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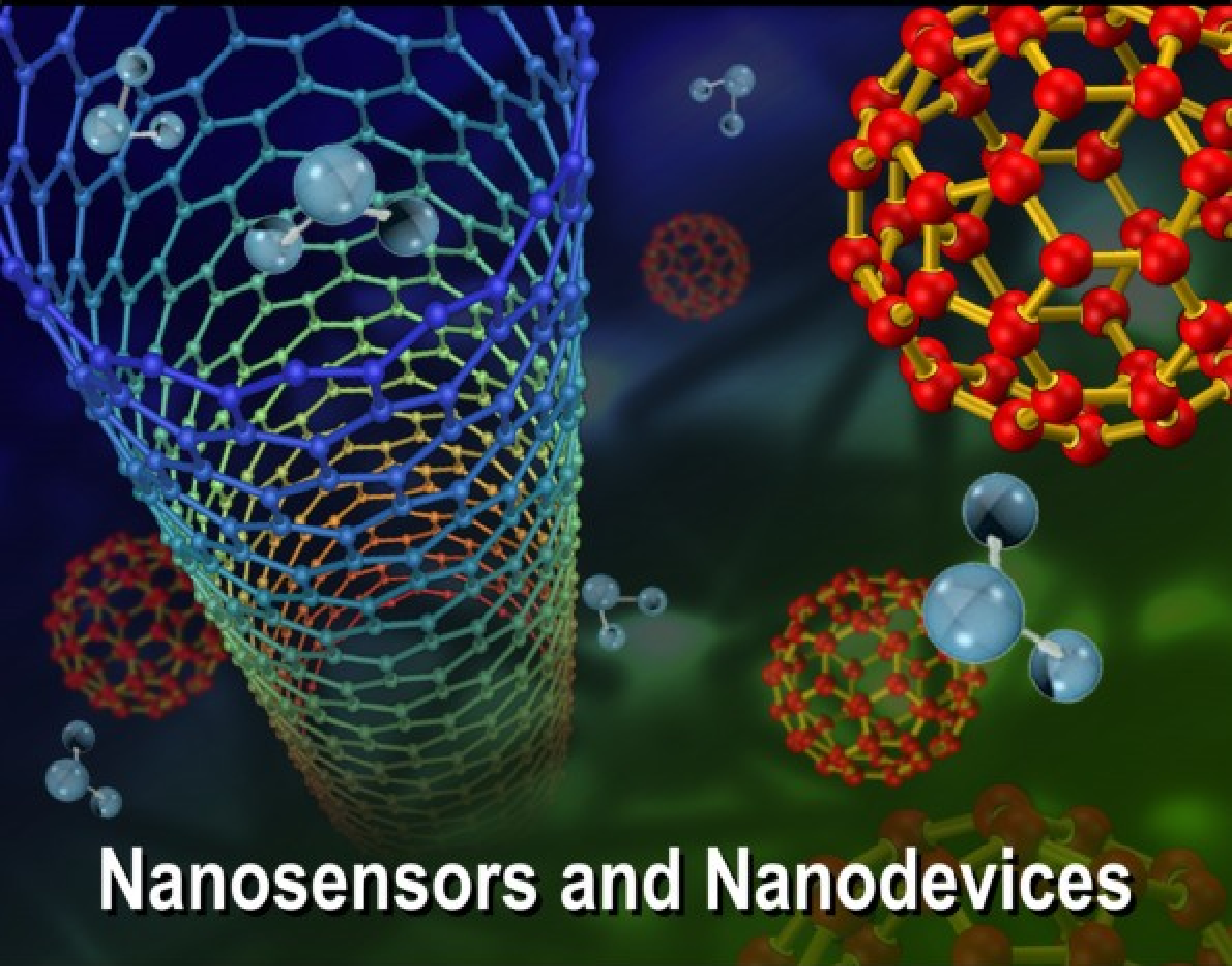

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All-digital PLL System for Self-oscillation Mode of Microcantilevers with Integrated Bimorph Actuator and Piezoresistive Readout

