Towards a FPGA-controlled deep phase modulation interferometer

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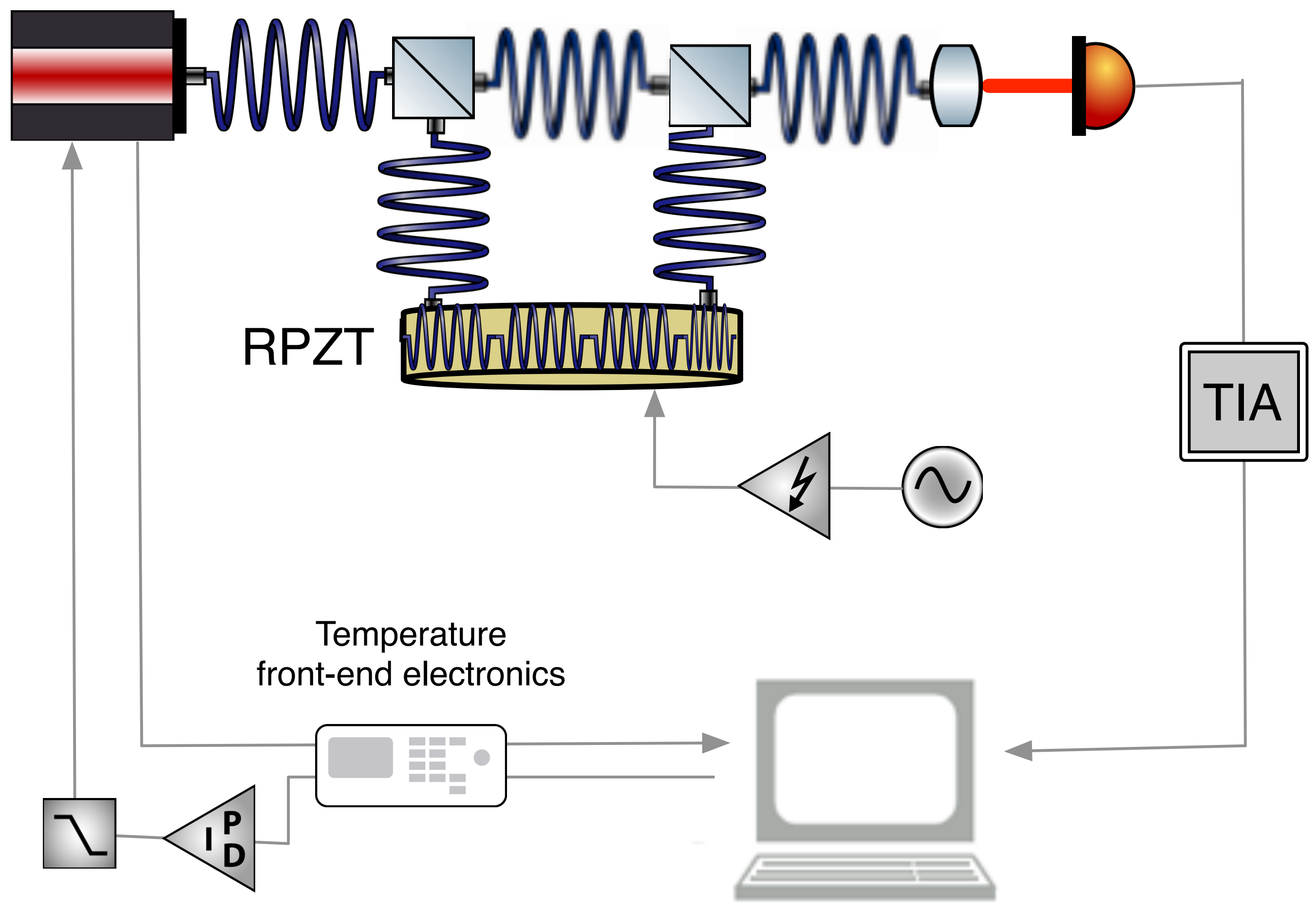
Introduction

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. 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.

Current experiment setup



We have implemented a setup to test deep phase interferometry. It is an all-fiber Mach-Zehnder interferometer which use a piezo tube with 5 m of optical fiber wrap around it to increase the pathlength in one of the interferometer arms. Our source is a laser diode at 1064nm.

In our current setup, we have modified the LISA Pathfinder temperature front-end electronics to control the laser temperature. Data acquisition and post-processing is performed in a PC. All these functionalities together with the modulation of the piezo are planned to be controlled by a FPGA in a future version of the experiment.

Deep phase modulation

The output signal of a phase modulated homodyne interferometer can be expressed as [1]

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

with

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

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

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.

