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***High stability laser for interferometric earth gravity measurements***

*K. Dahl*

*K. Nicklaus*

*M. Herding*

*X. Wang*

*et al.*



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## HIGH STABILITY LASER FOR INTERFEROMETRIC EARTH GRAVITY MEASUREMENTS

K. Dahl<sup>1</sup>, K. Nicklaus<sup>1</sup>, M. Herding<sup>1</sup>, X. Wang<sup>1</sup>, N. Beller<sup>1</sup>, O. Fitzau<sup>2</sup>, M. Giesberts<sup>2</sup>, M. Herper<sup>2</sup>,  
R. A. Williams<sup>3</sup>, G. P. Barwood<sup>3</sup>, P. Lovelock<sup>3</sup>, P. Gill<sup>3</sup>, H. Koegel<sup>4</sup>, A. Sell<sup>4</sup>.  
<sup>1</sup>SpaceTech GmbH, Germany. <sup>2</sup>Fraunhofer-Institut für Lasertechnik, Germany. <sup>3</sup>National Physical Laboratory, UK. <sup>4</sup>Airbus Defence and Space GmbH, Germany

### I. INTRODUCTION

ESA's Gravity field and steady-state Ocean Circulation Explorer (GOCE) mission and the American-German Gravity Recovery and Climate Experiment (GRACE) mission map the Earth's gravity field and deliver valuable data for climate research. The latter mission uses a microwave ranging system to measure the inter-satellite distance [1]; GOCE was equipped with six ultra-sensitive accelerometers [2]. Follow-up missions like GRACE Follow-On will use laser interferometry, further improving the detection accuracy. An ESA Next Generation Gravity Mission (NGGM) [3] requires an investigation of the inter-satellite laser-ranging interferometer concept. One key specification for a high interferometric measurement sensitivity is the frequency noise of the laser source because any frequency fluctuation mimics a path length change between the satellites. Lasers for NGGM require a frequency stability of

$$\sqrt{S_v(f)} \leq \frac{40 \text{ Hz}}{\sqrt{\text{Hz}}} \sqrt{1 + \left(\frac{10 \text{ mHz}}{f}\right)^2} \quad (1)$$

in the frequency range of 0.1 mHz to 1 Hz which is about one order of magnitude more demanding than for LISA. Depending on the concept an output power of either > 90 mW or > 500 mW is desired. To date and to our knowledge, no space-qualified laser exists which fulfils these requirements.

Within the ESA funded development of a "High-Stability Laser with Fibre Amplifier for Interferometric Earth Gravity Measurements + Laser Stabilisation Unit for Interferometric Earth Gravity Measurements" an elegant breadboard (EBB) has been designed, manufactured, and characterized in performance. The EBB's critical components are representative in terms of power consumption, mass and dimensions w.r.t. a later flight model, enabling environmental tests without major redesign. Besides the aforementioned frequency stability the EBB's key requirements are a fibre-coupled, modular, and diffraction-limited laser system emitting light at 1064 nm with an output power of > 500 mW and a relative intensity noise (RIN) of  $10^{-3}/\sqrt{\text{Hz}}$  between 10 mHz and 1 Hz increasing with  $1/f^2$  towards 0.1 mHz; see Tab. 1.

This paper presents a summary of the design and performance characterization of the EBB.