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Abstract: Self-oscillation system for microcantilevers with integrated actuator and piezoresistive read-out has been newly developed. The presented concept uses Phase Locked Loop approach which forces the system to lock at resonance frequency of the microcantilever sensors and to follow its changes. The system has been implemented in FPGA and tested with microcantilever sensors. The feedback response and signal spectrum have been investigated. *Copyright © 2008 IFSA.*

Keywords: Microcantilever, Self-oscillation, AFM

1. Introduction

Microcantilevers are widely used as high-sensitive detectors in many applications as Atomic Force Microscopy (AFM), real time recognition and monitoring of chemical and/or biochemical species, etc. Their unique characteristics as high sensitivity, fast response, small size, and compatibility with standard silicon micromachining and CMOS-technology makes them incontestable candidates for large number of low-cost sensor applications. Further development of microcantilever technology has led to high-compacted devices with integrated signal read-out part and actuation mechanism, which causes the cantilever to oscillate in resonant mode [1], [2]. In the present time, this design has evaluated to fully on-chip integrated sensor array allowing large number of sensors with individual read-out actuators to work in parallel, this, providing considerable increasing the speed of sensing process [3].

Currently, both Amplitude Modulation (AM) and Frequency Modulation (FM) detection methods are used in many practical implementations of AFM technology. FM mode includes various possible implementations, but in general, the change of the signal phase (phase shift) relative to the actuation signal is detected. FM is especially preferred in applications where fast response of the system is needed (e.g. surface scanning in vacuum), because of the smaller time constant of the phase changes FM. Self-oscillation mode is approximately new practical implementation of FM where the cantilever is integrated in a stand-alone oscillation block which generates at its output a signal with frequency equal to the resonance frequency of the cantilever. Such oscillating microcantilever systems have been reported in [4], [5]. In general, these examples are based on positive feedback electronics with manually adjustable phase shifter, and have been demonstrated for single-cantilever systems with external piezo actuator, running on 1st resonance frequency.

In this article, we present an all-digital, PLL-like system, which enables stable self-oscillations in different resonance modes of the cantilever with integrated thermal bi-morph actuator. The presented system automatically “locks” at the resonance frequency of the cantilever without any adjustments and then tracks it changes.

2. Theory of Operation

2.1. Basic Concept

In spite of variety of physical designs, microcantilever exhibits typical amplitude and phase characteristics of the mechanical resonance system. In dynamic mode of operation, the cantilever sensor is driven by integrated actuator at a frequency f_{ACT} equal or close to the eugen-frequency f_0 of the cantilever given by:

$$f_0 = \frac{1}{2\pi}\sqrt{\frac{k}{m_{eff}}}\ , \tag{1}$$

where m_{eff} is effective mass of the cantilever, and k is the spring constant. The force interactions between cantilever and sample surface cause a change in both the amplitude and phase shift (relative to the actuator signal) of the cantilever oscillations due to the change of the effective eugen-frequency f'_0

$$f_0^{'} = \frac{1}{2\pi}\sqrt{\frac{k + \frac{\partial F}{\partial z}}{m_{eff}}}\ , \tag{2}$$

where F is force acting on sensor in z direction.

The phase shift $\Delta\phi$ between driving signal f_{drive} and output signal can be evaluated by [6]:

$$\Delta\phi = \arctan\left(\frac{f_{drive}}{Qf_0\left(1-\frac{f_{drive}^2}{f_0^2}\right)}\right), \tag{3}$$

or, in terms of effective mass and spring constant:

$$\Delta\phi = \arctan\left(\frac{2\pi f_{drive}\sqrt{m_{eff}k}}{Q\left(4\pi^2 f_{drive}^2 m_{eff} - k\right)}\right). \tag{4}$$

Simulated phase characteristics for typical cantilever are shown in Fig. 1.

