 pump combiner). 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 am-

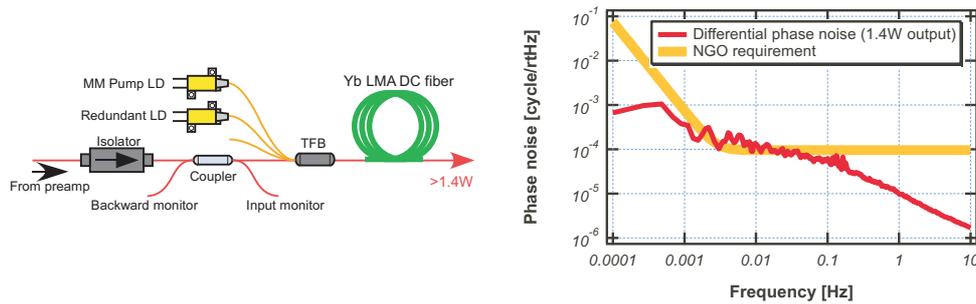


Figure 4. (Left) schematic diagram of power amplifier. (Right) differential phase noise of amplifier, compared to the NGO requirement.

plifiers. The TFB was identified as the most risky component within the amplifier, and was pre-screened by a thermal imager and repackaged using suitable compounds for higher reliability in space.

Originally, the length of the gain fiber was ~ 5 m. It produced ~ 6 W maximum output, which is too high for the LISA-like missions but useful to test damage issues. In the next version, the gain fiber length was reduced to ~ 3 m, to match the ~ 2 W requirement. We evaluated the noise performance of the power amplifier, using a commercial NPRO as a seed source. The power amplifier added negligible frequency noise to the carrier light of the seed. The differential phase noise [Tröbs et al. (2010)] is not suppressed by the control loop and has to be kept low. Figure 4 (right) shows the differential phase noise of the power amplifier with the shorter gain fiber. We have learned that this level is sensitive to the measurement environment (e.g., temperature stability), as well as the amplifier design and the operating condition (e.g., pump current). The intensity noise of the amplifier was also measured and stabilized to $\sim 10^{-4}/\sqrt{\text{Hz}}$ at 1 mHz by controlling the pump LD current.

To look at the amplifier reliability, we performed vacuum thermal cycling and gain fiber irradiation. The amplifier showed negligible change in performance after 100 hours of vacuum thermal cycling between 0°C and 60°C . We also looked at the effect of gamma irradiation on the gain fibers from different vendors, with an accelerated exposure of 60 krad over five hours. We tested a fiber from a U.S. vendor, and that fiber showed low-enough damage to be acceptable for space. Another fiber from a different U.S. vendor showed unacceptable level of damage.

6. Summary

We have presented our research at the NASA/GSFC on precision laser systems for the interferometric gravitational-wave missions. NASA/GSFC has been involved in research on spaceborne lasers since the 1990s and is actively seeking innovative solutions to meet future science missions' goals. We have invested approximately \$1.2 million over three years on laser development for the LISA-type missions. Our research has included amplifier development, noise measurements, and PW-ECL reliability studies. We will continue our laser system development with a goal of achieving TRL (technology readiness level) 5-6 in the 2014-2015 time frame.

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