Digital phase-analyzer for low frequency applications based on reconfigurable hardware

G. Macias-Bobadilla, I. Serroukh, L. A. Franco-Gasca
División de Estudios de Posgrado, Facultad de Ingeniería, Universidad Autónoma de Querétaro
Centro Universitario, Cerro de las Campanas S/N, Querétaro, Qro., C.P. 76010, México

M. López-Romero, F. Jiménez-Tapia
División de Tiempo y Frecuencia, Centro Nacional de Metrología, CENAM
Km. 4.5 carretera a los Cues, El Marques, 76241, Querétaro, México
(Recibido: 17 de junio de 2009; Aceptado: 23 de abril de 2010)

In Photoacoustic experiments and low frequency Photodiode applications, Phase sensitive detection is one of the basic operations performed by a lock-in amplifier. Regrettably, it is common to use only basic functions of those devices, in spite of their high cost. The objective of this research is to show the results that were obtained from the development and design of a basic phase shift sensitive device using reconfigurable hardware, which allows a reduction in experimental costs while generating the possibility to apply the developed device in different research fields.

Keywords: Phase sensitive detection; Lock-in amplifier; Photoacoustic-Photodiode applications

1. Introduction

Phase Sensitive Detection (PSD) is one of the fundamental operations that lock-in amplifiers (LIAs) use to single out the component of an AC signal at a given modulation frequency and to reject noise signals at another frequencies [1].Many kinds of LIAs exist, and their fundamental variants are based on analog or digital PSD. The former devices employ an analog multiplier to make the convolution process which is intrinsic to PSD. Obviously, this part of the analog LIAs is one of the most expensive elements. In this case, if a better exactitude is required then the costs become higher. The second kind of LIAs employs a digital multiplier to make the convolution process which is cheaper when compared to the analog multiplier. The exactitude is directly related to digital resolution of the applied multiplier [2].

Other variants of LIAs should be classified according to the frequency range that can be handled by their internal oscillator, i.e. LIAs for low frequency as Photoacoustic, Photothermal and low frequency Photodiode applications, middle frequency applications as like Radiometry and high frequency applications such as Photon Counting [1-4].

Photoacoustic and Photothermal are relatively new techniques that allow investigators to obtain a qualitative and quantitative characterization of a material without invading it [5 – 7]. Many articles have been written about Photoacoustic and Photothermal experiments that employed commercial LIAs. In most of the cases only basic functions of the commercial device are used [6, 8 – 15].

The purpose of this research is to show results from designing and implementing a custom digital PSD device for basic Photoacoustic applications, it was implemented on a reconfigurable hardware circuit such as Field Programmable Gate Arrays (FPGA). As it was aforementioned, digital PSD is easier and cheaper to develop. In this case the internal multipliers from the FPGA were used to implement this detection process, after digitizing analog measured signals from the experiments.

In order to stimulate the samples to be studied, a synthetic sinusoidal signal, which frequency and phase are known, was used and implemented in the same device. In addition the design of the device allows the selection of appropriate frequencies depending on the kind of experiment or studied material.

The developed device can measure and generate signals from 1 Hz to 10 KHz; the reconfigurable system based on FPGA may be implemented on a wide frequency range depending on the Digital to Analog Converter (DAC) and the Analog to Digital Converter (ADC) used during implementation.

Another advantage of the developed reconfigurable system is that it can be implemented with on-line systems or as part of a permanent monitoring system using low cost circuitry, a minimum amount of area and energy. This essentially eliminates the need to purchase an expensive device that is not used with its full capacity. [11-15].

Some resolution experiments are presented herein to demonstrate the operation ranges and the resolution of the developed device.