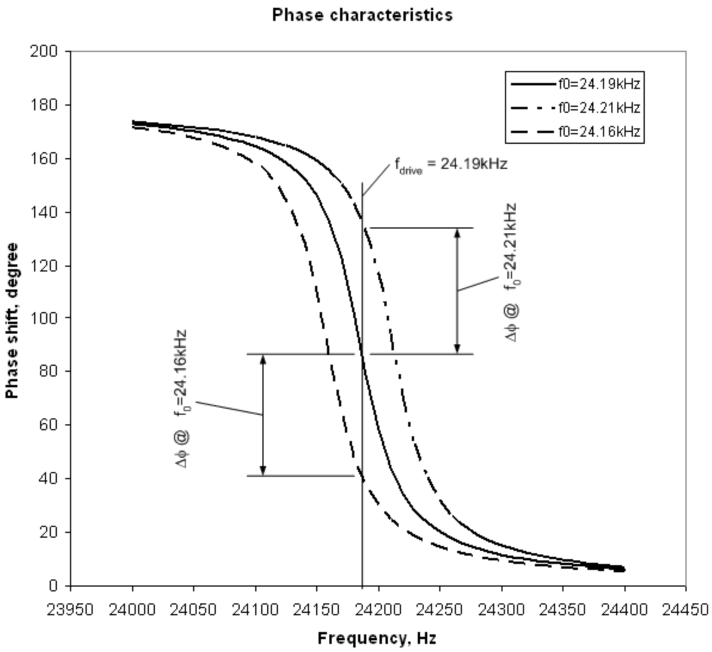


Fig. 1. Simulated phase curves for typical microcantilever with integrated bimorph actuator and piezoresistive read-out.

Let's suppose that the cantilever is driven by external generator at fixed frequency f_{drive}. As seen in the figure, the resonance frequency shift causes a change of the phase shift between output signal and driving signal. This phase shift can be used as an error signal for a feedback-controlled generator which drives the cantilever. Thus, every change of resonance frequency of the cantilever, due to the changes of spring constant, or effective mass, will force the feedback-controlled generator to oscillate at desired resonance. The operation principle of such system is the same as well known PLL architectures [7], [8].

2.2. Functional Diagram of the PLL Self-oscillating System

Fig. 2 illustrates the realization of the idea. The output of the driving generator is used as a reference signal. The amplified signal from the sensor read-out is fed to the phase sensitive detector, which provides at its output a phase difference between these two signals. Then, the phase shift signal is lowpass filtered and fed to the PI controller block which controls the driver generator. The set-point of the PI controller corresponds to the phase shift at the resonance, thus, enabling the driving generator to "lock" at the resonance frequency of the sensor and then, to follow its changes within certain lock range.

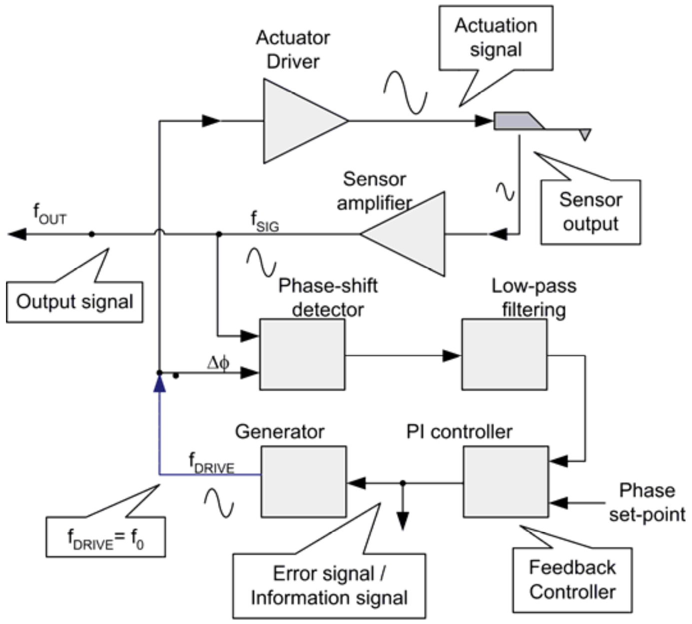


Fig. 2. Functional diagram of PLL based system enabling self-oscillating mode of cantilever.

