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Accurate Multi-Channel QCM Sensor Measurement Enabled by FPGA-Based Embedded System Using GPS

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Abstract: This paper presents a design and implementation proposal for a real-time frequency measurement system for high-precision, multi-channel quartz crystal microbalance (QCM) sensors using a field programmable gate array (FPGA). The key contribution of this work lies in the integration of a frequency measurement and mass resolution computation based on Global Positioning System (GPS) signals within a single FPGA chip, utilizing Input/Output Blocks to incorporate logic QCM oscillator circuits. The FPGA design enables parallel processing, ensuring accurate measurements, faster calculations, and reduced hardware complexity by minimizing the need for external components. As a result, a cost-effective and accurate multi-channel sensor system is developed, serving as a reconfigurable standalone measurement platform with communication capabilities. The system is implemented and tested using the FPGA Xilinx Virtex-6, along with multiple QCM sensors. The implementation on a Xilinx XC6VLX240T FPGA achieves a maximum frequency of 324 MHz and consumes a dynamic power of 120 mW. Notably, the design utilizes a modest number of resources, requiring only 188 slices, 733 flip-flops, and 13 IOBs to perform a double-channel sensor microbalance. The proposed system meets the precision measurement requirements for QCM sensor applications, exhibiting low measurement error when monitoring QCM frequencies ranging from 1 to 50 MHz, with an accuracy of 0.2 ppm and less than 0.1 Hz.

Keywords: embedded systems; FPGA-based applications; IOB interfaces; quartz crystal microbalance; frequency measurement; GPS

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1. Introduction

Nowadays, many industrial applications that involve the handling or processing of physical, chemical, or biological substances rely heavily on high-precision measurement instrumentation. One of the most commonly used systems for this purpose is the QCM (quartz crystal microbalance), which detects the resonance and frequency shifts of quartz crystal resonator (QCR) sensors. In this context, QCM sensors are widely used in different application domains. QCM sensors find wide application in various domains due to their high sensitivity and real-time capability of measuring minute mass changes (typically in the order of a few ng/cm^2) within a broad dynamic range (100 µg/cm^2). This makes them particularly attractive for applications such as bio-sensors, analysis of biomolecular interactions, and studying cell–substrate interactions [1]. Usually, to perform high-precision measurements, accurate frequency (/time) measurement techniques are employed using electronic resonators based on circuits containing capacitors, resistors, and/or inductors [1]. These circuits generate alternating current by periodically fluctuating between two voltage levels. Oscillators working with optimal stability rely on vibrating quartz crystals, which exhibit a stable frequency when a direct current is applied. Similarly, a piezoelectric oscillator circuit uses a piezoelectric crystal in combination with electronic passive components to generate a stable frequency depending on crystal properties and environmental conditions [2]. Factors such as temperature, pressure, acceleration, radiation, electric fields, and electromagnetic fields can introduce variations in the nominal generated frequency oscillation. As a result, sensors based on piezoelectric oscillators offer accurate measurement of these physical variables [3]. Therefore, piezoelectricity based on the quartz crystal microbalance is one of the most popular mass sensing techniques in industrial applications, including gas and liquid sensors [2–4] and electronic tongues [5]. These applications include molecular recognition [6–8] and food quality control [4,9–11]. QCM is a low-cost and highly sensitive mass measurement technique that was discovered in 1959 by Sauerbrey [12]. Sauerbrey established a relationship between the mass on the surface of the crystal and its resonance frequency. More precisely, as depicted in Figure 1, the addition of mass distributed over the quartz crystal surface alters the nominal oscillation frequency. This frequency variation can be described by the following Sauerbrey Equation (1):

$$\Delta f = \frac{-2 \times {f_0}^2}{A \times \sqrt{\rho_q \times \mu_q}} \times \Delta m. \tag{1}$$

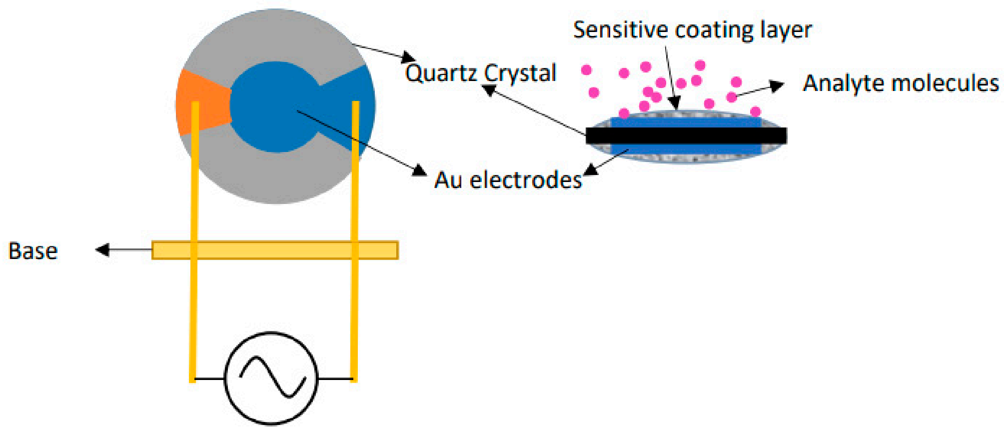


Figure 1. Basic working principle of quartz crystal microbalance sensor [13].

Here, Δf represents the normalized frequency change (Hz) as a function of the mass change Δm (gram), f_0 is the resonant frequency (Hz), A is the piezoelectrically active crystal area (area between electrodes, cm^2), ρ_q is the density of quartz (2.648 g/cm^3), and μ_q is the shear modulus of quartz for AT-cut crystal (2.947×10^{11} g·cm^{-1}·s^{-2}).

