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To cite this article: M Terán *et al* 2015 *J. Phys.: Conf. Ser.* **610** 012042

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Towards a FPGA-controlled deep phase modulation interferometer

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Abstract. Deep phase modulation interferometry was proposed as a method to enhance homodyne interferometers to work over many fringes. In this scheme, a sinusoidal phase modulation is applied in one arm while the demodulation takes place as a post-processing step. In this contribution we report on the development to implement this scheme in a fiber coupled interferometer controlled by means of a FPGA, which includes a LEON3 soft-core processor. The latter acts as a CPU and executes a custom made application to communicate with a host PC. In contrast to usual FPGA-based designs, this implementation allows a real-time fine tuning of the parameters involved in the setup, from the control to the post-processing parameters.

1. Introduction

Deep phase modulation interferometry [1] was proposed as a method to enhance homodyne interferometers to work over many fringes, allowing for instance continuous real-time tracking of free falling test mass, as required for space based gravitational wave detectors [2].

The advantage of the proposed deep phase modulation scheme is that simplifies the required optical setup, driving and modulation electronics when compared with heterodyne based detection experiments [4]. The technique was proposed as an extension of the so called $J_1 \dots J_4$ [3] methods, which involve a sinusoidal phase modulation at a fixed frequency with modulation depths up to 5 rad in one arm of the interferometer. These methods extract the encoded phase by means of analytical formulae to solve for the unknowns, among them the phase.

The deep phase modulation scheme uses however higher order harmonics ($n \geq 10$) to extract the phase information from the modulated output. For a phase modulated homodyne interferometer, this can be expressed as

$$V_{PD}(t) = V_{DC}(\phi) + \sum_{n=1}^{\infty} a_n(m, \phi) \cos(n(\omega_m t + \Psi)) \quad (1)$$



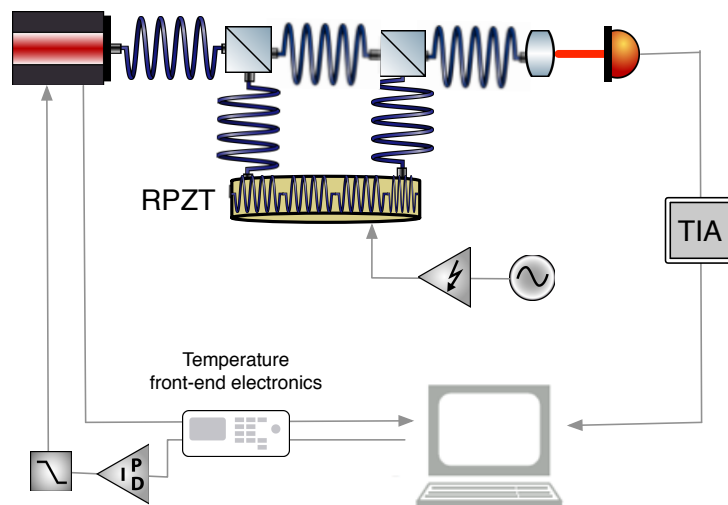


Figure 1. Deep phase modulation is implemented through an all-fiber Mach-Zehnder interferometer that uses a piezo tube with optical fiber coiled around it as a phase modulator. The measured output voltage is post processed in an external PC.

with

$$a_n(m, \phi) = k J_n(m) \cos\left(\phi + n \frac{\pi}{2}\right) \quad (2)$$

$$V_{DC}(\phi) = A(1 + C J_0(m) \cos \phi) \quad (3)$$

where $J_n(m)$ are Bessel functions, ϕ is the interferometer phase, m is the modulation depth, ω_m is the modulation frequency, Ψ is the modulation phase, C is the contrast, and A combines nominally constant factors such as light powers and photodiode efficiencies. Hence, the proposed scheme requires an implementation that allows high index phase modulation and precise phase extraction, as we describe in the following.

2. Experiment description and results

Our implementation of the deep phase interferometry is an all-fiber Mach-Zehnder interferometer operating at 1064 nm which uses a piezo tube with 5 m of optical fiber wrap around it to increase the pathlength in one of the interferometer arms. In our current setup, displayed in Fig.1, we have modified the LISA Pathfinder temperature front-end electronics [5] to control the laser temperature. Data acquisition and post-processing is performed in a PC.

In order to obtain the interferometer phase, the Fourier coefficients $a_n(m, \phi)$ in Eq. (2) are first obtained through a Fast-Fourier Transform of a segment of data. Then, the coefficients $\{k, m, \phi, \Psi\}$ are obtained by minimisation of

$$\chi^2 = \sum_{n=1}^{10} |\tilde{V}_{PD}(n) - a_n(m, \phi) e^{i n \Psi}|^2 \quad (4)$$

where $\tilde{V}_{PD}(n)$ is the n-th harmonic of the measured voltage at the output of the photodiode. A Levenberg-Marquardt algorithm is used to process the measured output and obtain the set