Proposed as an extension of the so called $J_1 \ldots J_4$ [2] methods, the deep phase modulation scheme uses higher order harmonics ($n \geq 10$) to extract the phase information from the modulated output.

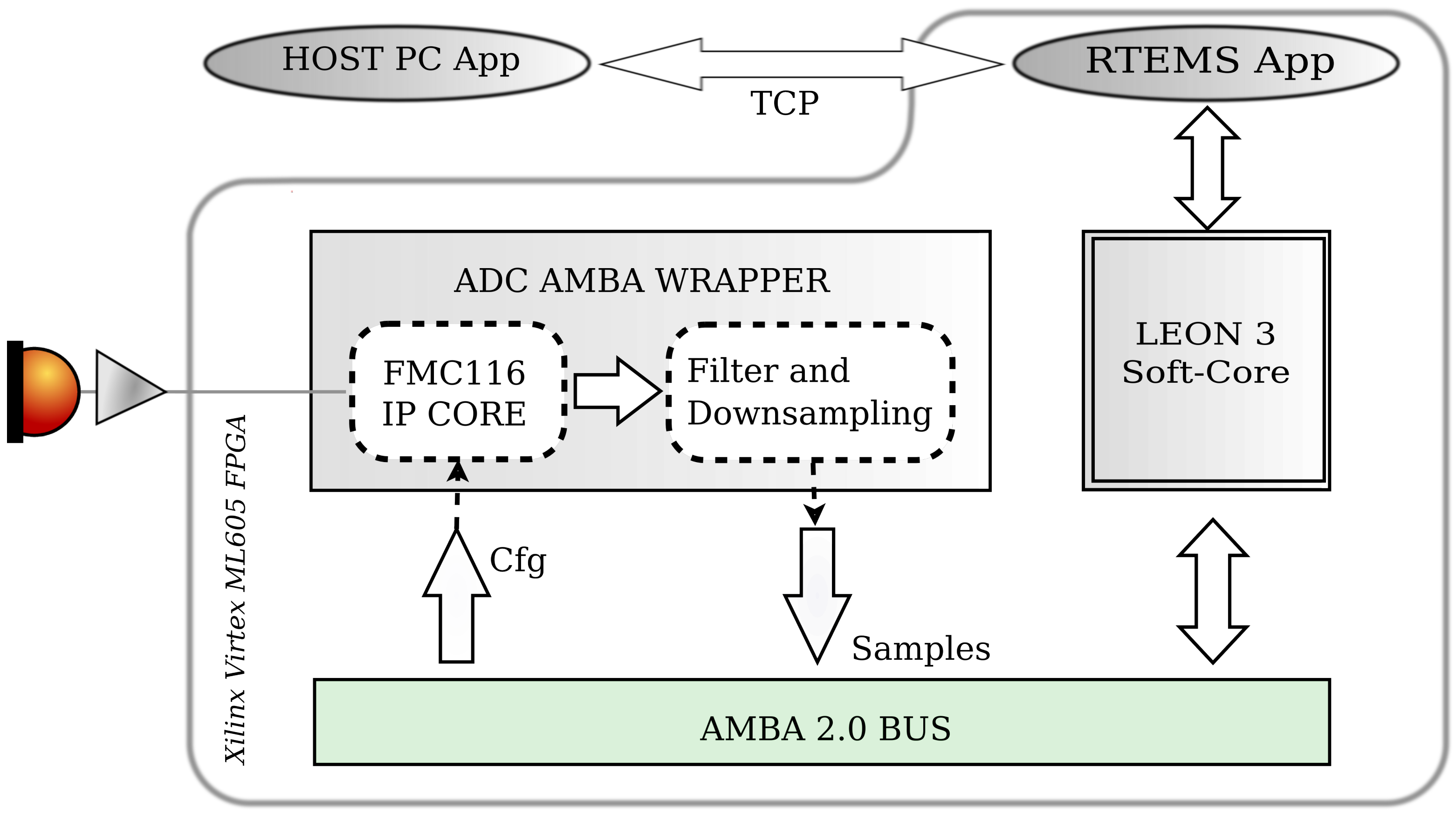
Phase extraction

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

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

where $\widetilde{V}_{PD}(n)$ 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 of coefficients.