Therefore, the resonance and subsequent frequency shift of the quartz crystal resonator is detected by a QCM measurement system. A QCM crystal consists of a thin quartz crystal with metallic electrodes of a certain thickness on both sides. This pellet is produced with different thicknesses, resulting in different frequencies. Gold is often used for the electrodes due to its resistance to corrosive environments [14]. There are three main electronic techniques used for frequency shift measurements: impedance measurement, quartz crystal microbalance with dissipation (QCM-D), and oscillator-based measurements [15]. Among these techniques, impedance measurement provides the most precise results for resonance frequency analysis [16]. It involves applying a sweeping frequency signal to a quartz crystal resonator and collecting impedance spectrum (or admittance) data to determine the resonant frequency and dissipation outputs. QCM-D is a type of quartz crystal microbalance based on the ring-down technique. It is often used to determine film thickness in a liquid environment, such as the thickness of an adsorbed protein layer. It can be used to study other properties of the sample, such as its softness. The QCM-D technique allows measurement of several times per second in a vacuum, gaseous, or liquid environment [17]. Additionally, it is possible to switch between fundamental frequency and overtones [18]. Although QCM-D and impedance measurement systems are efficient and commercially available, they are often expensive and cumbersome. They are not adequate for on-site use. The principles of oscillator-based measurement, distinguishing inverting and non-inverting amplifier oscillators, are illustrated in Figure 2. On the one hand, the inverting amplifier, known as a Pierce oscillator (shown in Figure 2a), adds a 180° phase shift which is compensated by the feedback network (based on R_a, C_1, C_2 passive components and the quartz crystal) to meet the phase requirement in the Barkhausen criterion. On the other hand, the non-inverting amplifier (shown in Figure 2b) acts on the sensor as a series resonator satisfying the phase condition at the series resonance frequency by only using resistor components (R_a, R_b). Figure 2c illustrates another non-inverting amplifier known as a Colpitts oscillator, where the sensor functions as a high-quality inductor through its connection in parallel with R_1, C_2 passive elements.

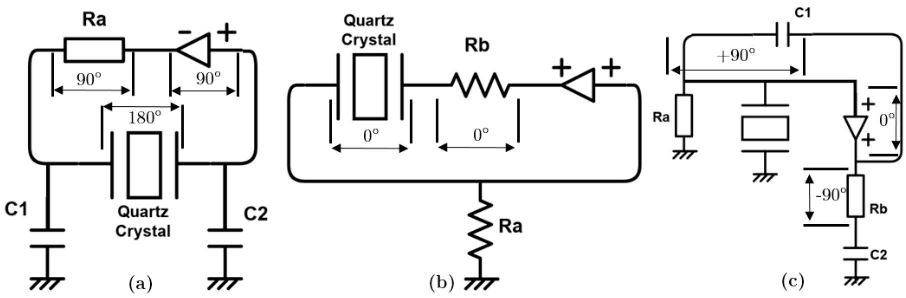


Figure 2. Typical oscillator circuits: (**a**) with an inverting amplifier (Pierce oscillator); (**b**) with a non-inverting amplifier, and (**c**) with a Colpitts oscillator [16,19].

The QCM is widely used due to its extreme sensitivity to the characteristics of the materials it comes into contact with, leading to shifts in its resonant frequency. However, the effectiveness of the QCM is constrained by the noise specifications of the crystal oscillator and the resolution of the frequency counter employed to measure frequency variations. Usually, the standard QCM System is a stand-alone instrument with the built-in quartz crystal oscillator electronics, frequency counter, and CPU/microcontroller ensuring the measurement, the monitoring, and the display (on a front panel) of the shifts in resonance frequency, which is dependent on the material with which the QCM is in contact. Consequently, an input stimulus induces a frequency shift in the sensor. Therefore, precise quantification of changes in the input stimulus is achievable, provided an appropriate frequency counter/meter is utilized. Unfortunately, it is well known in the field of time–frequency metrology that attaining higher measurement accuracy necessitates longer measurement times. To mitigate this, QCM systems incorporate a phase-locked loop (PLL) electronic circuit, which reduces the measurement time [20]. Nevertheless, such systems are neither cost-effective nor suitable for developing a multi-channel QCM system. Each QCM would require a quartz crystal resonator oscillator, a PLL, a low-pass filter, and an amplifier circuit.

Static random-access-memory-based field programmable gate array (SRAM-Based FPGA) technology provides a parallel computation capability which offers performance improvements while ensuring flexibility compared with traditional CPU processing architectures. Moreover, FPGAs provide Input/Output Blocks (IOBs) which can be used to implement additional logic with CLBs to improve design performance by increasing available logic and routing resources. Previous works show interest in using FPGA for the integration of a frequency measurement technique providing a trade-off between performance and accurate measurement [21]. Similarly, several works have explored the utilization of FPGAs in QCM systems for conventional counter-based frequency measurement, with or without compensation circuits [22,23]. For example, a low-cost prototype of a multi-channel quartz crystal microbalance data acquisition system for QCM sensor investigation was developed in 2018 [10]. It uses a totally external oscillator to keep the oscillation down. The 16-bit time counters of the PIC16F allow frequency measurement to be performed by QCM sensors with a sensitivity of 1 Hz. However, all of these prior works required additional external chips to realize the QCM oscillators and generate the reference signal based on a subdivision of a highly accurate local clock oscillator.

This paper presents a proposal to implement a commonly used Pierce-gate crystal oscillator based on a quartz crystal using configured Input/Output Blocks (IOBs) within an FPGA. By incorporating digital inverters and a feedback resistor, the inner digital CMOS inverter can be linearized, effectively transforming the logic inverter gate into an analog amplifier. This approach allows for the utilization of low-cost external passive components (such as C1 and C2 reactance and Rs) that satisfy the Barkhausen criteria.

Input/Output Blocks connect internal FPGA architecture to the external design via interfacing pins, eliminating the need for external chip oscillators, such as resonators, PLLs, amplifier circuits, or filters. Moreover, the FPGA's logic elements, which serve as the fundamental building blocks, can be programmed to carry out different functions as required by the design, enabling the implementation of accurate frequency measurement using the GPS as a reference signal. The main novelty of the proposed FPGA-based system lies on the use of internal IOBs and its ability to perform a multi-QCM measurement system composed of several oscillators, each equipped with a QCM. Within this system, Pierce oscillators utilize on-chip inverting amplifiers within the IOBs of the FPGA, striking a balance between achieving accurate frequency measurements (which can be enhanced through fine measurements based on a ring oscillator or time-to-digital approach) while minimizing the use of logic resources within the FPGA and external components. Therefore, the frequency measurement is accomplished through the implementation of a 32-bit reconfigurable reciprocal frequency meter architecture, which relies on the GPS reference signal and the measurements taken when it is connected to different QCMs.