### II. HIGH STABILITY LASER

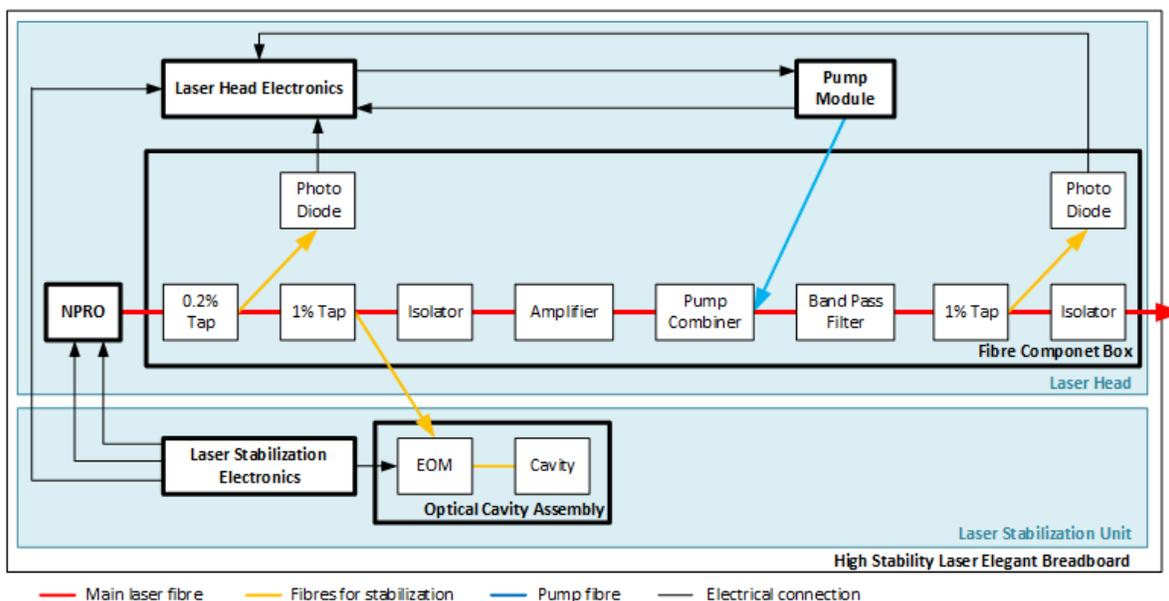
The EBB architecture of the high stability laser (HSL) (see Fig. 1) comprises a laser head with a low-power master oscillator and a subsequent fibre power amplifier that is pumped by one pump diode and frequency-locked to a high finesse optical cavity. In addition the EBB contains dedicated laser head electronics and laser frequency stabilisation electronics. The following subsections summarize the building blocks of the EBB.

#### A. Master Oscillator

The master oscillator is an off-the-shelf, fibre-coupled non-planar ring oscillator (NPRO) with an optical output power of 25 mW at a wavelength of 1064 nm; see Fig. 2. It is comparable in terms of performance and function to the space-qualified NPRO by Tesat. The oscillator's single-mode, polarisation-maintaining output fibre is spliced to the fibre power amplifier.

#### B. Fibre Power Amplifier

The fibre power amplifier consists of two boxes: the first one (see Fig. 3) houses a volume Bragg grating stabilized pump diode emitting light at a wavelength of 976 nm. The second box, the so-called fibre component box (see Fig. 4), comprises the all fibre-based amplifier. The multi-mode fibre of the pump diode is spliced to the fibre amplifier. The light from the pump diode is contra-directionally coupled into an active Yb-doped fibre via a pump combiner inside the fibre amplifier box; see [5] for further details.



**Fig. 1.** Block diagram of the High Stability Laser Elegant Breadboard.

### C. Laser Head Electronics

The laser head electronics is responsible for the thermal stabilization of the pump diode, the optical power stabilization and the readout of photo diodes. For control of the optical power stability of the laser system 1 % of the fibre amplifier output is monitored by a photo diode via the use of a tap coupler. The laser head electronics features an ADC, DAC, and a microcontroller for data acquisition and control loops.

### D. Optical Cavity Assembly

The optical cavity assembly (see Fig. 5) consists of a high finesse, cubic Fabry-Perot reference cavity of 50 mm length [6] which is made from an ultra-low expansion glass, a heat shield in a vacuum enclosure, an optics arm, and a fibre-coupled electro-optic modulator.

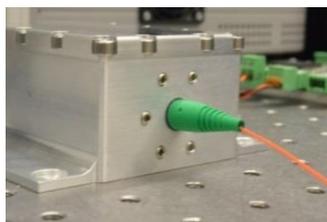
The incoming light (emitted by a fibre) is coupled into the cavity via a free-space optics arms which comprises off-the-shelf parts, e.g. a fibre collimator. The cavity assembly has been designed such that it possesses full performance and a high-alignment stability in the GOCE temperature environment [4] over the full operational temperature range. The structural resonances of the cavity assembly are above 140 Hz and the cavity mounting design has been improved to withstand launch vibration and shock loads.

