

# RING OSCILLATORS AS THERMAL SENSORS IN FPGAS: EXPERIMENTS IN LOW VOLTAGE

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## ABSTRACT

In this paper, some experiments about thermal sensors based on ring-oscillator in low-voltage Virtex series FPGAs are presented. A non linear effect in the frequency-temperature response has been detected, and the sensibility of frequency with respect to voltage variations is greater than the measured in previous works. A quadratic polynomial function fits better the sensor response, and an increment in the number of inverters in the oscillator is effective to reduce the voltage sensibility.

## 1. INTRODUCTION

High temperature decays exponentially the reliability of integrated circuits [1], [2]. Die temperature can be monitorized using embedded diodes and transistors. In this first case, the error is ranged between  $-2^{\circ}\text{C}$  and  $2^{\circ}\text{C}$ , meanwhile transistors reduce it to  $-1^{\circ}\text{C}$  and  $0.8^{\circ}\text{C}$  [3]. Embedded diodes are used in FPGA technology.. Virtex-5 has a dedicated block called System Monitor. It includes a diode located in the center of the die, as well as an embedded microcontroller to monitor the temperature. Other thermal management actions like power down, interfacing, and data acquisition of small bandwidth signal can be also performed by this block. The absolute error is around  $4^{\circ}\text{C}$  [4].

Other alternative to measure die temperature is the use ring-oscillators, an idea reported in [5] and [6]. In [5], a programmable ring oscillator is designed to adjust a real-time image processor respect to temperature and voltage. The output frequency of the sensor is modeled by a 4<sup>th</sup>-order model, and allow the designer to measure both voltage and temperature of operation. In [7], the influence of temperature and voltage on the delay, for low-voltage electronics is thoroughly analyzed. Four ring oscillators are implemented in  $0.7\ \mu\text{m}$  technology. Using 104-inverter ring-oscillators, the authors conclude that more inverters

reduce sensitive to the voltage. But at the low-voltage and high-temperature corner, the delays are smaller than the corresponding values at a lower temperature. This phenomenon, known as reversed temperature, is also reported in [8]. Another characteristic of the delay at low-voltage is its non linear shape, as opposite to the linear behavior observable at higher voltages.

The utilization of ring-oscillators as thermal sensors on FPGAs was first explored in [9]. The advantages of ring-oscillators in a reprogrammable logic framework are multiple: it allows the designer the detection of hot spots or signal contentions [10], as well as the possibility of inserting an array of sensors using dynamic configuration to get a real-time thermal map of the FPGA [11]. Such techniques and other applications of ring-oscillators have been extended in recent years by other research groups on FPGAs [12]-[17].

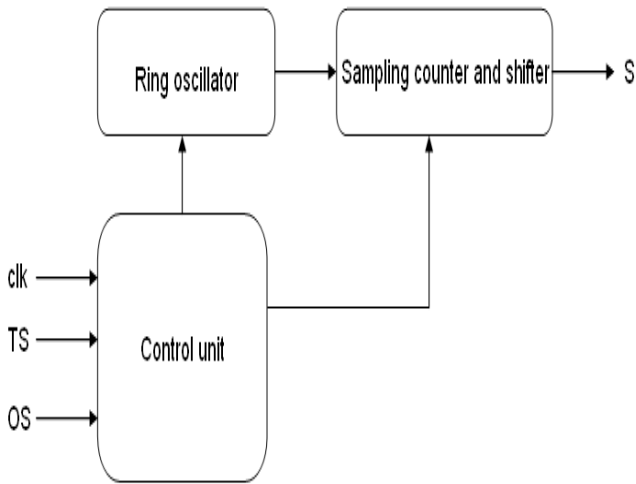
In this paper, some updated experiments of thermal sensor based on ring-oscillators in a 1.0 V core power supply Virtex-5 are presented. As it was pointed above, the operation of the sensors in low-voltage technologies lead to different results. The work is organized as follow. In the next section, the experimental setup is described. In Section 3, main results are shown. Finally, the main differences respect to previous results are summarized.