The remaining sections of the paper are structured as follows. Section 2 outlines the proposed system, which integrates parallel quartz crystal oscillators using only IOBs connected to multiple QCMs simultaneously. This section describes the reciprocal counter implemented in FPGA (with the potential for enhanced accuracy through the implementation of a time-to-digital converter (TDC) in the FPGA). Section 3 investigates the resonant conditions for various QCMs, providing details on the experimental setup, measurement results, and subsequent discussion of the findings. Finally, Section 4 presents the conclusion of the study along with directions for future work.

2. Frequency Measurement Electronic System

Figure 3 illustrates the overall electronic measurement system of the proposed multi-channel QCM data acquisition system, which incorporates two QCM resonators. The embedded frequency measurement system comprises both hardware and software components.

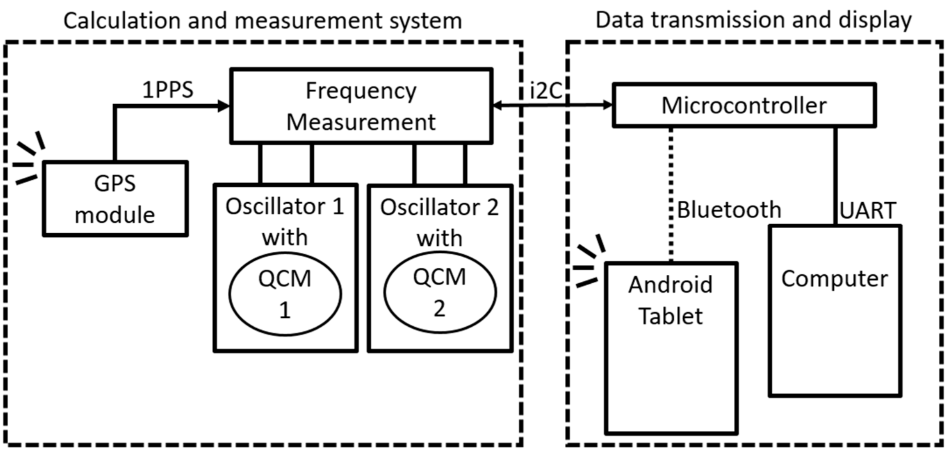


Figure 3. Block diagram of multi-channel QCM data acquisition system.

The embedded hardware employed in this study utilizes an accurate FPGA-based frequency measurement system implemented on the Xilinx Virtex 6 FPGA ML605 stand-alone platform [24]. The software part, executed on a microcontroller, is responsible for collecting frequency data and transmitting this to a display. This proposed electronic communication system incorporates an embedded processor that utilizes Bluetooth communication with a custom-developed Android application. This application receives and stores data from the frequency measurement hardware system in the form of a spreadsheet. This electronic system ensures the transmission of data acquired from the sigma-delta converter through the utilization of the I2c protocol. More precisely, serial data (SDA) and clock (SCL) signals are used to perform the I2c protocol ensuring data transmissions. One on-board microcontroller on the red PIC32MX470 development board manages the communication with the FPGA via the I2c protocol. The timer configuration is used to set the measuring rate. The UART link is used to send the results from the microcontroller to the computer in order to fill in a spreadsheet. The timer defines the delay between each acquisition request for digital frequency values. The Android application manages the reception of measured values via the Bluetooth protocol and displays in one tablet device. In summary, the microcontroller is responsible for managing frequency measurements, which are conducted by the FPGA directly connected to multiple QCM measurement channels.

A multi-channel reciprocal counter is implemented within the FPGA Virtex-6, utilizing a 200 MHz local clock reference signal. The timegate (measurement time) for counting rising edges of the reference signal is set to one second, corresponding to a 1PPS GPS signal received with a jitter of approximately 20 ns from the MediaTek GPS Chipset MT3339 of the Adafruit GPS module [25]. This received GPS reference signal provides an efficient, stable, and cost-effective solution for generating an accurate timegate reference signal, enabling high-frequency resolution in frequency measurements. Figure 4 showcases a photo of the proposed embedded hardware system for QCR oscillator multi-channel frequency measurements.

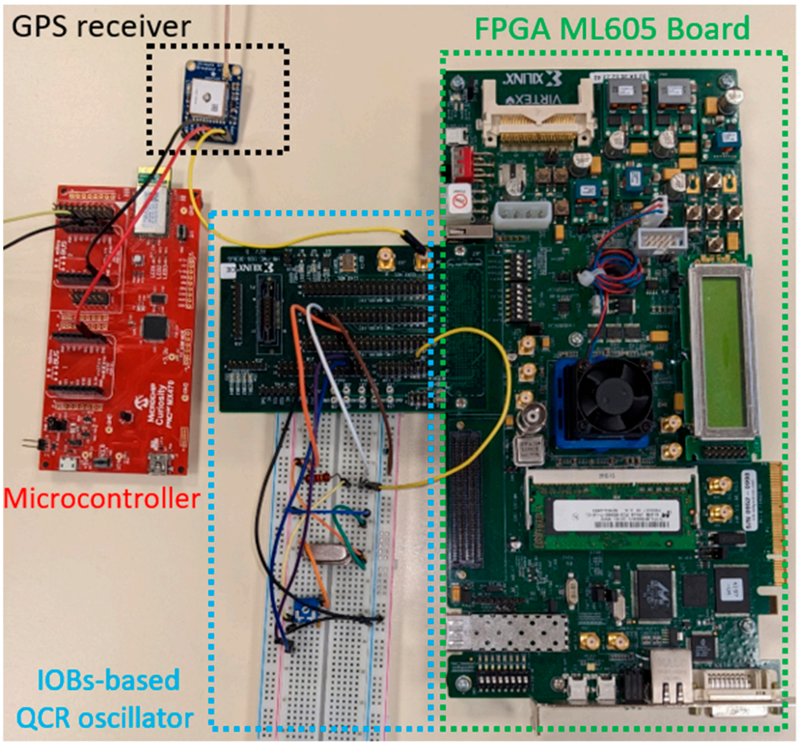


Figure 4. Photo of the proposed resonator multi-channel reciprocal counter implemented in the FPGA-Virtex-6-based GPS clock reference signal.

