Thermal Testing on Reconfigurable Computers

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Ring-oscillators are useful to monitor the thermal status of reconfigurable computers. No analog parts exist, and the sensors can be dynamically inserted, moved, or eliminated.

The exhaustive changes of the hardware context in configurable computing machines increase the risk of configuration errors and signal contentions—two situations that produce erroneous processing, reduce system life, or even cause permanent system damage. Excessive chip heat can also be caused by the peculiarities of a machine configuration: Fine-grain pipelined data paths, heavily loaded buses, or high off-chip capacitance can lead to an unforeseen power overhead. Consequently, the designers of configurable computing machines can detect several failures by adding some thermal monitoring mechanisms.

For years, temperature has been a primary parameter of hardware debugging techniques. In the past, low temperature identified bad vacuum tubes. Today, burning ICs points to potential problems. Even in the era of complex instrumentation, hardware designers keep the habit of detecting faulty circuits by touching the chip packages. In this way, the increasing tendency to include temperature sensors on current electronic systems has been a natural step. The concept of thermal testing, introduced in Székely et al.,[1] is now incorporated into several electronic products. For instance, thermal protections have been adopted in commercial configurable computing machine boards,[2,3] and two pins connected to an internal diode have been recently included in a new FPGA series to sense junction temperature.[4] Finally, semiconductor manufacturers are offering complete families of chips to control temperature on PC boards.[5]

An important difference between PC boards and reconfigurable systems is that in the latter, the processing tasks are dynamically distributed between several chips that change their functionality at the hardware level. As a consequence, the detection of hot spots requires sensing the temperature in each IC in the system. However, if the machine is large, using classic thermal transducers is impractical. Thermocouples, thermistors, or integrated sensors require both extra wiring and hardware that must be immune to the influence of the high-frequency signals usually existing in the machine. Moreover, the designer must pay attention to details like sensor positioning, thermal coupling, or analog instrumentation. The implementation of on-chip sensors is an alternative to avoid several of these inconveniences, but the main techniques[6] require a full-custom chip redesign. Thus, the question is how a system designer can insert thermal sensors inside commercial reconfigurable chips. This article explores three straightforward ways to solve this problem: to construct ring-oscillators, to use built-in oscillators available on many FPGAs, and, finally, to reuse the I/O pad clamping diodes for thermal purposes.

Some on-chip, end-user-oriented alternatives to thermal testing

It is well-known that microelectronic delays increase with temperature. As a consequence, a way to measure chip heating is to construct an oscillator and calibrate its output drift in

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MHz per °C or °F, an idea originally proposed in Quenot et al.[7] This solution establishes a natural link between temperature (an analog magnitude) and FPGAs (digital chips) through the only analog magnitude that can be directly measured by a digital circuit: the frequency.

A direct way to get frequencies in FPGAs is to map a ring-oscillator. A ring-oscillator consists of a feedback loop that includes an odd number of inverters needed to produce the phase shifting that maintains the oscillation (Figure 1). The resulting period is twice the sum of the delays of all elements that compose the loop. The inversions can be done using the look-up tables (LUTs) of the configurable logic blocks (CLBs) or the programmable inverters included in the I/O blocks (IOBs) of the FPGA. In any case, it is useful to insert an external signal to open the loop, as well as an output buffer to prevent frequency variations due to different loads.

The advantages of oscillators as thermal transducers are multiple:

- They can be easily implemented with few chip elements.
- Some FPGA families include built-in oscillators.
- Like other on-chip sensors, the junction temperature instead of the package temperature is measured.
- All signals are digital; thus, they can be processed using the general resources of the board.
- The sensors are small: Practical circuits use two logic blocks, and a minimum-size sensor can be fitted in just an I/O block.
- A sensor or even an array of them can be placed in any position of the chip, making possible the construction of a thermal map of the die.
- The sensors can be dynamically inserted, moved, or eliminated.