### E. Laser Stabilization Electronics

The laser stabilization electronics locks the frequency of the master oscillator to the length of the optical cavity using the Pound-Drever-Hall technique. It is responsible for the rf modulation of the electro-optic modulator, the demodulation of the avalanche photodiode signal, and the servo control of the laser frequency providing feedback to the master oscillators piezo actuator and crystal temperature. It comprises analogue hardware and software including automatic lock (re-) acquisition.



**Fig. 2.** Master oscillator.



**Fig. 3.** Pump diode box.



**Fig. 4.** Fibre component box.



**Fig. 5.** Optical cavity assembly.

### III. TEST CAMPAIGN

This section covers the results of the full performance tests of the HSL EBB. In contrast to the first results presented in [4] and [5], the operational tests were performed with a frequency and power stabilized HSL EBB.

#### A. Performance Characterization

For the performance tests the pump diode box, the fibre component box, and the optical cavity assembly were mounted on a temperature-stabilized base plate allowing tests at various temperature levels. For the first two items the operational temperature range is 18-22 °C while for the cavity the range is 20-30 °C. The performance characterization was measured at minimum, maximum and middle of the temperature range.

The set of performance requirements is listed in Tab. 1. During the test campaign all requirements except for the relative intensity noise were verified; see for instance Fig. 6 for the measured frequency noise at mid temperature. The frequency stability of the EBB is well within the requirement in the whole measurement band from 0.1 mHz to 1 Hz even in a thermal environment significantly worse than the GOCE environment.

Fig. 7 depicts the relative intensity noise at mid temperature. The requirement is not met between 2 mHz and 0.5 mHz. The polarisation orientation in the fibres of the fibre amplifier has been observed to be temperature sensitive, leading to power of up to 3 % in the orthogonal polarisation. The downstream optical isolator translates these polarization fluctuations into intensity noise. The photo detector in the power control loops is located before the isolator, such that the power control loop has no impact on the intensity changes caused by the isolator. Furthermore, the coupling ratio of the used tap couplers for power stabilisation was found to be polarisation sensitive. In combination with polarisation changes due to temperature changes, this led to a degradation of relative intensity noise performance. This issue will be tackled in a next design iteration of the fibre amplifier.

**Tab. 1.** HSL EBB performance requirements.

Requirement Parameter	Requirement Value
Output wavelength	1064 ± 0.8 nm
Frequency noise spectral density	$< \frac{40 \text{ Hz}}{\sqrt{\text{Hz}}} \sqrt{1 + \left(\frac{10 \text{ mHz}}{f}\right)^2}$ for 0.1 mHz < $f$ < 1 Hz
Spectral linewidth	< 10 kHz
Spectral purity	< 45 dB (nominal polarisation state) < 40 dB (orthogonal polarisation state)
Wavelength tunability	> 4 GHz
Optical output power	> 500 mW
Output power stability	$< \frac{10^{-3}}{\sqrt{\text{Hz}}} \sqrt{1 + \left(\frac{10 \text{ mHz}}{f}\right)^4}$ for 0.1 mHz < $f$ < 1 Hz
Output polarisation	Linear, > 100:1
Spatial mode, $M^2$	TEM <sub>00</sub> , $M^2 < 1.2$
Power consumption	< 50 W

