Implementation of a lock-in amplifier with internal reference signal generation on an FPGA board with an attempt for high-speed SPI-protocol-based data transfer to Raspberry Pi for ambient gas concentration measurement applications

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Abstract: An implementation of a lock-in amplifier (LIA) with fixed internal reference signal generation at the frequency of 8 kHz and 16 kHz on a Nexys 4 DDR FPGA board is demonstrated. An attempt to enable high-speed transfer of lock-in detected data to a Raspberry Pi for real-time wavelength modulation spectroscopy (WMS) based ambient gas concentration is also described. The satisfactory working of FPGA-based LIA could not be verified as the transfer of lock-in detected data from FPGA is still a work in progress.

1. Introduction

Tunable diode laser spectroscopy (TDLS) with wavelength modulation (WMS) is a well-established technique for ambient gas detection and measurement [1]. It is imperative to make a mobile gas detection setup to take the techniques established in the lab environment out in the real world. In this spirit, a mobile ambient water-vapour measurement system has already been developed [1]. However, the water-vapour system is only capable of estimating gas concentration after every one and a half minutes time. This computation time is quite large in comparison to the changes that might take place in the environment. Here, the high-speed data processing capabilities of an FPGA board can be harnessed to reduce the aforesaid computation time. Hence, an internal reference signal-generating lock-in amplifier (LIA) was implemented on a Nexys 4 DDR FPGA board. The Nexys 4 DDR board has an Artix-7 FPGA with 15,850 logic slices, each with four 6-input LUTs and 8 flip-flops providing ample logic resources for a lock-in amplifier implementation. It has an on-chip analog-to-digital converter (XADC) capturing data at 1 MSPS with a 12-bit resolution, which is sufficient for our application. It also has a clock speed exceeding 450 MHz, enabling high computation speed and various Pmod ports [2], which were utilized for SPI communication with Raspberry Pi. The lock-in detected signal is being transferred from the FPGA to Raspberry Pi to enable further curve fitting required as part of the WMS procedure. The overall signal flow of the intended system is as follows:

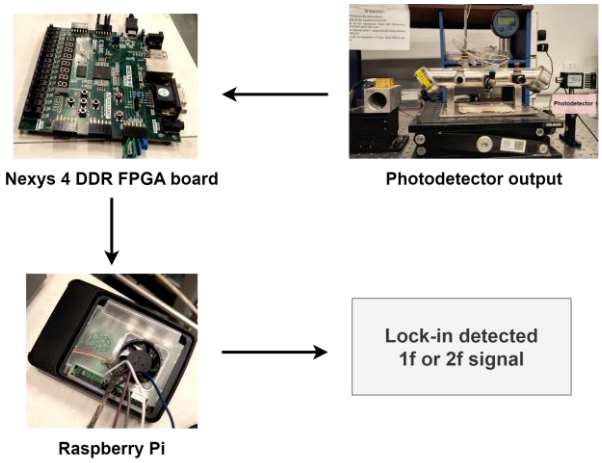

Fig. 1. Flow of signal in the FPGA-based LIA setup

2. Details of the FPGA implementation of lock-in amplifier

Our implementation of LIA only calculates the amplitude of the signal of the desired frequency as per the needs of the WMS algorithm. The photodetector output is acquired on the FPGA board using its XADC. The reference signals, i.e. sine and cosine waves, are pre-computed and saved in arrays. Currently, we are only generating reference signals at the frequencies of 8kHz and 16kHz, as required for our application. The multiplication and addition operations are carried out by the multiplier and adder modules, respectively, from the IP catalog in Vivado 2022.2 (an FPGA design software). The square root operation is performed using the 'CORDIC' module, and a low pass filter of the cutoff frequency of 80Hz is implemented using the 'FIR compiler' module.

A Jupyter notebook was also created for a better understanding of the lock-in detection operations, which can be accessed at this link.

