An ultra-stable thermostat to explore optical metrology in the low-frequency regime

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Introduction

Current research aiming at testing fundamental physics, like measuring gravitational waves, require environments being highly stable over long periods in order to achieve high precision in the low frequency, i.e. the millihertz band. Temperature noise is the main contribution in these time scales and therefore it needs to be either suppressed or actively compensated. In this contribution we present the development of a Mach-Zehnder interferometer into an ultra-stable thermal environment. The interferometer set-up is based on the deep phase modulation scheme where the demodulation step takes place in a FPGA with a LEON3 soft-core processor. In order to study the noise contributions in the low-frequency regime, the interferometer is located in a vacuum chamber and inside a passive thermal shield. Moreover, an active control is also applied to reduce laboratory perturbations. Here we report the thermal characterisation of our thermostat by means of a series of applied thermal injections.

Experimental scheme

The basic design of our experiment is a Mach-Zehnder interferometer inside a vacuum chamber with a very stable environment. Inside the vacuum chamber and to ensure an ultra-stable thermal environment, five concentric cylinders have been mechanized. To control the temperature 11 thermistors are glued around the different locations. To vary and command the temperature inside the vacuum chamber we have 6 peltiers around the outer cylinder. These peltiers can be instructed to give a certain signal or to execute a PID controller.

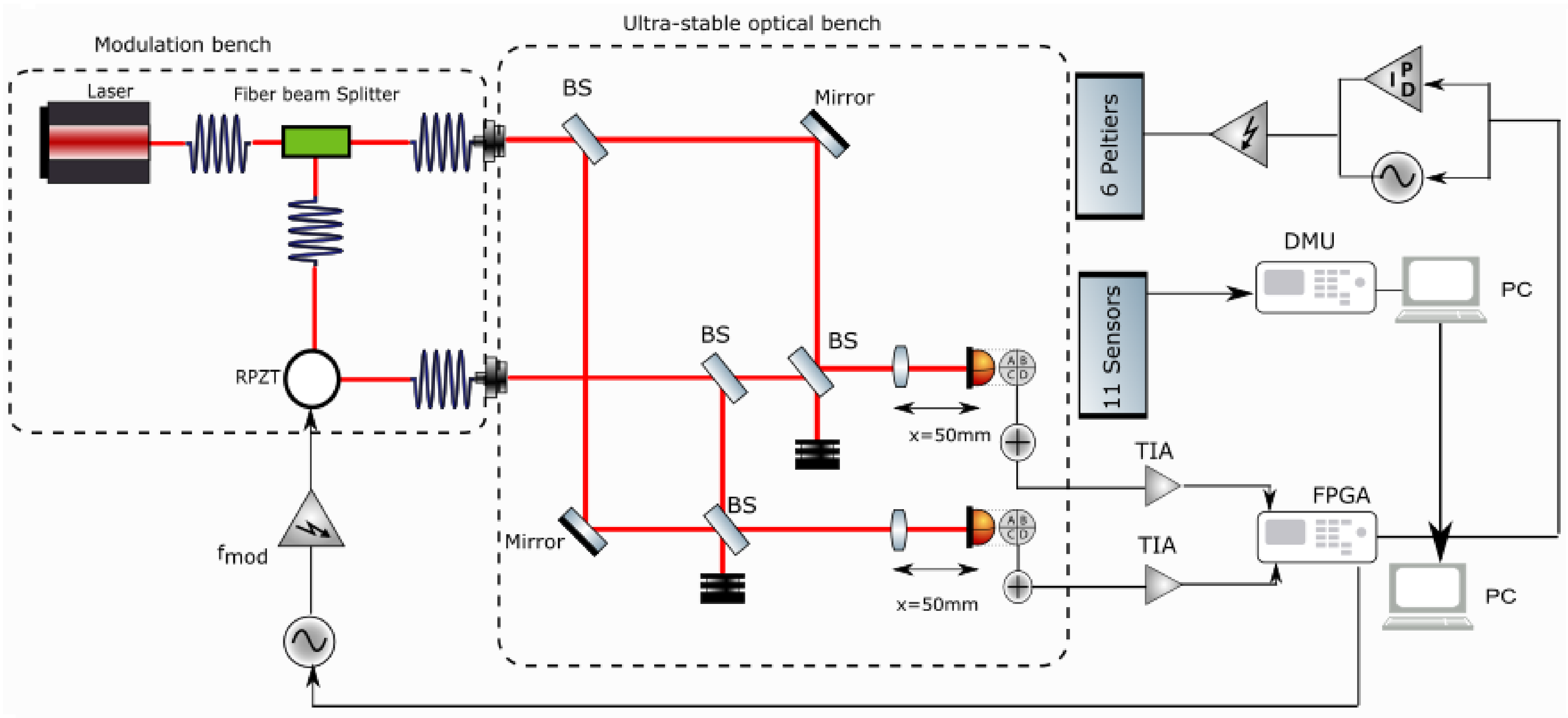

Figure: Experimental scheme implemented at the laboratory.