## 2. BUILDING AND CALLIBRATING RING-OSCILLATORS ON FPGA

Essentially, a thermal sensor based on ring-oscillators is a closed loop with an odd number of inverters. A time-base counter activates the circuit during a short time, capturing the frequency using a counter. To avoid self heating an AND gate is added to star/stop the oscillation. Wiring delay can be minimized in FPGAs by using a RPM (relative placement macro). A ring-oscillator can be embedded in just one LUT, but output frequency is too high. Practical rings on FPGAs require between 5 and 25

inverters. Each sensor implementation must be calibrated using a temperature-controlled oven.

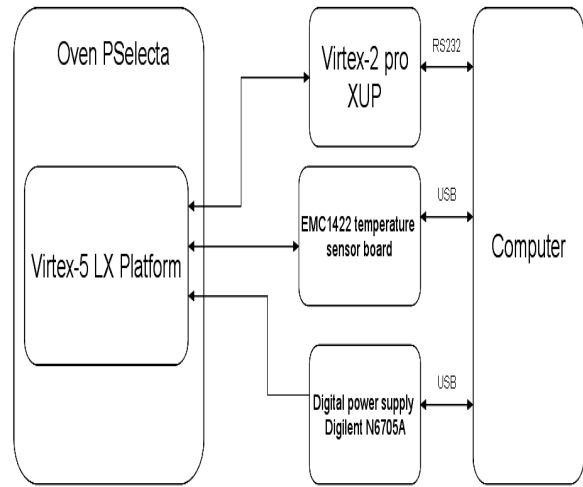
A scheme of the sensor utilized in this paper is depicted in Figure 1. A counter captures the frequency during a fixed window generated by a base time block. An external clock (clk) controls the process, and a shifter is used to take out the samples. The others external signals are intended to control the acquisition process. TS starts a measure, and OS indicates to the control unit when to shift the count through signal S.



**Fig. 1.** Architecture of temperature sensor based on ring oscillator.

Figure 2 shows the experimental setup, which include a Virtex-5 LX30FF676-1 FPGA board [18], a XUP board [19], a temperature-controlled oven Pselecta Digitronic 2005131 [20], a Digilent digital power supply N6705A, and an EMC1422 temperature sensor board [21]. The FPGA under test is situated into the oven.

The XUP board includes a Microblaze microprocessor which gives the appropriate commands to the thermal sensor to start the acquisition through a simple four wired interface (signals clk, TS, OS, and S). Once finished, the data are sent back to the computer through a RS232 interface. The EMC1422 temperature sensor board is utilized to take comparative temperature samples based on the embedded diode situated in the center of the Virtex-5 FPGA. The digital power supply provides a trustworthy way to vary the FPGA core voltage and keep it constant when the oven temperature is changed. The information about variations in voltage and input current is registered through an USB interface. All measures are captured and analyzed in a PC.

