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

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Abstract

We have designed and built an ultra-stable thermostat to explore optical metrology in the low-frequency regime. The thermostat includes five concentric cylinders acting as thermal shields and an active control temperature. Inside the 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.

Introduction

Current research aiming at testing fundamental physics, like measuring gravitational waves, requires 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 we have designed an ultrastable thermal environment, five concentric cylinders have been mechanized. To control the temperature 11 thermostats are glued around the different locations. To vary and command the temperature inside the vacuum chamber we have 6 Peltier elements around the outer cylinder. These Peltier elements can be instructed to give a certain signal or to execute a PID controller.

Optical bench implementation

Nestled inside the vacuum chamber we have implemented a setup to test deep phase interferometry. It is a Mach-Zehnder interferometer glued around the different locations. To vary and command the temperature inside the vacuum chamber we have 6 Peltier elements around the outer cylinder. These Peltier elements can be instructed to give a certain signal or to execute a PID controller.

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 4DSP® FMC116 Analog to Digital Converter (ADC)
- Wrapper to access Digital to Analogue Converter (DAC)
- Single Biir Filter Transform to the desired harmonics applied to the signal read from ADC

These components 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 through Ethernet TCP/IP. This Host PC Application, in parallel, manages the user interface to customize the system and data persistence.

Optical setup

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Results

Temperature noise

Laboratory temperature fluctuations, determined by measurement, are of the order of 10⁻³ K/√Hz at 10⁻³ 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.

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:

- 10⁻⁴ K/√Hz at 7 × 10⁻⁶ Hz using the thermal shields.
- 10⁻³ K/√Hz at 3 × 10⁻⁵ 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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Figure 1: Peltier elements glued around the outer cylinder.