FPGA architecture


HOST PC App

TCP

RTEMS App

ADC AMBA WRAPPER

FMC116
IP CORE

Filter and
Downsampling

LEON 3
Soft-Core

Cfg

Samples

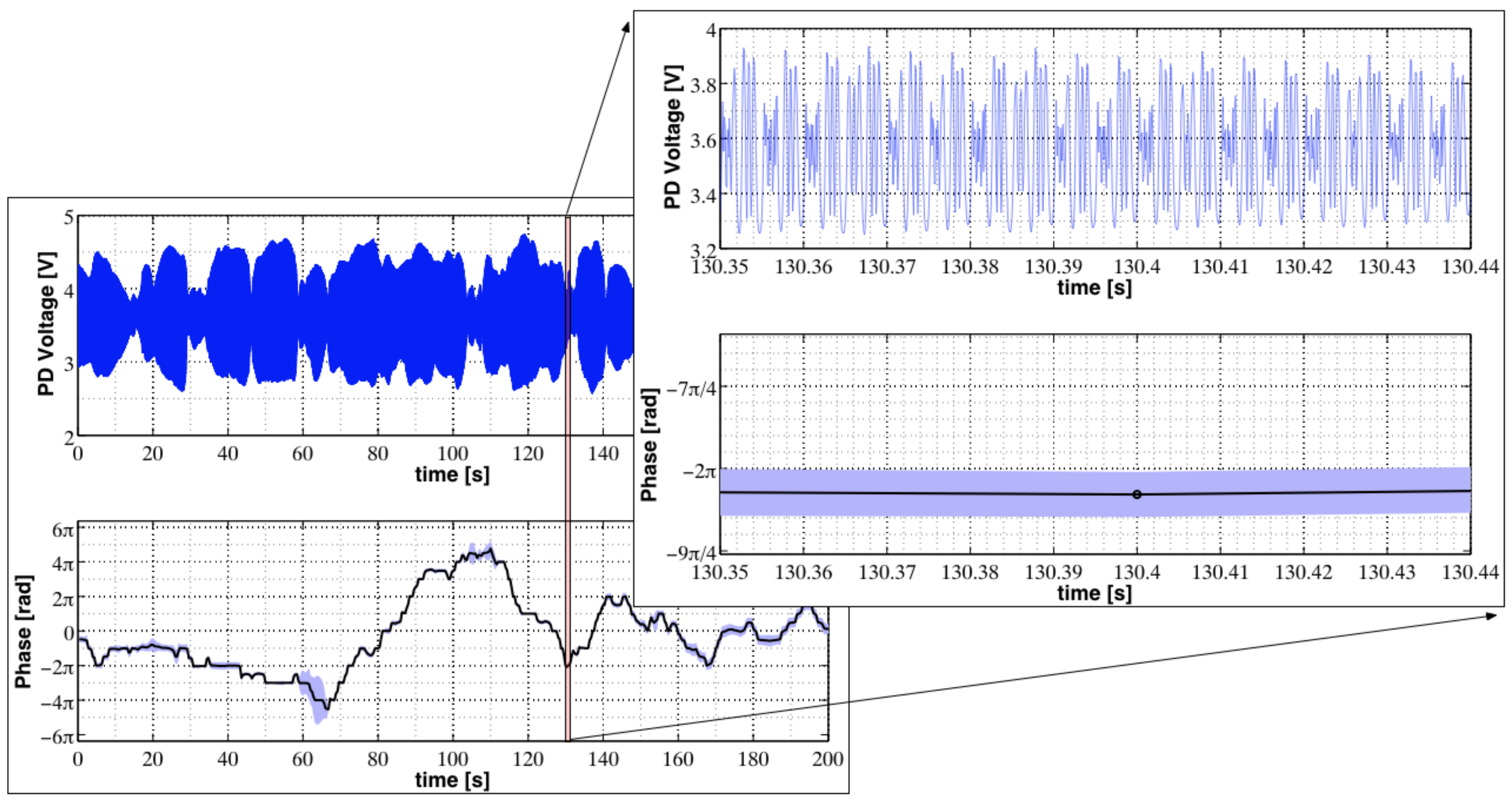
AMBA 2.0 BUS

Xilinx Virtex ML605 FPGA

The System On Chip (SoC) approach has been used with the following components 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.

The Host PC Application, manages the user interface to customize the system and data persistence.

Results



In our proof-of-principle implementation we have applied a 200 Hz modulation signal to the piezo with a modulation depth $\mathrm{m} \simeq 9$. Our current low frequency sensitivity with a table-top experiment on air is $10\,\mu\mathrm{m}/\sqrt{\mathrm{Hz}}$ at 10 mHz.

In the figure above the top panel corresponds to 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.

Future improvements

Our next steps include:

- Integration of the FPGA in the optical experiment.
- Implementation of the digital analysis, modulation and post-precessing in the FPGA.
- Integration of the metrology experiment in vacuum conditions.

References

- G.Heinzel *et al.*, *Deep phase modulation interferometry*, Opt. Exp., Vol. 18, No. 18, 19076 (2010)
- V.S. Sudarshanam, R. O. Claus, *Generic $J_1 \ldots J_4$ method of optical-phase detection: Accuracy and range enhancement* , J. Mod. Opt. 40, 483-492 (1993)

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