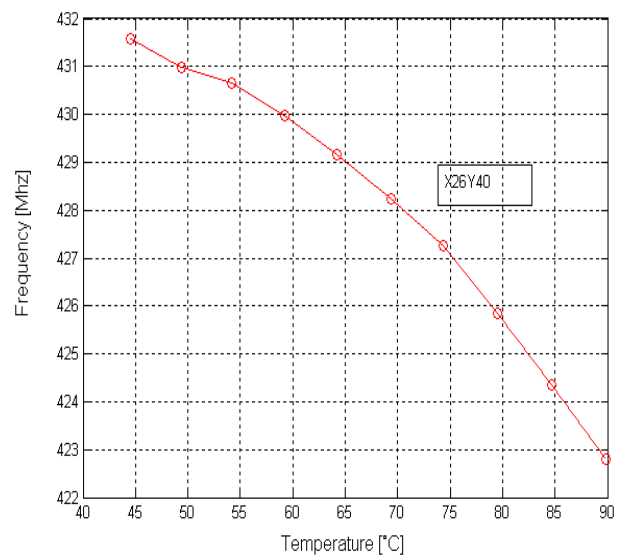


**Fig 2.** Experimental setup scheme

### 3. EXPERIMENTAL RESULTS.

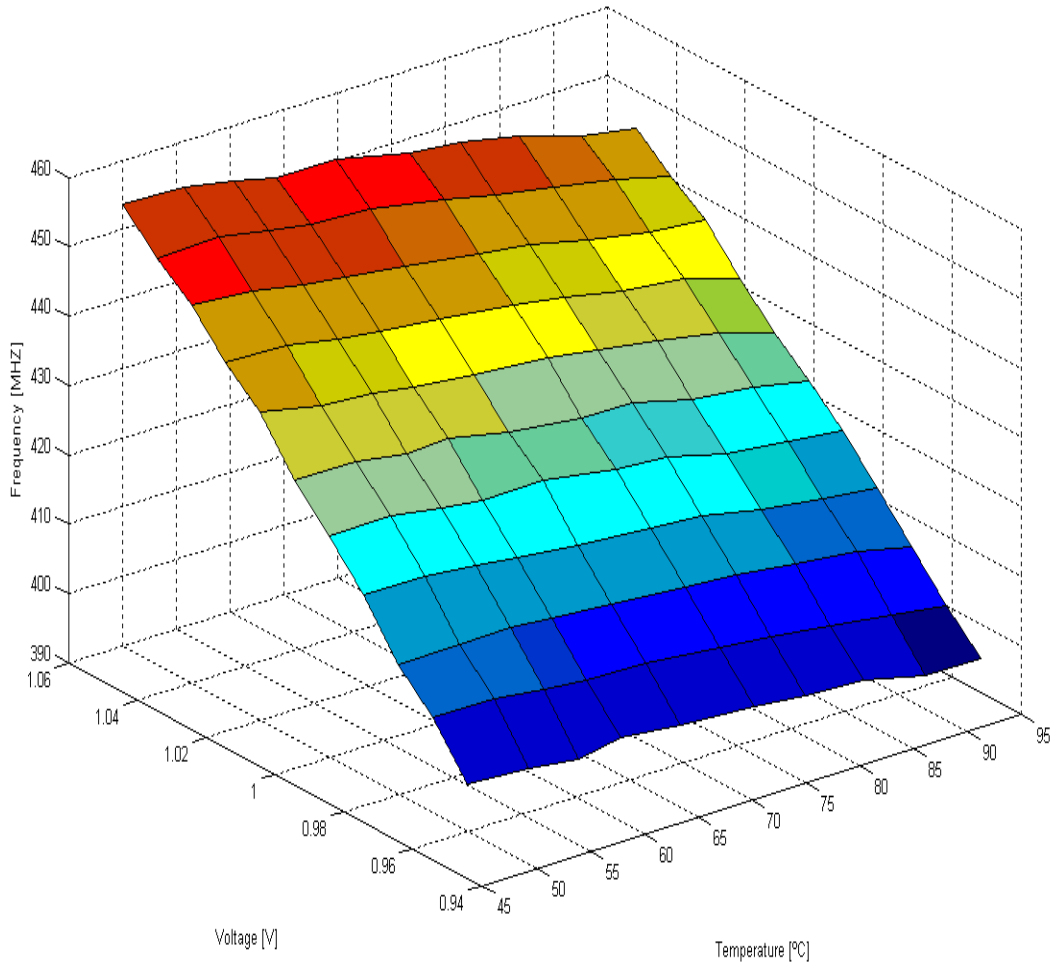
The behavior of a three-inverter oscillator respect to temperature is depicted in Fig.3. This sensor is located aside the thermal diode (in the position X26Y40 of the FPGA grid) in order to minimize measurement errors. The measured points show a non linear behavior.