3. All Digital FPGA Implementation

3.1. Blocks Diagram

All functional blocks of the proposed system, except sensor amplifier and actuator driver were implemented in Field Programmable Gate Array (FPGA). The digital implementation provides high stability, very good noise performance and design flexibility.

The block diagram of the FPGA design is shown in the next Fig. 3.

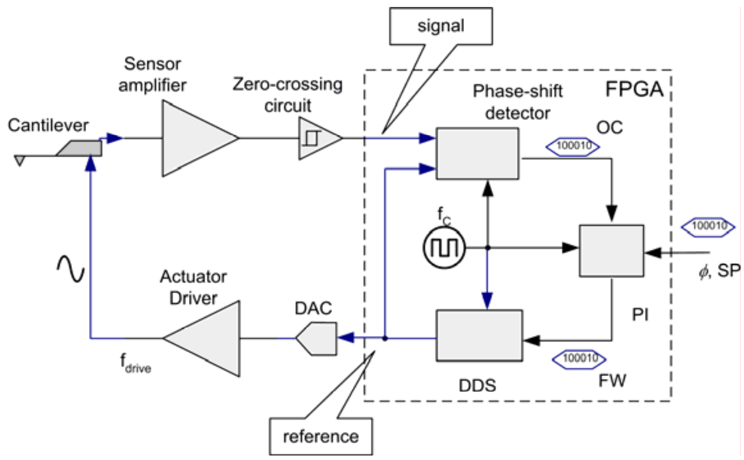


Fig. 3. Block diagram of all-digital PLL based system realized in FPGA.

The Direct Digital Synthesizer (DDS) produces a sine wave signal with a frequency of f_{drive}, which corresponds to the Frequency Word (FW) - code at the input of DDS. The output signal is divided into two paths - the reference signal for the phase-shift detector and the driving signal which is fed out of the FPGA. The signal from the sensor, together with the reference one is directed to a phase-shift detector. The output code from the latter is a signed number, which is proportional to the phase difference $\Delta\phi$ between the signal and the reference and is given by:

$$OC = \Delta\phi \frac{fc}{f_{drive}}, \tag{5}$$

where f_C is an internal global clock and f_{drive} is the output frequency of the DDS.

Here, f_C is the frequency of the clock feeding all digital blocks. Output code is passed to a PI-regulator block. The other input of PI is the phase Set-Point (SP). Its value corresponds to certain phase difference between the signal from the sensor and the actuator input, chosen from the phase-to-frequency characteristic of the cantilever at the resonance. The output of PI - FW is an accumulator type, which value is actually proportional to the difference and is updated each cycle of the signal. Hence the frequency f_{drive} changes until set-point at PI is reached by the OC. Further changes of f_{drive} are random and small.

3.2. Physical FPGA Implementation

The physical realization of the system has been performed on Xilinx ™ Spartan-3 family chip XC3S400-4PQ208 (400 kGates); high-speed Digital to Analog Converter (DAC) has been used for DDS output code conversion. All module parameters (central frequency, phase set point, PLL capture range, feedback gain, etc) are programmable via USB.

The device utilization is presented in Table 1. As seen from the table, the design consumes small part of FPGA resources, thus, allowing multiple self-oscillating channels to be implemented on single chip.

Table 1. Device Utilization Report for Xilinx XC3S400-4PQ208.