2.1. Frequency Measurement System

Usually, low-cost FPGA-based frequency measurement relies on a frequency counter that incorporates timers and logical counters. The basic digital measurement of frequency involves counting the number of rising edges of the input signal during a predetermined time interval, utilizing a stable clock reference signal. The resonance frequency can then be obtained using Equation (2), where f represents the measured resonance frequency, N denotes the measured number of input pulses, and t indicates the measurement time.

$$f = \frac{N}{t}. \tag{2}$$

Depending on the frequency of the clock reference signal, the accuracy of the measurement improves as the duration of the measurement time increases. If we use a basic frequency counter (according to Equation (2)) with a measurement window of one second, we will reach a maximum accuracy of ±1 Hz. However, for QCM applications that require higher frequency resolution and/or shorter measurement time, modern frequency counters employ the reciprocal counting method [26]. Unlike previous approaches that solely rely on a high-frequency reference signal, the proposed reciprocal counter utilizes two signal references: a high-frequency clock signal for frequency calculation and the received GPS signal for period measurement. This approach offers an alternative solution for achieving more accurate measurements without the need for subdivision of the high clock reference signal. Figure 5 illustrates the reciprocal counting method using the GPS Signal.

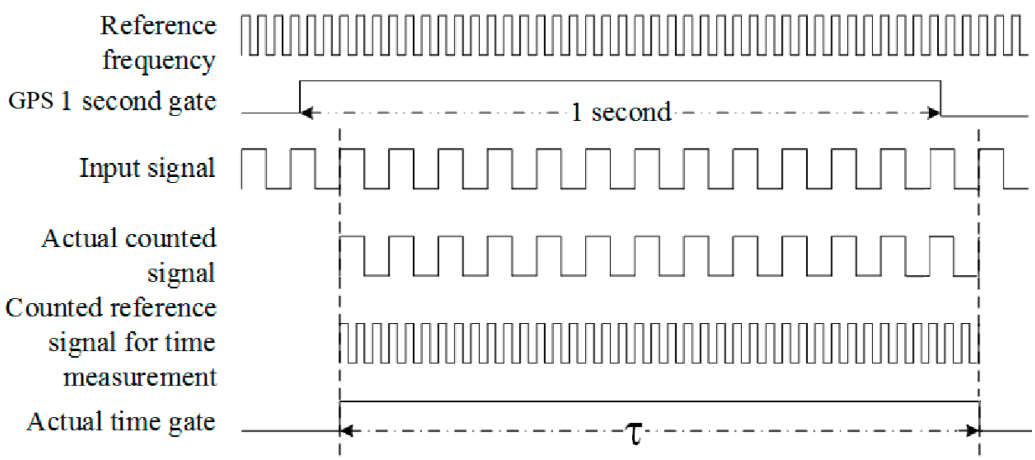


Figure 5. Reciprocal counter based on an input reference GPS signal.

For a duration of one second, each clock edge of the input signal is counted N times. Simultaneously, a reference signal is also counted for the exact same duration. This duration, referred to as τ, represents the time delay between the first rising edge of the input signal following the rising edge of the one-second period signal, and the first rising edge of the input signal following the falling edge of the 1 Hz signal. The main advantage of this method is its resolution, which remains unaffected by the input frequency and can be enhanced through the utilization of low-cost FPGA-based digital counting techniques (DCTs) for time stamping the start and stop edges of the input signal. Moreover, the error remains constant across the entire range of input signal frequencies and can be reduced as the reference clock frequency increases or as the gate time extends.

Figure 6 illustrates the internal architecture of the FPGA reciprocal counter designed for measuring the frequency of a single QCR oscillator. This design incorporates three digital counters, each 32 bits in size, responsible for counting the various edge events of the input oscillation signal. These counters enable the calculation of the frequency value or frequency shifts resulting from the input QCM stimulations connected to the FPGA's IOBs. The first counter, denoted ValeurFrequenceRef, provides the count result of the high frequency reference delineated by the input GPS signal. This measurement provides a real-time accurate measurement of the reference frequency. The second counter, referred to as C_Freq, counts the number of rising edges of the signal to be measured (the output oscillation signal for one Pierce QCM oscillator) within the time period τ. Finally, the last counter performs the task of counting the number of rising edges of the reference signal during the designated period τ in order to obtain the frequency measurement of the input signal by considering Equation (2).