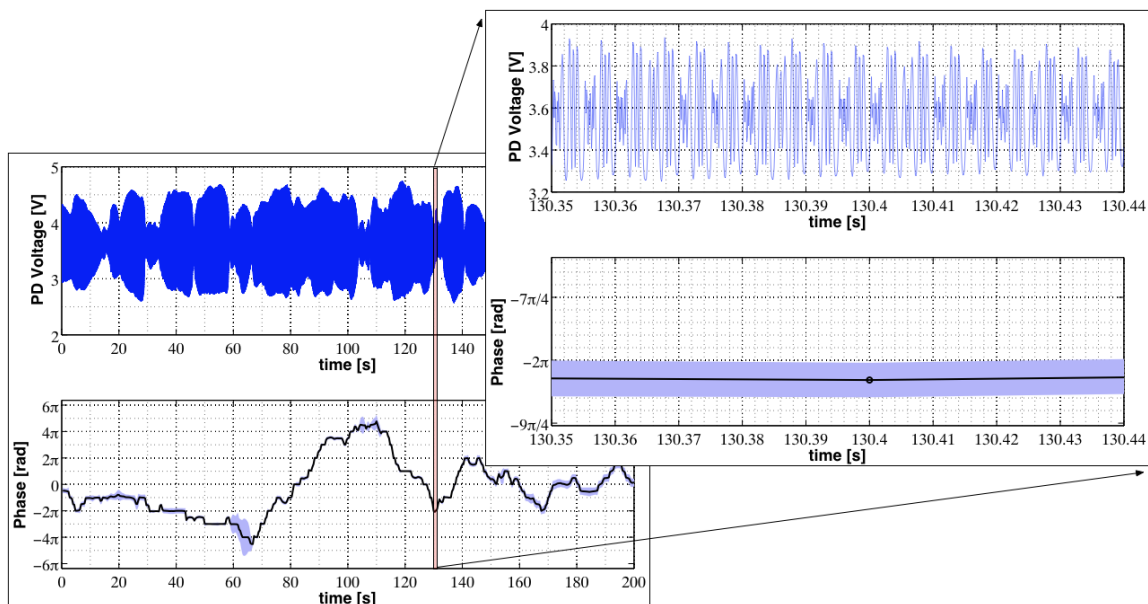


Figure 2. *Top:* Output voltage measured at the photodiode. *Bottom:* Measured phase after the post-processing. The shadowed area shows 95% confidence intervals due to fit errors. The inset shows a zoom on a 54 ms period where the phase modulation on the measured voltage can be clearly appreciated.

of coefficients. In our proof-of-principle implementation we have applied a 200 Hz modulation signal to the piezo with a modulation depth $m \simeq 9$. Our current low frequency sensitivity with a table-top experiment on air is $10 \mu\text{m}/\sqrt{\text{Hz}}$ at 10 mHz. Figure 2 shows the photodiode output sampled at 10 kHz while the bottom panel is the associated phase after post-processing in windows of 4000 samples, yielding an effective phase sampling of 2.5 Hz. The shaded areas show 95% confidence intervals due to fit errors.

3. The System On Chip approach

While the original deep phase modulation interferometer was implemented in a scheme similar to the one shown in Fig. 1, recent developments have improved the design to shift the generation of signal modulation and the phase extraction to a FPGA [6].

In the same line, we have developed the software infrastructure that will allow a FPGA-based phasemeter configurable in real-time thanks to the System On Chip (SoC) approach. As shown in Fig 3, the following components have been synthesized in a Xilinx[©] FPGA: A Gaisler[©] LEON 3 Soft-Core CPU, a 4DSP[©] FMC116 ADC wrapped in a custom made component that communicates directly with the CPU using AMBA technology bus, and a custom embedded RTEMS Application running on SoC, that is in charge of acquiring, processing and transmitting data to Host PC Application trough ethernet TCP/IP, system monitoring and configuration managing. In parallel, the Host PC Application manages the user interface to customize the system and data persistence.

4. Conclusions

We have shown an implementation of deep phase interferometer based on an all-fiber Mach-Zehnder interferometer with a piezo tube with fiber coiled around it acting as a phase modulator.

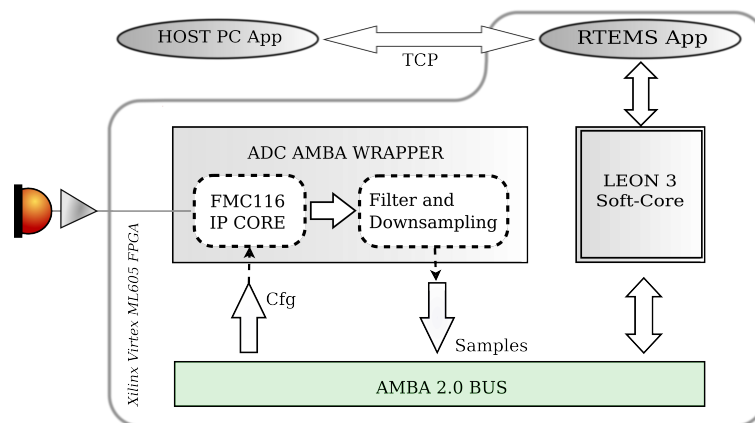


Figure 3. A schematic of the System On Chip (SoC) infrastructure in our current design.

Our proof-of-concept experiment achieves a low frequency performance of $10 \mu\text{m}/\sqrt{\text{Hz}}$ at 10 mHz.

We have also implemented the required software infrastructure to run the required post processing tasks in a dedicated FPGA. Our effort has been focused so far in achieving a data acquisition system based on the SoC approach where we can build more complex data processing tasks at later stages. The LEON 3 Soft-Core CPU embedded in the FPGA will allow a more flexible control of the experiment once it is fully integrated in the optical setup.

Future developments of our setup include the already mentioned integration of the FPGA in the optical experiment, the implementation of the digital analysis, modulation and post-processing in the FPGA and the integration of the metrology experiment in vacuum conditions.

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