Frequency response of one sensor (X26Y40) with constant voltage core (1.0 V)



**Fig. 3.** Calibration curve of the thermal sensor with three inverters.

Sensor response with three inverters varying temperature and voltage, position X26Y40



**Fig. 4.** Calibration surface varying voltage and temperature.

Figure 4 shows the calibration of the same sensor but changing voltage too. The voltage variation was ranged between 0.95 V and 1.05 V in steps of 10 mV and temperature variation was between 40°C and 90°C.

The surface describes a pronounced change in the frequency axis due to voltage. A mathematical model was adjusted using the lowest sum of squared absolute error criterion (LSSQC). Many functions were analyzed but equation (1) gave the lowest error: 16.

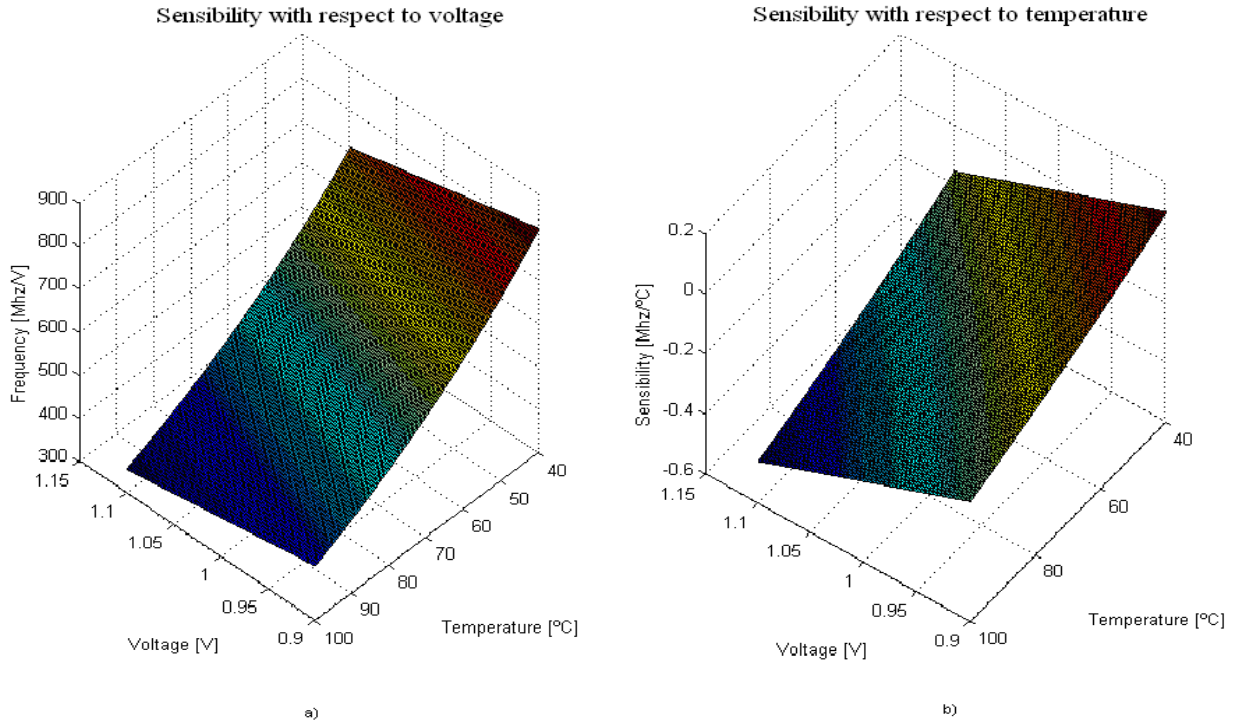
$$f = a + \frac{b}{v} + ct + \frac{d}{v^2} + et^2 + g \frac{t}{v} \quad (1)$$

In (1),  $f$  is the frequency,  $v$  is the core voltage, and  $t$  is the temperature.