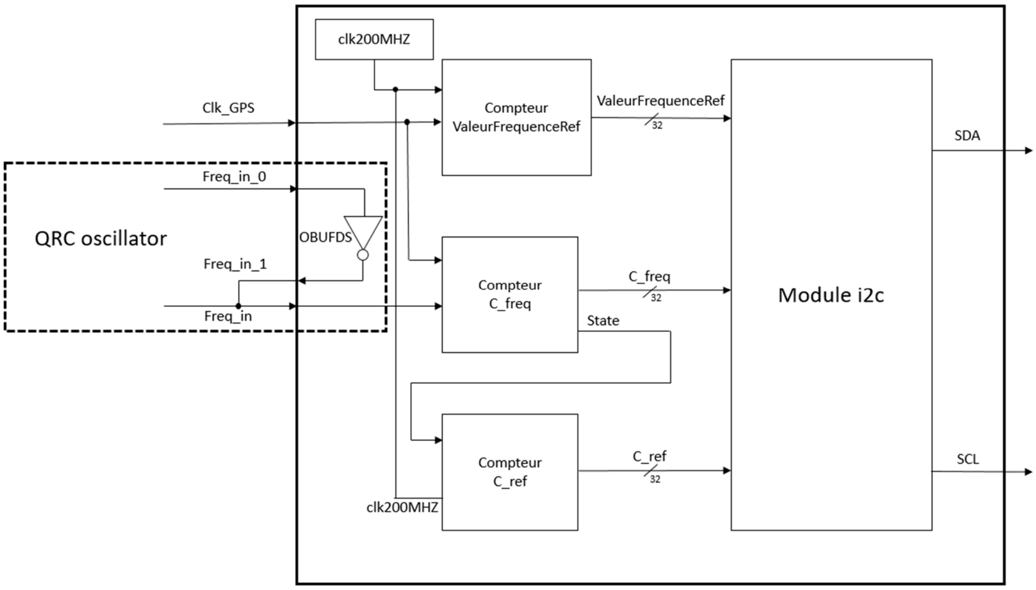


Figure 6. Architecture of reconfigurable frequency meter.

Behavioral simulations and timing were conducted to evaluate the accuracy of the proposed test using the Xilinx Virtex-6 ML 605 platform. These simulations demonstrated the highly accurate frequency measurement of the oscillating QCM signal obtained from an on-chip FPGA IOB logic inverter. The simulation results of the proposed architecture, which utilizes the GPS-based reciprocal counting method, are presented in Figure 7. These results were obtained through the utilization of VHDL description and the Xilinx FPGA ISE Environment design tool.

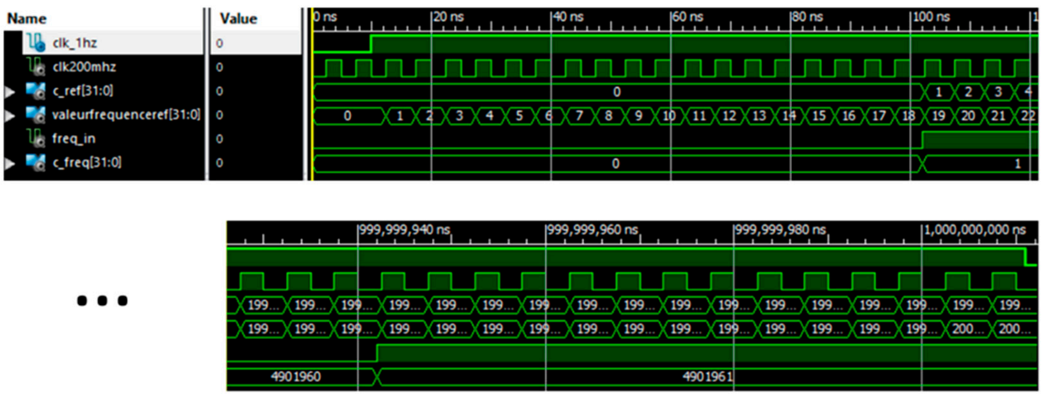


Figure 7. Timing behavioral simulation results of accurate frequency measurement based on reciprocal counter design.

The design of the proposed reconfigurable frequency meter incorporates the GPS and oscillating QCM signals as inputs (represented by clk_1 hz and freq_in signals in Figure 7). The behavioral simulation results demonstrate the functionality and the accurate values obtained by three counters (C_Ref, ValeurFrequenceRef, C_Freq) in accurately measuring the frequency of the freq_in signal. These measurements take advantage of the precision of the GPS sensor (clk_1 hz signal) and a local clock frequency of 200 MHz (clk200mhz signal).

The accurate frequency calculation is performed according to Equation (3), as depicted in Figure 5.

$$f = \frac{C\_Freq * ValeurFrequenceRef}{C\_Ref}. \quad (3)$$

2.2. Oscillator Realization

The resonance time of QCM crystals exhibits a low oscillation amplitude, typically measured in millivolts. Therefore, sensors are connected directly to the oscillator circuit to preserve the signal level and shape. However, the crystal signal can suffer from attenuation and interference as it traverses various contact points such as the crystal holder and connectors before reaching the circuit. To address this issue, great care has been taken in selecting the connecting components, and proactive measures have been employed to position the oscillator components away from strong magnetic fields and power connections.

As mentioned, the on-chip IOB inverters of the FPGA are configured as OBUFDS elements [27] to directly facilitate the implementation of Pierce QCR oscillators. This novel approach, not previously proposed in the existing literature on multi-channel QCM measurement systems, enables the realization of low-cost QCR oscillators. Figure 8 describes the proposed IOBs' configuration and connection to create multi-channel QCR oscillators. Pierce oscillators are implemented with QCM connected to the FPGA realizing the inverting gate for the oscillator circuits responsible for generating the frequency oscillation signals to be measured. For this purpose, some input pins of the FPGA are connected to QCR by using the connection pins of the FMC XM105 expansion card (see Figure 4). For the input frequency signal to be measured (i.e., the oscillator output signal), "Clock Capable" pins ending in "_CC_" are used. For the OB output signal of the OBUFDS component, pins ending in "_N" must be used, and for the O output signal of the OBUFDS component, pins ending in "_P" should be used. In order to ensure adjacent output ports, the positive and negative outputs are positioned on the same IOB side.