Optical setup

Optical bench implementation

Nested inside the vacuum chamber we have implemented a setup to test deep phase interferometry. It is a Mach-Zehnder interferometer which use a piezo tube with 9m of optical fiber wrap around it to increase the path-length in one of the interferometer arms. Our source is a laser diode at 1064nm and we are using a quadrant photodetector to measure the power. Data acquisition and post-processing is performed in a FPGA. To extract the phase we use the deep phase modulation method [1].

The assembly of the Mach-Zehnder interferometer has been done on circular optomechanical breadboard made of Carbon Fiber Reinforces Plastic(CFRP) with flat working surface.

Figure: Mach-Zehnder interferometer assembled on the breadboard.

Signal post-processing

We have developed the software infrastructure that will allow a FPGA-based phasemeter [2], configurable in real time thanks to the System On Chip(SoC) approach. Inside the *Xilinx*© FPGA, a *CobhamGaisler*© LEON 3 Soft-Core and following custom IP-cores have been synthesized:

- Wrapper to access 4*DSP*© FMC116 Analog to Digital Converter (ADC)
- Wrapper to access Digital to Analogue Converter (DAC)
- Single Bin Fourier Transform to the desired harmonics applied to the signal read from ADC

These component communicate directly with the Soft-core CPU using AMBA technology bus, and a custom embedded RTEMS Application running on it, is in charge of acquiring, processing and transmitting data to a Host PC application trough Ethernet TCP/IP. This Host PC Application, in parallel, manages the user interface to customize the system and data persistence.

Ultrastable thermal environment

To suppress temperature fluctuations inside a vacuum chamber we have designed an ultrastable thermal environment. It consists of 5 concentric cylinders acting as thermal shields and an active control temperature.

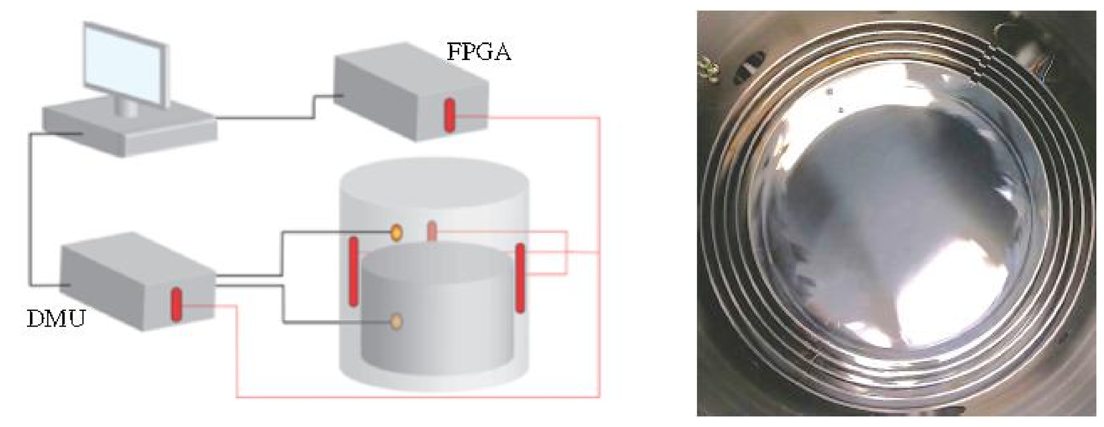

Figure: Scheme of the ultrastable thermal environment and the lower part of the 5 concentric cylinders inside the vacuum chamber.

Thermal shields characterization

The thermal shields have been mechanized with stainless steel and have polished mirror surfaces. This thermal shields acts as low-pass filters following the that mathematical model [3]:

$$\tilde{H}_{ij}(\omega) = \frac{\tilde{T}_j(\omega)}{\tilde{T}_i(\omega)} = \frac{1}{1+\frac{m_j c_j \beta_{ij}}{4\sigma A_j T_0^3} i\omega} \quad (1)$$

In order to characterize them we have applied an input thermal signal at the output cylinder using Peliter elements.

The results of the transfer function estimation is plotted in the following figure.

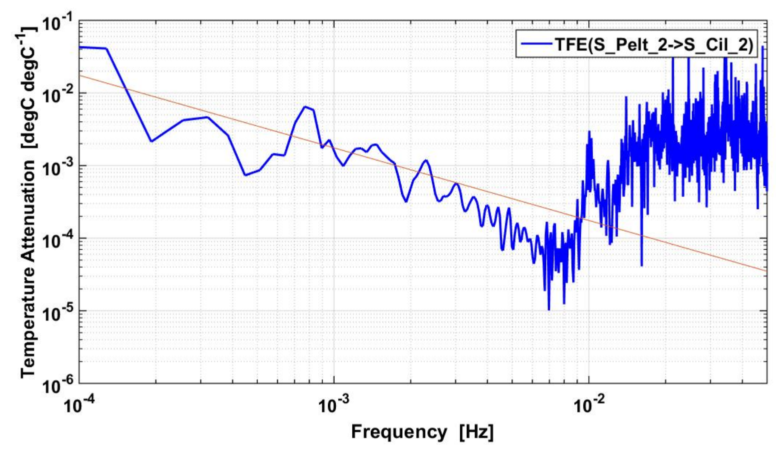

Figure: Transfer function estimation of the cylinder.