Parameter	Value	Percentage
Selected device	3s400pq208-4	
Number of Slices	676 out of 3584	18%
Number of Slice Flip Flops	923 out of 7168	12%
Number of 4 input LUTs	611 out of 7168	8%
Number of bonded IOBs	39 out of 141	27%
Number of BRAM	2 out of 16	12%
Number of GCLKs*	4 out of 8	50%
Number of DCM_ADVs	1 out of 4	25%

** Common resource*

4. Experiments and Analysis

4.1. Testing the PLL Self-oscillation Setup

Using the presented self-oscillation setup, a number of experiments with microcantilevers with integrated bimorph actuator and piezoresistive read-out have been performed. The whole test setup comprised all-digital FPGA self-oscillation block, low-noise sensor amplifier and actuator driver. Cantilevers with different first resonance frequencies between 22 kHz and 51 kHz have been used. The system demonstrated stable locking at the resonance frequency in the explored range of sensors. Working at higher resonance modes between 150 kHz and 200 kHz has been successfully confirmed as well.

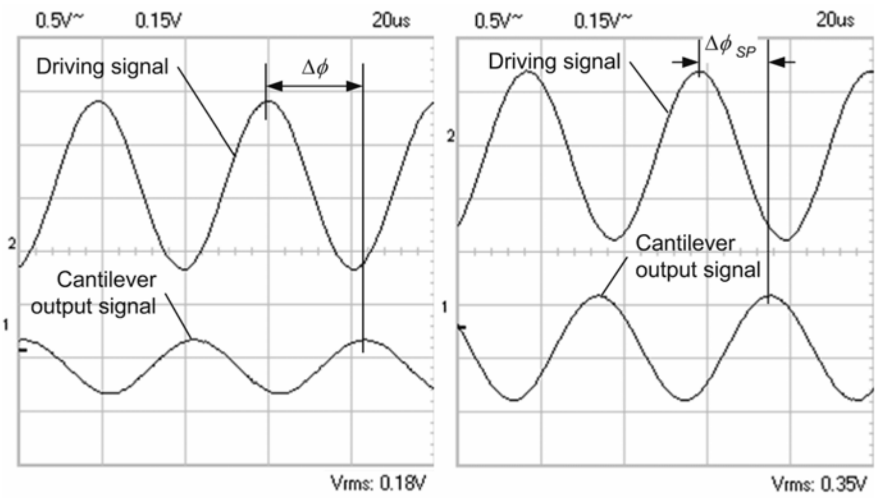


Fig. 4. Self-oscillation at second resonance of 24190 Hz. a) Open feed-back loop; the output generator runs free at fixed frequency 24270 Hz. The AC RMS value of the amplified output signal is 180 mV. b) Closed feed-back loop. The self-oscillation block enters the phase control mode and locks at the resonance frequency 24190 Hz. The AC RMS value of the amplified output signal is 350 mV.

In Fig. 4, two states of the system are shown: Fig. 4a presents the setup with open feed-back loop. In this state, the DDS is free running at fixed frequency near to the resonance. Fig. 4b shows the state when the phase feed back loop is closed. The DDS self-adjust its output at the resonance frequency of the cantilever. Fig. 5 presents the same experiments at second resonance mode.