2. Experiments

2.1. Basic PSD digital detection theory

There are many ways to detect the phase from a measured signal. Some analog techniques use high speed switch systems to select the desired frequency. The resulting signal is passed through a low pass filter used as a rectifier to obtain a near DC signal that is related to the phase as is shown in Fig. 1. In this case, the measured signal is

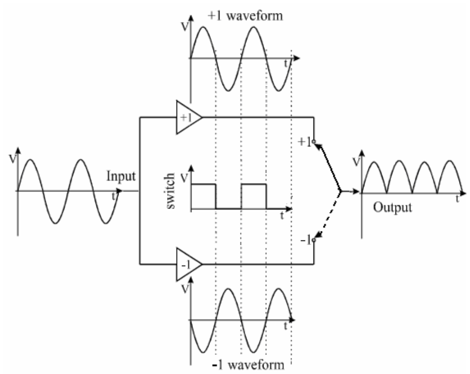

Figure 1. High speed switch system.

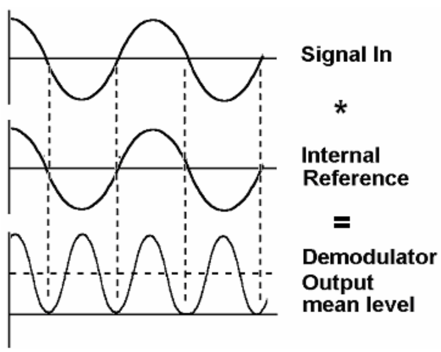

Figure 2. The Average signal result of multiplication from the measured signal and reference signal is related to phase difference between both signals.

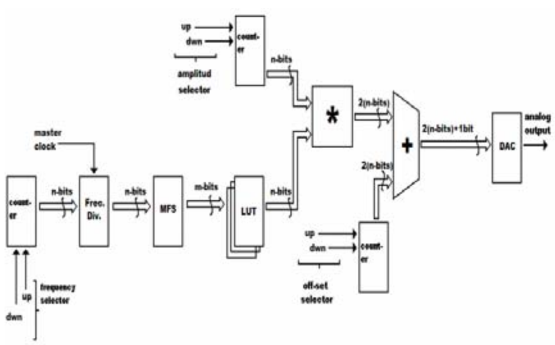

Figure 3. Basic block diagram of the signal generation section designed.

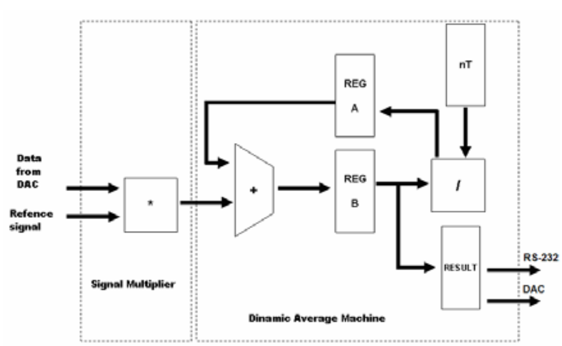

Figure 4. Dynamic Average Machine designed.

affected by the switch frequency and phase, and the resulting signal is proportional to the difference of phase [16].

Another way to detect the phase is to multiply the measured signal by a reference signal using an analog multiplier. In this case the reference can be a square wave signal; meaning that the resulting signal is similar to the signal obtained from a high speed switch system. If the reference signal is a sinusoidal wave, the result will be a signal from the sum of frequencies from reference and measured signal in which case the average of the resulting signal is related to the phase, as shown in Fig. 2. Note that noise in the measured signal has no effect or has a minimal effect on the average of the resulting signal. In both cases the resulting signal is passed through a low pass filter as a rectifier to obtain a near DC signal; as was aforementioned this analog technique is expensive [1-4].

The most common way to detect the phase is to use a digital multiplier in order to multiply the digitized measured signal by the digital reference signal. In such cases it may be easy to change the kind of reference by using another signal, i.e. square, sine or triangle waves, and then to select the phase of reference signal to the convenience of appropriate to the experiment. The result of multiplying the digitized measured signal by the digital reference signal is similar to the analog process. The difference is that the result is digital and the average of the result may be calculated easier than in analog systems. The exactitude of the result is directly related to the resolution of the DAC used to digitize the measured analog signal, the resolution of the digital internal reference, and finally the resolution used for the multiplier and average operation [1, 2].

There are many other advantages to this digital method of detecting phase which are fully documented in current literature [1-4].