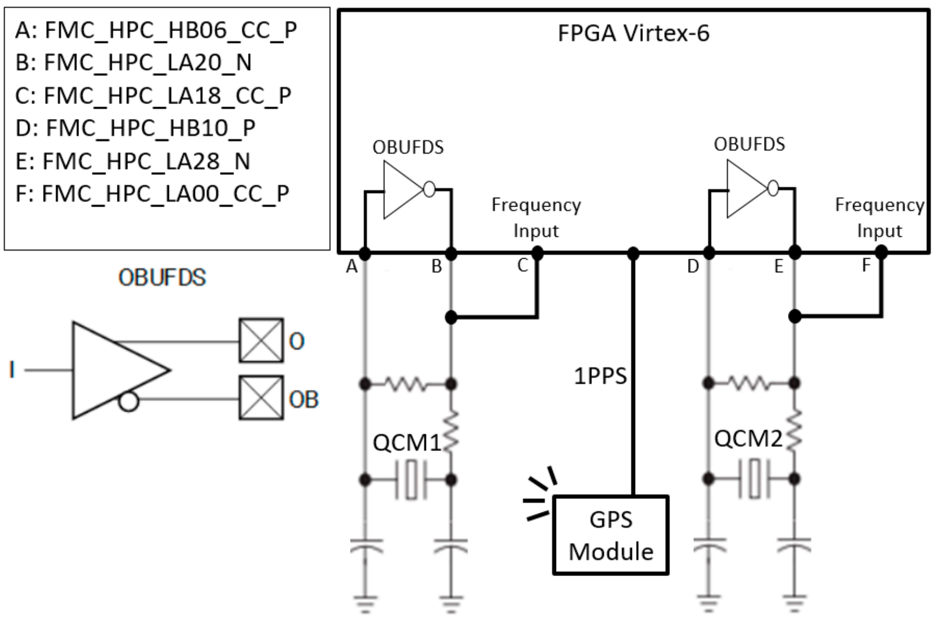


Figure 8. Design of Pierce-QCR-oscillator-based inner logic inverters of IOB FPGA.

3. Implementation and Experimental Results

The proposed reconfigurable standalone measurement platform with communication capabilities combines both software resources, which bring the necessary versatility, and the logic hardware resources in which the accurate frequency measurement unit is implemented. To implement and test with multiple QCM sensors, the proposed design based on the Xilinx XC-6 ML 605 technology is integrated as a new core with specific components as described by the corresponding block diagram shown in Figure 9. The proposed block design includes the following four main modules:

- The Frequencemetre module, which corresponds to the proposed reciprocal counter and delivers a 32-bit sequence of three counter values representing the digital frequency measurement, as determined by Equation (3).
- The I2c_Slave_top module, which represents a hierarchical communication using the I2c protocol that is connected to and exchanges data with the microcontroller for the purpose of frequency measurement display. This module receives the counter values from the Frequencemetre module and transmits them via the I2c communication link to the microcontroller (PIC32MX) for further processing and display of the corresponding normalized frequency change (in Hz) based on the QCM microbalance oscillation.
- The OBUFDS block, which is the inner logic oscillator circuit that provides the oscillating QCM signal while reducing the need for extra external logic circuits to function as an inverting amplifier oscillator.

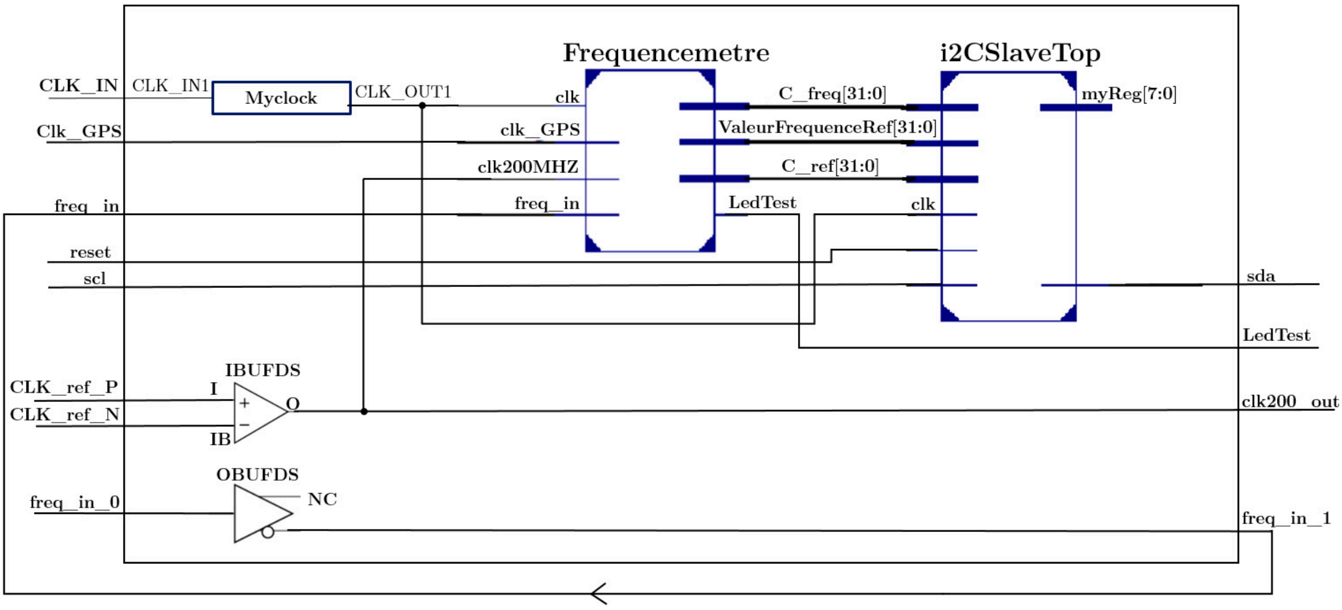


Figure 9. Design block diagram of GPS-based frequency measurement by QCM sensors.