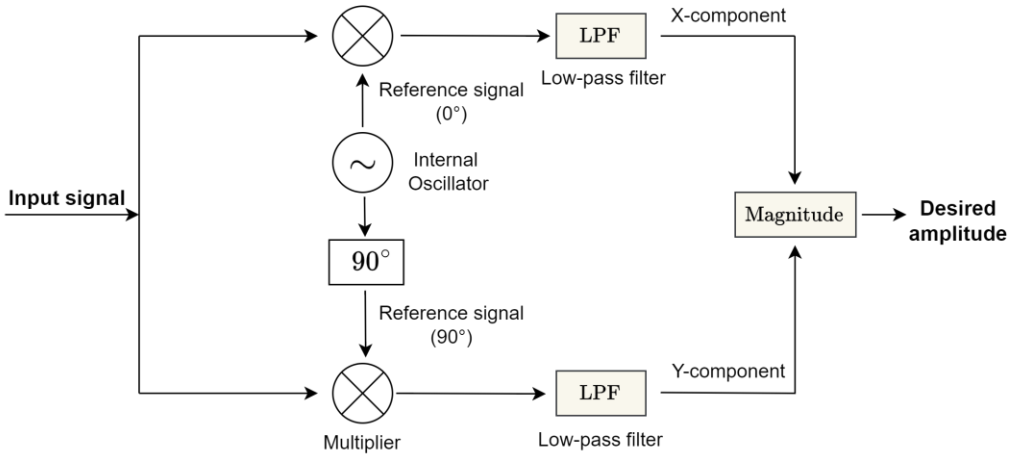

Fig. 2. Operations taking place in the FPGA

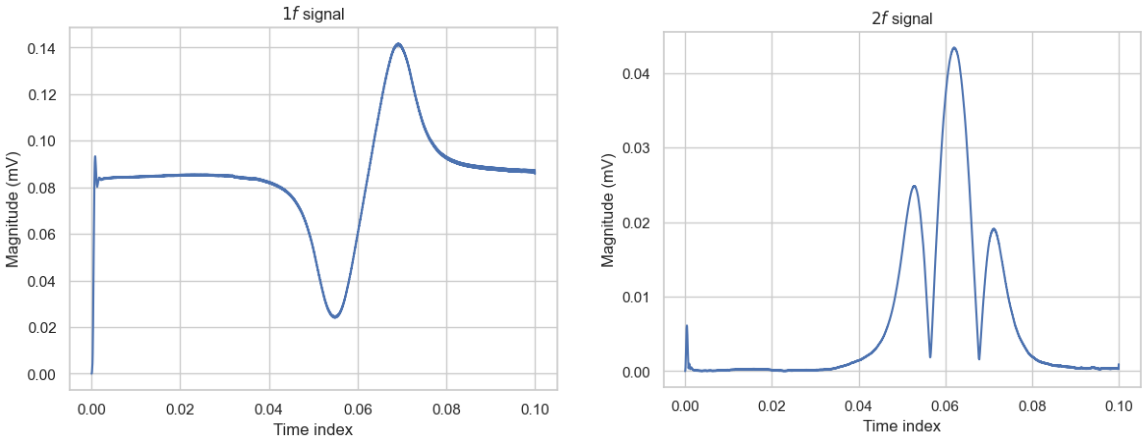

Fig. 3. Illustrative 1f and 2f (1st harmonic and 2nd harmonic respectively) plots from the Jupyter notebook

3. Data transfer from FPGA to Raspberry Pi

Serial Peripheral Protocol (SPI) based high-speed communication was implemented between FPGA and Raspberry Pi. 'spidev', a python-based library for SPI communication, was used on the Raspberry Pi, and a custom implementation of SPI [3] in Verilog was used on the FPGA board. The Raspberry Pi acted as the master (as 'spidev' only supports being the master) and FPGA as the slave in SPI communication. The dedicated SPI GPIO pins were used on the Raspberry Pi and the Pmod pins were used on the FPGA board. A key step in getting a stable data transfer was to have a ground between the FPGA board and Raspberry Pi. A maximum SPI clock speed of 7

MHz was achieved for reliable data transfer. However, a clock speed of at least 12 MHz is necessary to achieve a true real-time data transfer. A possible solution is to store some values on the FPGA board and then transfer them to achieve a lossless data transmission. Furthermore, a triggering mechanism also needs to be implemented to view the current waveform on Raspberry Pi.

4. Conclusion

A lock-in amplifier with internal reference signal generation was implemented on the FPGA board. An attempt to enable real-time transfer of the lock-in detection data was made using the SPI protocol. Further experimentation and tweaking are required to get the correct output from the FPGA board. Currently, we do get a DC value when a sine wave input is given to the lock-in amplifier, but its voltage value does not correspond to the RMS value of the sine wave. A mechanism to store data on the FPGA board prior to transmission also needs to be implemented to prevent data loss. This would enable us to visualize the 1f (first harmonic) signal, our ultimate goal of FPGA implementation of a lock-in amplifier.

5. References

[1] S. De, D. Paul, K. T. V. Grattan and A. L. Chakraborty, "Design and Validation of a Vehicle-Mounted Near-IR If Wavelength Modulation Spectroscopy System for On-Road Measurements of Ambient Water Vapour in Gandhinagar-Ahmedabad, India," 2023 IEEE SENSORS, Vienna, Austria, 2023, pp. 1-4, doi: 10.1109/SENSORS56945.2023.10325201.

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