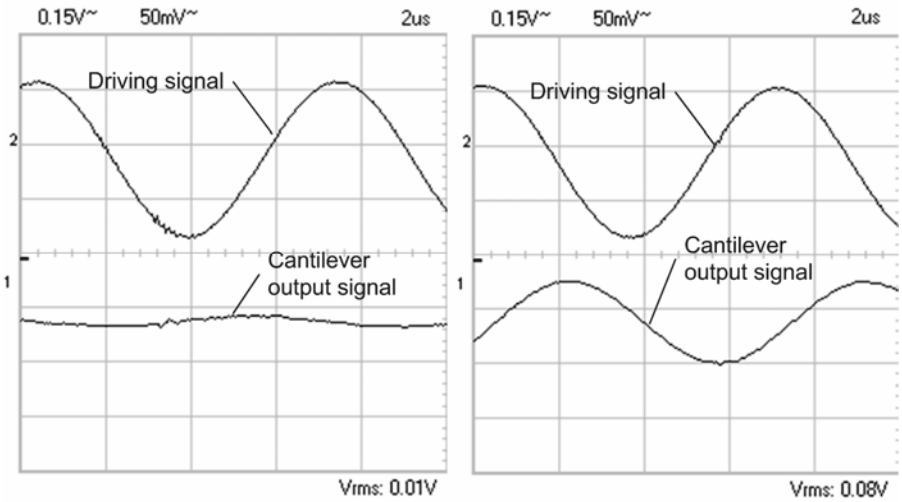
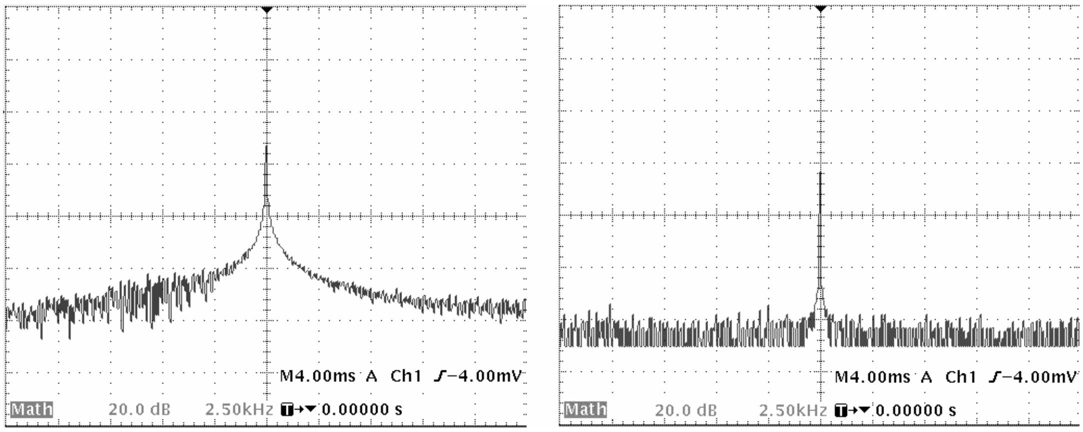


Fig.5. Self-oscillation at second resonance of 144 kHz. a) Open feed-back loop; the output generator runs free at fixed frequency near to the second resonance. The AC RMS value of the amplified output signal is 10 mV. b) Closed feed-back loop. The self-oscillation block enters the phase control mode and lock at the second resonance frequency. The AC RMS value of the amplified output signal is 80 mV.

Fig. 6 presents a spectral plot of cantilever vibration in air exited by the PLL self-oscillating block. The experiments confirmed stable sinusoidal oscillations at different phase set points within the capture range of the system. A spectral plot of cantilever vibration driven by external commercial DDS generator by SRS is presented for comparison (Fig. 6b).



a) b)

Fig.6. Spectra plot of (a) self-oscillation system, (b) oscillations exited by external commercial DDS generator.

4.2. PLL Self-oscillation System Analysis

4.2.1. Capture Range and Lock Range

The capture range of the PLL self-oscillating system is determined by the monotonous relationship between frequency and phase shift which is approximately linear within narrow range around the resonance. This range depends on the resonance frequency and Q factor of the cantilevers. For the cantilevers tested in our experiments, this range is approx. ± 100 Hz at 25 kHz first resonance frequency.

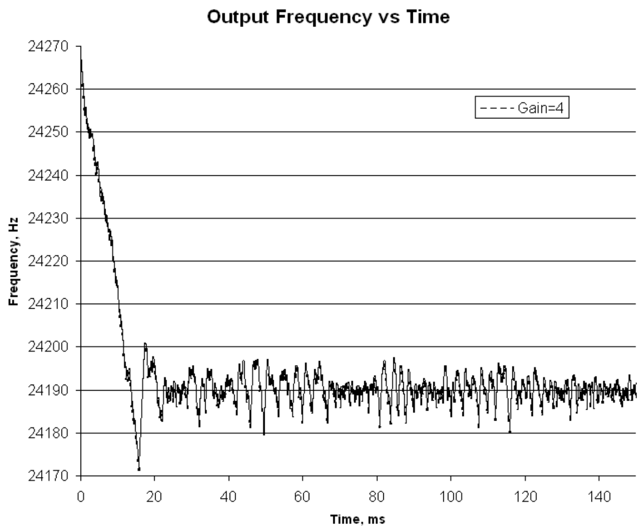
Once locked, the system tracks the changes of the resonance frequency of the cantilever. In general, the lock range is approximately equal to the capture range but also depends on the feed-back loop gain.