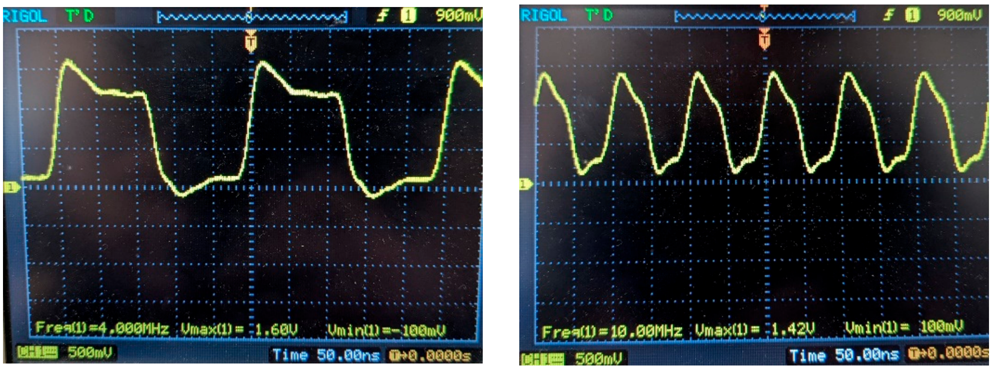
As shown in Figure 9, the configured IOBs function as external oscillators ensuring multi-channel measurement as illustrated in Figure 8. For this purpose, two IOBs are necessary to achieve a single-channel QCM oscillator. More precisely, one IOB (OBUFDS block) is configured as one logic inverter, which is combined with the external passive elements (C1 and R1 as described in Figure 2) to create an on-chip piezoelectric QCM oscillator within the FPGA. The second IOB is configured as a single-input buffer (IBUFDS-configured IOB), serving as an intermediary element that ensures the signal source remains unaffected by the load attributes while delivering a voltage and current similar to what it receives at its input.

The proposed accurate multi-channel frequency measurement is described by using hardware description language (VHDL), and the final binary configuration file is implemented on Xilinx Virtex 6 XC6VLX240T-1FFG1156 FPGA. Table 1 provides a breakdown of the required logic synthesis resources for the system, which include two QCR oscillators connected to the FPGA. The resource utilization is as follows: 733 Slice registers, no DSP multipliers, and no block RAM. This results in a low-cost logic consumption, with 188 slices, 733 flip-flops, and 13 IOBs, all operating at a maximum frequency of 324 MHz. The architecture exhibits a dynamic power of 0.120 W, with a total supply power of approximately 3.618 W. Compared with a similar previous work [28], the proposed system for multi-channel measurement eliminates the need for Block RAM or specific digital clock managers (DCMs) associated with multiple GCLKs used as delay-locked loop (DLL) for accurate measurement [28]. Moreover, due to the Xilinx FPGA technology, the proposed system consumes over five times less dynamic power than other DCM- or DLL-based systems which require a minimal dynamic power of 727 mW and 662 mW, respectively, with a 100 MHz clocking frequency [29].

Table 1. Comparison of FPGA Resource Utilization for Two Parallel QCMs.

	FPGA Technology	**GCLK**	**DCMs**	**BRAMs**	**LUTs**	**Slices**	**IOBs**	**FFs**	**Dynamic PWR (mW)**	**Fmax (MHz)**
Proposed Work	Virtex-6 XC6VLX240T	1 (12.5%)	0 (0%)	0 (0%)	527 (1%)	188 (1%)	13 (2%)	733 (1%)	120	324.4
Ref. [22]	Virtex-4 4vlx25fft668-10	2 (6%)	1 (12%)	X	1625 (7.5%)	922 (8.5%)	8 (1.5%)	774 (3.5%)	NC	102.963
Ref. [28]	Spartan-3 XC3S200	NC	1 (25%)	1 (9%)	460 (12%)	230 (12%)	5 (3%)	460 (12%)	NC	200

To validate the system's performance, a test platform consisting of multiple QCM sensors in a homogeneous liquid (distilled water) was utilized. Figure 10 displays the measurement obtained by the proposed multi-channel QCM from output signals of 4 MHz and 10 MHz QCR oscillators. These signals were obtained using OBUFDS differential inverters to perform 4 MHz and 10 MHz on-chip FPGA Pierce oscillator using only external passive components (see Figure 4). We observed that the IOBs of the FPGA ensure the oscillation of several quartz crystals without the need for additional external logic circuits, as commonly utilized in previous QCM measurement systems. Therefore, the proposed integrated QCRs maintain the oscillation of the signals; these are directly measurable by the Frequencemetre module within the FPGA. These tests validate the functionality of the FPGA-based multi-channel QCM measurement system, which operates effectively without external QCRs and provides accurate real-time frequency measurements.



(**a**) (**b**)

Figure 10. Frequency output signals of the QCR oscillators of the proposed multi-channel QCM measurement: (**a**) 4 MHz QCR and (**b**) 10 MHz QCR.

In order to assess the accuracy of the proposed FPGA-based frequency meter design, we conducted a series of comparative measurements. We used an input signal from a 10 MHz MicroCrystal OCXO oscillator, reference "OCXOV-AV5-10.000", which provided a frequency stability of ± 0.2 ppm. This reference signal is measured both by a frequency meter (Rohde and Schwarz Hameg HM8123 (OCXO Version)) and the proposed FPGA Virtex-6 frequency measurement system. The HM 8123 counter frequency measurement error is 1.25×10^{-8}. It represents the frequency instability of the counter, in the temperature range of 0–50 °C. A 120-second series of measurements can be seen in Figure 11. On all the measurements taken, it can be seen that the difference (Δf) between the mean value of measured frequencies by the HM8123 m and the mean values measured by the frequency meter implemented in the FPGA is less than 0.1 Hz. In Figure 11, Δf is approximately 0.09 Hz. We can therefore consider that under normal operating conditions, the accuracy of our system is better than 0.1 Hz.

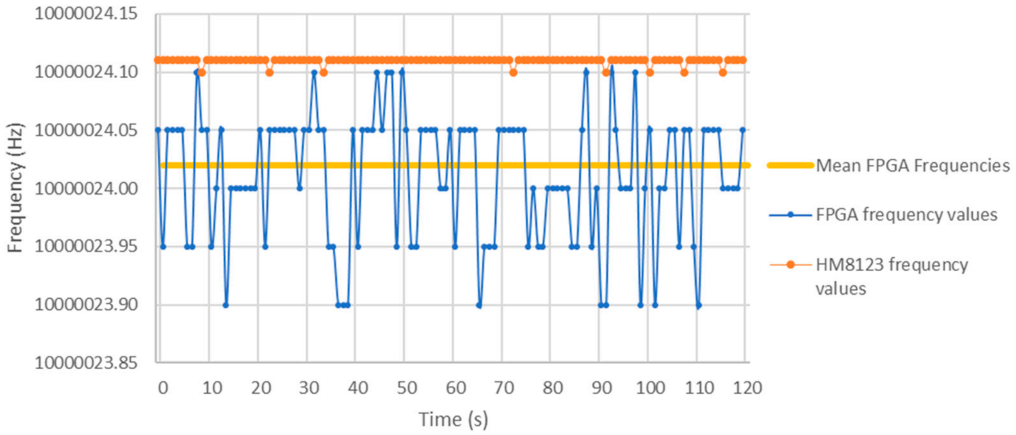


Figure 11. Frequency measurement results for a gate time of one second.