2.2. Minimal System Requirements

It is important to define the range of the parameters used in Photoacoustic and low frequency Photodiode experiments as a justification of the operation range of the developed system. Also it is important to mention some considerations that have been taken into account in the experimental hardware setup.

2.3. Usual hardware configuration used in Photothermal and Photoacoustic experiments

In the case of the Photoacoustic experiments, usually a cell is used to contain the sample under study. This sample is irradiated by modulated intensity laser light beam. The Photoacoustic cell is connected to a microphone (often an electret ones), using a small diameter duct, and the electrical signal from the microphone is supplied to a pre-amplifier or amplifier section before being processed with a commercial LIA. Data filtered by the LIA are recorded

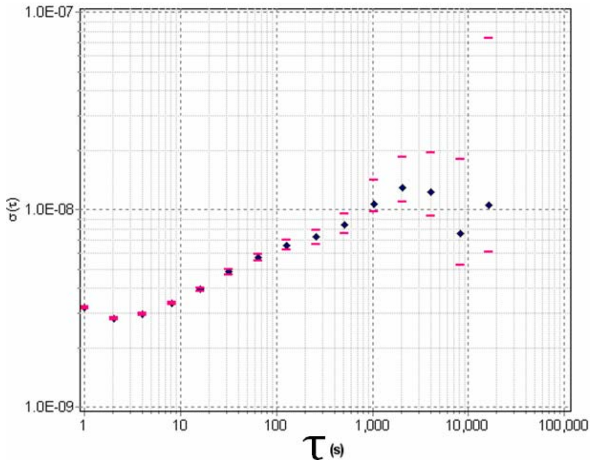

Figure 5. Results obtained from stability frequency analysis using Allan deviation.

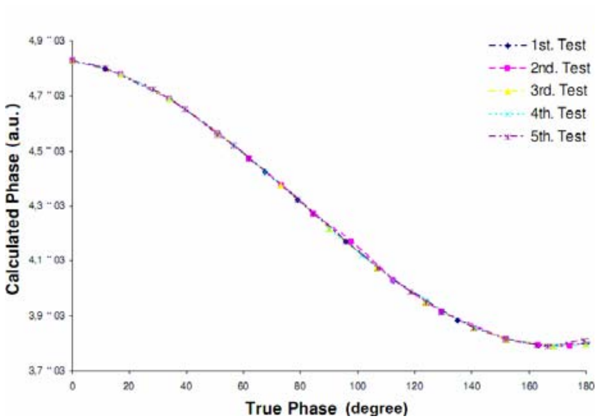

Figure 6. Results obtained from precision phase shift detection from 0-180°.

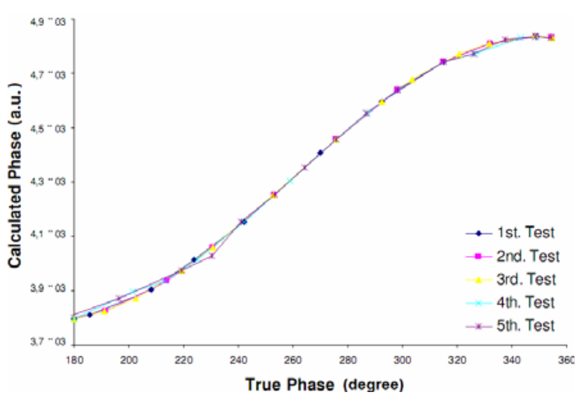

Figure 7. Results obtained from precision phase shift detection from 180°-360°.