4.2.2. Capture Time and System Stability

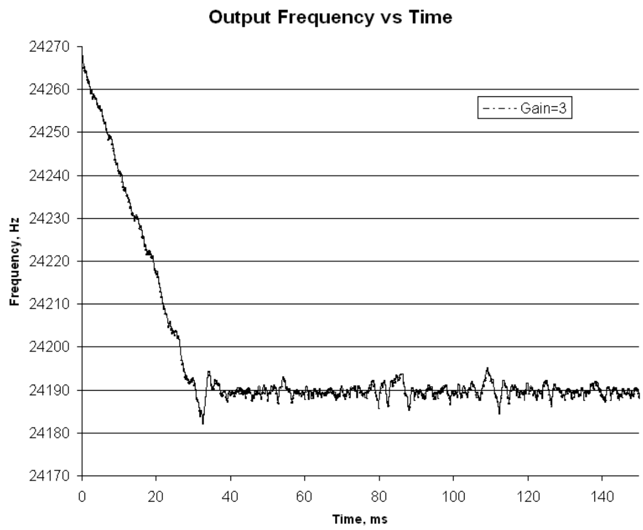
The capture time depends on the parameters of the feedback loop and on the oscillation frequency as the output of the phase-shift detector is updated after every period of the input frequency. Fig. 7 presents the locking process after closing the feedback loop at three different feedback gains. Once locked, the system exhibits a high stability of the oscillations. For the presented example, the standard deviation of the output frequency at feedback gain = 2 (Fig. 7c) is 0.501 Hz, or 0.0021 %.

4.2.3. Locking at Different Phase Set-points

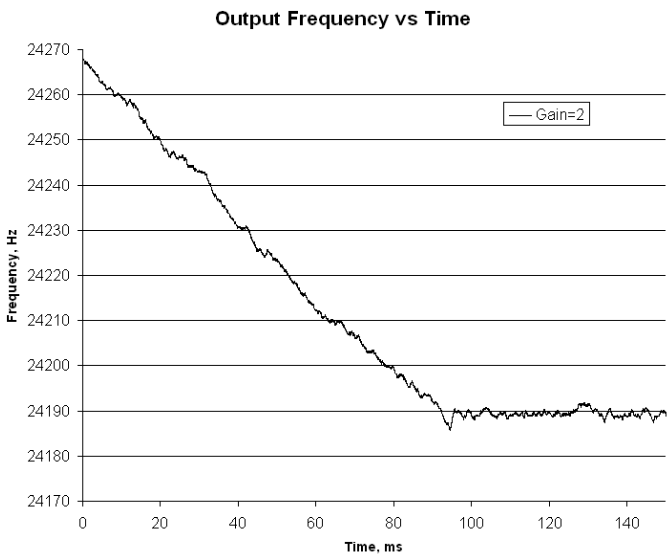
Our experiments demonstrated the ability of the proposed PLL self-oscillating system to lock at the resonance frequency only, but at any frequency within the capture range where the amplitude of the output signal is large enough to be detected by the “zero-crossing” circuit (Fig. 3). This feature allows the high-order resonance modes to be captured by the system as well, which have been successfully demonstrated during the experiments.



(a) Feedback gain = 4.



(b) Feedback gain = 3



c) Feedback gain = 2

Fig. 7. Process of locking at the first resonance of 24.19 kHz using different parameters of the feedback loop.

5. Conclusion

In this article, a PLL based, all-digital system enabling self-oscillation mode of microcantilevers with integrated bimorph actuator and piezoresistive readout has been presented. The system has been implemented in FPGA device, and series of experiments with cantilever sensors have been performed. The experimental results proved the functionality of the system, and its ability to lock at certain capture range around first and second resonance frequency. The system design can be easily multiplied in FPGA, thus, allowing multi-channel self-oscillation system to be realized.