**Table 1.** coefficient values

constant	value
a	711.672835
b	81.022020
c	-1.3704875
d	-360.990225
e	-0.0021678
g	1.477546

Sensibility of sensor can be obtained taking partial derivative respect to voltage and temperature.



**Fig. 5.** a) Surface of voltage sensibility. b) Surface of temperature sensibility.

The sensibility of frequency with respect to temperature is:

$$S_T = c + 2et + \frac{g}{v} \quad (2)$$

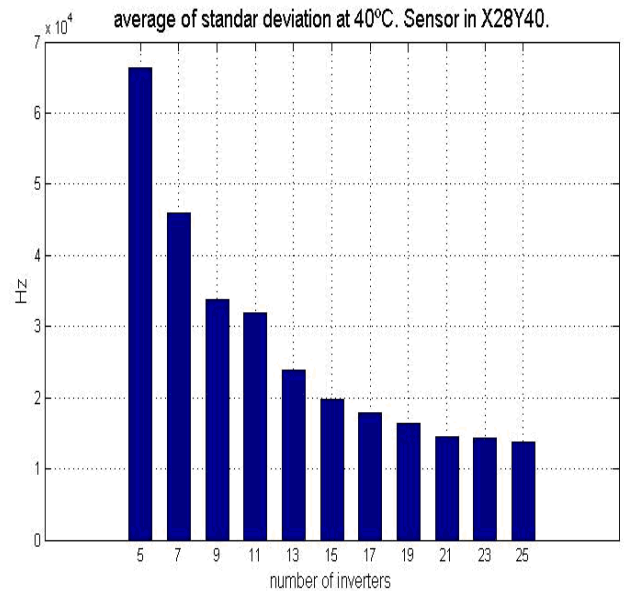
and the sensibility of frequency with respect to voltage is:

$$S_v = -\left(\frac{b + gt}{v^2}\right) - \frac{2d}{v^3} \quad (3)$$

Figure (5) reveals that a small change in voltage core at low voltage produces a high variation in the frequency of the sensor, and the contribution of the temperature is less significant. Although at low-voltage the sensor has a non linear characteristic, each point in frequency has an unique pair voltage-temperature. This property can be used to monitor voltage at any point of the die.

To explore the effect of adding more inverters to the thermal sensors, 11 different implementations were calibrated, ranging from 5 inverters up to 25 ones. The temperature was kept constant at 40°C. The voltage was increased from 0.95 V to 1.05 V in steps of 10 mV. For each voltage point, 254 samples were taken. To determine the impact of inverters in the dispersion, the metric utilized was the average of standard deviation. Figure (6) shows how the dispersion average decreases while increases the number of stages. This fact has practical importance,

because the measurement error due to voltage variation is minimum too. Twenty-five inverters is an optimum number of stages that can be embedded without a significant increasing of area.



**Fig. 6.** Average of standard deviation of the oscillation frequency at 40 °C.

#### 4. CONCLUSION

The experiments in 1.0 V low-voltage core FPGA show that ring-oscillators sensors have a non linear behavior more pronounced than those previously implemented on FPGAs with voltage core of 2.5 V or higher. The characterize voltage-temperature-frequency can be adjusted by a non linear function: each frequency point has a single pair voltage-temperature. Finally, increasing the number of sensors helps to improve noise immunity and reduce the impact of parameters variation.

#### 5. ACKNOWLEDGE

This work has been granted by the CICYT of Spain under contract TEC2007-68074-C02-02/MIC. The authors wish to thank Juan José Noguera of Xilinx Research Labs at Dublin for the donation of Virtex-5 boards as well as for his valuable comments and suggestions. We also thank to Professor Sergio Lopez Buedo for his technical support during the setup of the experiments.

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