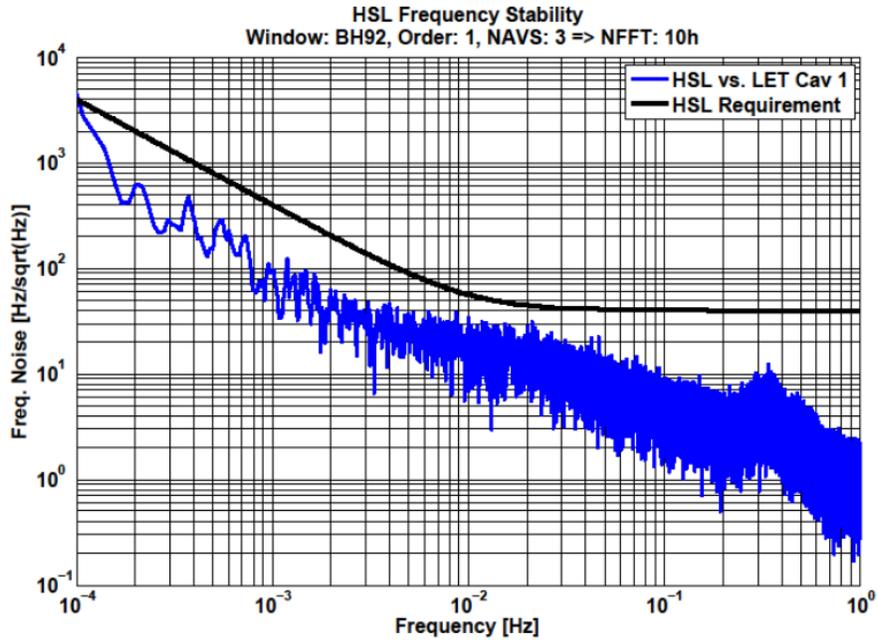


Fig. 6. The frequency noise of the EBB (blue) measured at an interface temperature at the fibre power amplifier of 20°C and a cavity interface temperature of 25°C is well below the requirement (black).

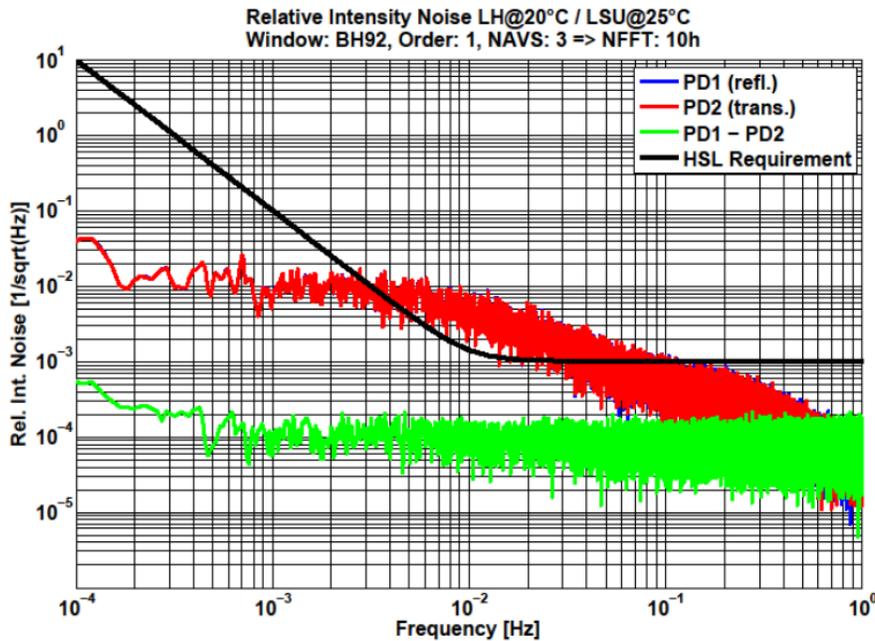


Fig. 7. The relative intensity noise (red) at fibre amplifier interface temperature of 20°C and cavity interface temperature of 25°C.

*B. Environmental Tests*

The optical cavity assembly and the fibre power amplifier (including the pump diode box) have successfully passed a non-operational thermal cycling test at ambient pressure. The temperature of the cavity was cycled from -20 °C to +50 °C and from -40 °C to +50 °C for the other two modules at a rate of < 2 K/min. The tests described in Section III were repeated and no degradation of the performance was detected in the subsequent performance characterization of the EBB.

#### IV. SUMMARY AND OUTLOOK

We have presented the design and performance characterization of a high stability laser EBB. The laser system meets all requirements except for relative intensity noise within a frequency range of 2 mHz to 0.5 mHz. Polarisation fluctuation in combination with the design of the control loop were found to cause this issue. This will be further investigated and tackled in the next design iteration.

In addition, initial environmental tests were performed. Further environmental tests of the fibre amplifier are scheduled in the ongoing ESA activity. These tests include operational thermal-vacuum tests within the operating temperature range from 20 °C to 30 °C, shock and vibration tests.

#### ACKNOWLEDGEMENT

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