The proposed PLL self-oscillating system can be applied in AFM technology, as well as in chemical and biochemical detection systems based on microcantilever sensors.

Acknowledgements

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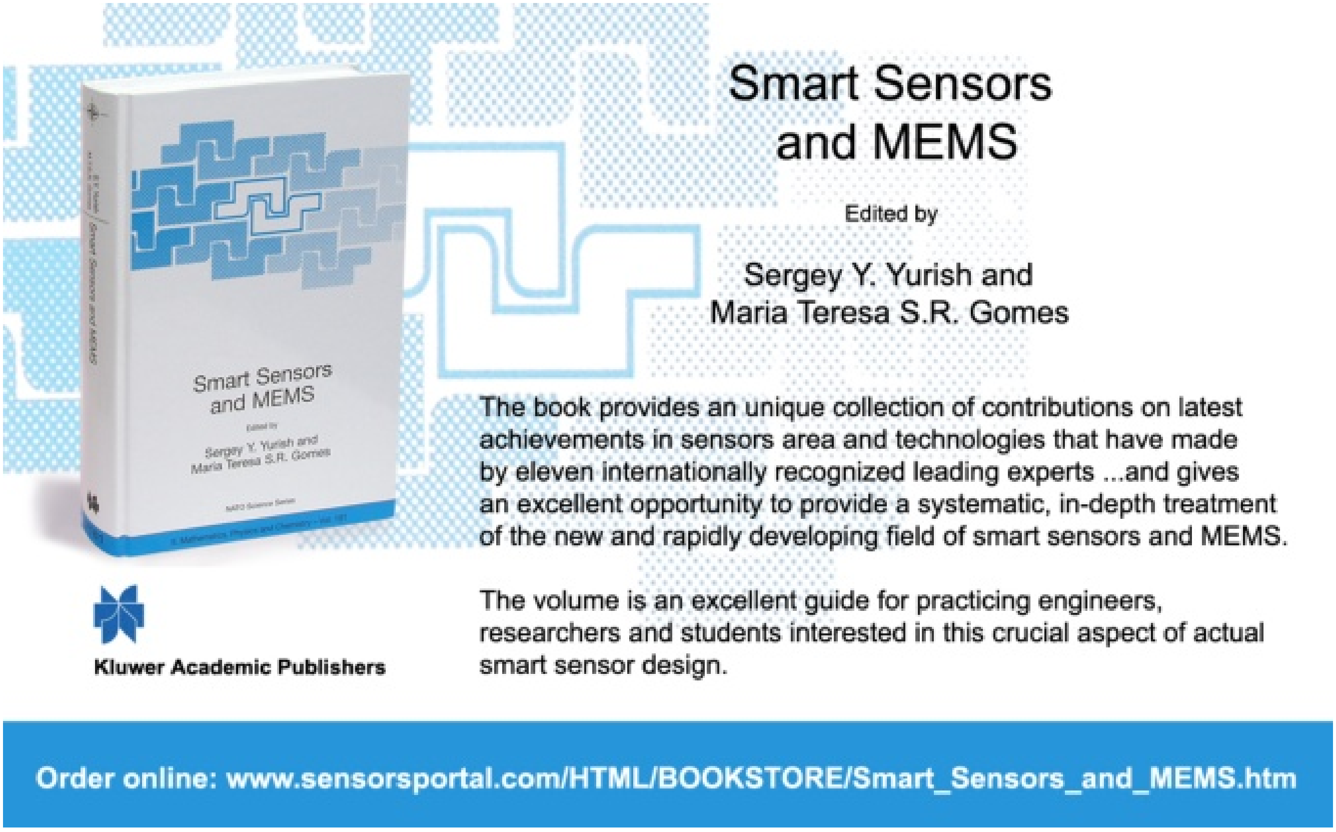

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- Virtual instruments;
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