Active control

A thermal active control has been implemented to eliminate laboratory perturbations. We have design a PID controller using Peltier elements as actuators. These actuators can be supplied using the FPGA or the Data Management Unit(DMU) [4] designed for Lisa Pathfinder.

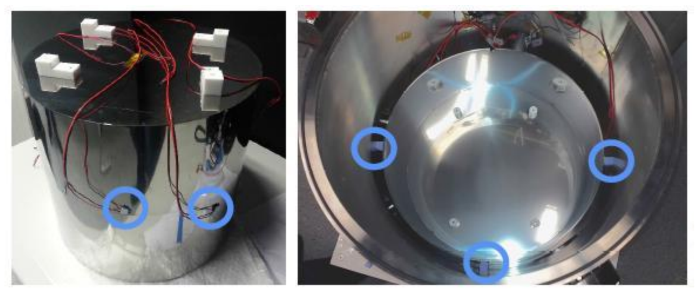

Figure: Peltier elements glued around the outer cylinder.

Results

Temperature noise

Laboratory temperature fluctuations, determined by measurement, are of the order of $10^{-1}\mathrm{K}/\sqrt{\mathrm{Hz}}$ at $10^{-3}\mathrm{Hz}$.

The temperature noise measured in our experiment is shown in the following figure where we plot the Power Spectrum Density of the temperature measured in vacuum conditions with thermal shields and the measurements with vacuum conditions, thermal shields and active control.

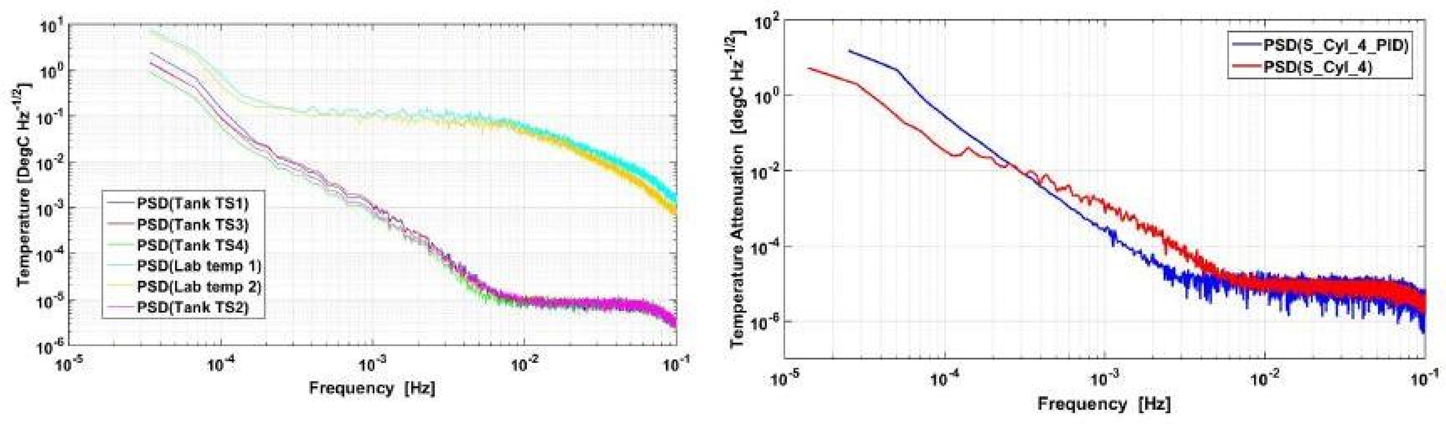

Figure: Temperature noise measured with and without active control. The horizontal line is our read-out noise.

Conclusions

To conclude and after the characterization of the thermal shields that have shown that experimental measurements resemble to the mathematical model the thermal stability has been measured, in both cases in vacuum conditions, a stability of:

- $10^{-5}\mathrm{K}/\sqrt{\mathrm{Hz}}$ at $7 \cdot 10^{-3}\mathrm{Hz}$ using the thermal shields.
- $10^{-5}\mathrm{K}/\sqrt{\mathrm{Hz}}$ at $3 \cdot 10^{-3}\mathrm{Hz}$ using the thermal shields and the PID controller.

Future improvements

Our next steps include:

- Integration of the FPGA in the optical experiment doing the digital analysis, modulation and post-processing.
- Integration of the metrology experiment in vacuum conditions and in ultra-stable thermal environment.
- Collect long interferometer runs.

References

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