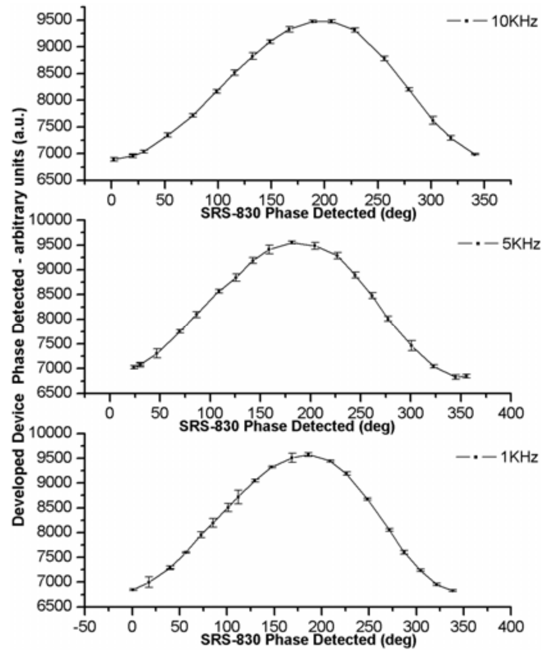

Figure 8. Phase detected from Developed Device versus SRS-830 at different frequencies.

and stored in a computer for later analysis [5, 6, 12-14].
For Photothermal analysis, the hardware setup is similar; being the cell with the microphone substituted by thermal sensors like a pyroelectric or an infrared one [7-10, 12, and 15].

2.4. Frequency ranges used in Photoacoustic and Photothermal experiments

In many Photothermal experiments, frequency scans are used to obtain some thermal parameters of the sample. Common reported frequency ranges are between 1 Hz and 10 KHz [6, 8, 10, 11-15].
This confirms the fact that in most of the Photothermal and other low frequencies Photodiode experiments the commercials LIAs are not used at full capacity.

3. Hardware Design

This section is divided into three sections: signal generation, signal acquisition for phase detection, and data transmission. Each one was designed taking into account the principal requirements of the Photoacoustic experimental setups, and developed using exclusive FPGA technology for the digital sections. For this experimental test a Spartan3–XCS200 from Xilinx was used.

3.1. Signal generation

The first requirement in the hardware design is to implement the signal generation section. This signal is necessary to select the operation frequency for the experiment. Commercial LIA usually employs sinusoidal signals as a modulation signal. For this design all the characteristics related to the generation of the modulation signal were implemented in digital format. To generate the sinusoidal signal a Look-Up Table (LUT) was used to store the wave forms. The control related to the selection of the frequency, amplitude, initial phase and off-set was implemented in digital format. Finally digital data were converted to analogue data using a DAC. For this experimental test a DAC0800 from National Semiconductor was used, and the developed FPGA based system permits scaling to any n-bit parallel DAC. Fig. 3 shows a block diagram of the developed signal generation section.

3.2. Signal acquisition for phase detection

In this section, to acquire data from the analogue signal it is necessary to use an ADC. For this experimental test an ADC0804 from National Semiconductor was used, but also the FPGA based system allows scaling to any n-bit parallel ADC. The digitized signal was digitally multiplied by the reference signal. This is according to the basic phase detection techniques. In this case the average of the operation is calculated using a dynamic average machine.

The result may be sent, via RS-232 protocol, to a computer or could be sent to the output as a proportional analogue signal. Fig. 4 shows the basic diagram of the dynamic average machine.

3.3. Data transmission

The data transmission was implemented using the synthesizable mini-UART core in VHDL code from the GNU public license which permits the data transmission, via RS-232, to store the results in a computer for future analysis.

4. Obtained Results

As a first test, the signal generation section was calibrated using an arbitrary frequency. For this experimental calibration a sinusoidal signal, at 9084 Hz, was selected from the developed system using a Timer/Counter/Analyzer CNT-91 50ps/300MHz from Pendulum locked to Primary Frequency Standard Cesium 5071A from Hewlett Packard at “Division de Tiempo y Frecuencia – CENAM, Mexico” laboratories, but any frequency in the range of 1 Hz to 10 KHz could be used and same results would be expected. Fig. 5 shows the results obtained from stability using Allan deviation as a stability analysis tool.

The complementary test for the developed system is related to the precision of the phase shift detection operation. This experimental test was made using a Timer/Counter/Analyzer CNT-91 50ps/300MHz from Pendulum at 1 KHz. Figs. 6 and 7 show the results obtained from five precision tests of the phase shift detection from 0-180° and 180°-360°, respectively.