4. Comparison with Similar Works

Several recent systems have been proposed to measure frequency shifts in QCM systems based on QCR [22,23,28,30–34]. Table 2 provides a comparison between the proposed accurate multi-channel QCM system and state-of-the-art works in terms of additional hardware resources, number of channels, number of external logic oscillator circuits (QCRs), reference time base source, accuracy, and required FPGA logic resources. Based on Table 2, it is evident that the proposed system achieves one of the highest accuracies. This is primarily attributed to the utilization of a GPS signal and the incorporation of QCRs specifically designed within the FPGA. These features enable the system to conduct multi-channel frequency measurements using just a single FPGA. In fact, compared with previous works, the achieved accuracy is better than 0.1 Hz, which is accomplished with only a reciprocal counter. Furthermore, compared with similar works, the proposed FPGA design utilizes 79% fewer slices, 5% fewer flip-flops, and 67% fewer LUTs compared with the architecture presented in [22]. Similarly, the proposed FPGA architecture design necessitates 45% fewer slices compared with the system suggested in [28]. Therefore, compared with previous systems, the proposed multi-channel QCM measurement system offers low-cost, highly accurate frequency measurement for multiple interconnected sensing QCM crystals in parallel for sensor investigations. Consequently, the proposed system provides a better trade-off in terms of performance and required logic resources while offering a cost-effective solution as it only requires external passive components to achieve multiple inverting QCM oscillators, allowing multi-channel QCM measurement using a single FPGA device. Moreover, the main advantage of the proposed system is that it enables multi-channel frequency measurement without the need for specific embedded blocks such as DSP, BRAM, DLL, or additional external logic circuits such as oscillators, PLLs, microcontrollers, etc. However, a limitation of the proposed system is its performance when ensuring simultaneous measurement of a large number of QCR frequencies in the FPGA, which requires high parallel computation and a large number of IOB (Input/Output Buffer) clocks.

Table 2. Comparison of QCR-based QCM measurement systems.

References	Hardware	Reference Time Base Source	Active QCR	Techniques	Precision Achieved	Resources for Frequency Measurement	Reconfigurability with Multi-Channel System
[28]	Xilinx Spartan 3	External 50 MHz oscillator	External	Conventional frequency counter, differential delay lines (DLL)	0.05 Hz	230 slices, 1 DCM, 9 IOBs, 17,280 BRAMs	Yes
[20]	Low-pass filter, amplifier, PLL with VCO, microcontroller, temperature sensor	NC	External	Phase-locked loop circuit (PLL)	0022 Hz	NC	Yes
[22]	Virtex 4, 32-bit MicroBlaze microprocessor	NC	External	Conventional frequency counter	<1 Hz	922 slices, 774 flip-flops, 1625 LUTs, 8 IOBs, 21 FIFO16, 1 GCLKS and 3 DSP48s	Yes
[30]	DE-2 board	PLL 200 MHz signal	External	Reciprocal counter, time-to-digital converters (TDCs)	0.25 Hz with reciprocal counter	NC	Yes
[31]	Arduino Atmega 2560 microcontroller, PIC16F628A per channel	Arduino 1 Hz signal	External	Conventional frequency counter	1 Hz	One microcontroller per channel	No
[32]	Spartan 3	External 50 MHz oscillator	External	Conventional frequency counter	1 Hz	NC	Yes
[33]	CPLD XC2C256	16.9344 MHz external TCXO oscillator	External	Conventional frequency counter	0.5 Hz	228 macrocells, 19 function blocks and 72% of registers	Yes
[34]	Spartan-3E (XC3S250E)	100 MHz TCXO oscillator	External	Reciprocal counter	0.1 Hz	NC	Yes
Our QCR with reciprocal counter	Virtex-6 ML605	GPS 1PPS signal from MediaTek GPS chipset MT3339	Internal	Reciprocal counter	<0.1 Hz	188 slices, 733 flip-flops, 527 LUTs, 13 IOBs	Yes

5. Conclusions and Future work

This paper presents a GPS-based accurate multi-channel QCM sensor measurement application using an FPGA directly interfaced with quartz crystal oscillators. Our system ensures multi-sensor measurement while integrating the reciprocal frequency measurement part within the FPGA. The reconfigurable embedded system performs the frequency measurement for high-accuracy QCM applications which has been implemented and behavior-tested using the FPGA Virtex-6 XC6VLX240T. The proposed system requires low FPGA logic resources while taking advantage of the computation concurrency. Furthermore, the suggested system eliminates the need for external oscillators or chips for conditioning or data processing. It enables the measurement and monitoring of QCM frequencies within the 1–50 MHz range with an accuracy of 2 ppm and a precision of under 0.1 Hz. Frequency values from multiple QCM sensors can be measured and recorded periodically, every second, using this system.

As part of our future work, we also plan to integrate compensation conditions (or calibration sensors) based on Allan deviation computation within the FPGA. This integration will accurately determine the influence of measurement conditions on oscillator behavior, frequency stability, and sensor mass resolution, thereby improving accuracy and processing time [33]. Additionally, we will measure temperatures and ambient humidity in sensor environments simultaneously to enhance high-temperature compensation and improve quartz crystal characteristics. To achieve higher accuracy in frequency measurement, we will consider incorporating a time-to-digital converter IP core for FPGA, enabling precise measurements [34]. Moreover, as sensors with high sensitivity require more time for accurate frequency shift measurements, we will explore the principle of rational approximations for measurement [35].

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