The units of the magnitudes of the Y axis in Figs. 6 and 7 are arbitrary units (a.u.). This is because the developed system may present results in decimal format using 7-segment displays, via RS-232 or in analog format (Voltage) using a DAC with the corresponding resolution. To avoid the presentation of multiple results of each output format, average results from Dynamic Average Machine are presented in decimal format. X axis shows the true phase calculated by Timer/Counter/Analyzer CNT-91 50ps/300MHz from Pendulum.

Also 3 comparative tests were made at different frequencies; Fig. 8 shows results of phase shift detection from developed device versus SR-830 commercial lock-in amplifier from Stanford Research Systems. The results were carried out from 0 – 360° at steeps of 15° from 3 different frequencies: 1 KHz, 5 KHz, and 10 KHz. The small variation in the measurements is reflected in the small value of standard deviation. It is important to mention that the result was calculated from 10 different measurements in both cases, made by the commercial lock-in amplifier and developed device.

5. Conclusions

As was illustrated in Fig. 5 the analysis of stability shows results from 1.0×10-8 and 1.0×10-9 at windows of 1 – 100, 000 seconds. This is considered a favorable behavior for frequency scans operations because these are commonly used since it has been reported in different publications.

Another important obtained result is the precision, shown on Figs.6 and 7, and the low standard deviation shown on Fig. 8. The low deviation is related to the possibility to repeat the experiment. This complies with the basic requirements used in low frequencies experiments, as photodiode phase-shift detection or low frequencies photoacoustic applications.

Finally, the reconfigurable platform, used for the developed system, permits the possibility of expanding the operation frequency range and offers the opportunity of incorporate the developed systems in other scientific applications, as on-line permanent monitoring systems.

Acknowledgments

The authors thank to CONACYT for financial support for this research, Professor Rene de Jesus Romero Troncoso for important recommendation regarding to FPGA synthesis and Silvia Stroet for English edition support.

References

[1]. Rastelli, R. Abbiati and A. Geraci, Rev. Sci. Instrum., **76**, 093112 (2005).
[2]. J. Gaspar, S. Feng, A. Gordillo, M. Hepp, P. Ferreyra and C. Marques, MICPRO, **28**, 157 (2004).
[3]. L. Barragán and J. Artigas, R. Alonso and F. Villuendas, Rev. Sci. Instrum., **72**, 247 (2001).
[4]. Gökmen, A. Ulgen and S. Yalçin, Spectrochim. Acta Part B, **91**, 97 (1995).
[5]. P. Morais, A. Oliveira, A. Tronconi, T. Goetze and N. Buske, IEEE-Transmag., **39**, 5 (2003).
[6]. J. Balderas-Lopez, Eur. Phys. J. Special Topics, **153**, 167

(2008).
[7]. Wang, Y. Liu, A. Mandelis and J. Shen, Eur. Phys. J. Special Topics, **153**, 415 (2008).
[8]. Matvienko, J. Jeon, A. Mandelis, et. al., Eur. Phys. J. Special Topics, **153**, 463 (2008).
[9]. Wang and A. Mandelis, Eur. Phys. J. Special Topics, **153**, 123 (2008).
[10]. Bendada, N. Baddour, A. Mandelis and C. Moreau, Int. J. Thermophys., **26**, 3 (2005).
[11]. J. Xia and A. Mandelis, Eur. Phys. J. Special Topics, **153**, 283 (2008).
[12]. G. Spirou, A. Mandelis, I. Vitkin and W. Whelan, Eur. Phys. J. Special Topic, **153**, 491 (2008).
[13]. R. Lindley, A. Parkes, K. Keen, E. McNaghten and A. Orr-Ewing, Appl. Phys. B, **86**, 707 (2007).
[14]. J. Balderas-Lopez, Eur. Phys. J. Special Topics, **153**, 163 (2008).
[15]. T. Toyoda, M. Hayashi, J. Sato and Q. Shen, J. Therm. Anals. Calorim., **69**, 1037 (2002).
[16]. Techniques of Low Level Light Measurement, Lasers & Applications, pp.41-45(1983).