During a discussion on an Internet newsgroup, Peter Alfke suggested another ingenious alternative to determine chip temperature: measure the junction forward voltage of the clamping diodes located in the FPGA pads.[8] This technique lets the designer obtain free, small, and abundant on-chip thermal sensors at the cost of some external analog circuitry and only one I/O pin. The method, also mentioned in Dewey and Emerald,[9] is based on the voltage–current relationship in an ideal diode:

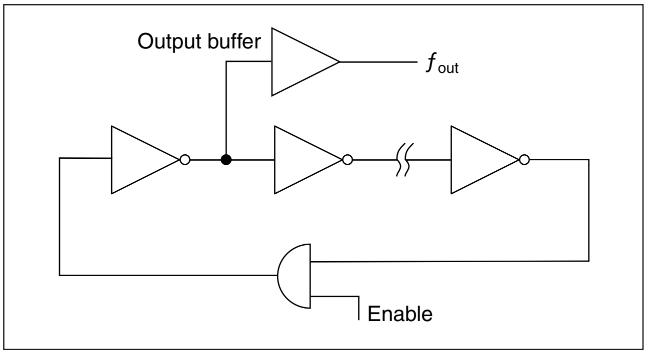

Figure 1. A ring-oscillator scheme.

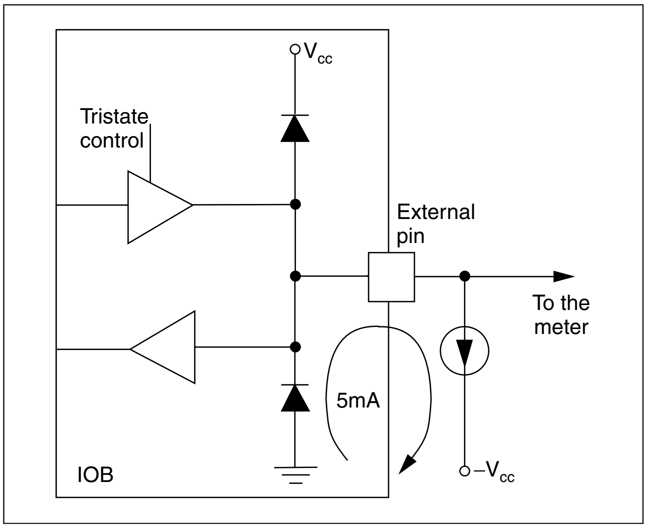

Figure 2. Bottom IOB clamping diode as thermal sensor.

$$I = I_s\left(e^{qV/kT} - 1\right)$$

I_s includes six parameters that depend on the temperature and nearly determine the overall thermal characteristics of the junction. In short, for a fixed diode voltage, the current rises almost exponentially with T; meanwhile, for a fixed current, the voltage across the junction diminishes almost linearly with T.[10] Practical applications[11,12] have used the second operation mode. The main advantage of the diodes as thermal transducers is their low sensitivity to power supply variations. Figure 2 shows a sim-

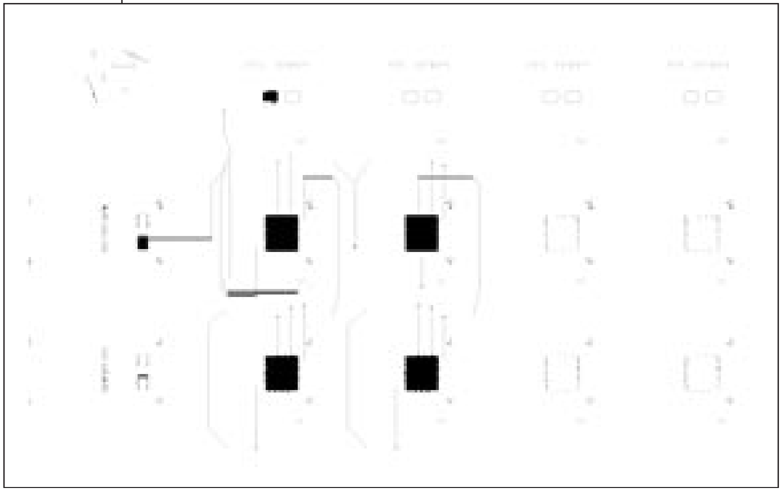

Figure 3. Layout of ring5.

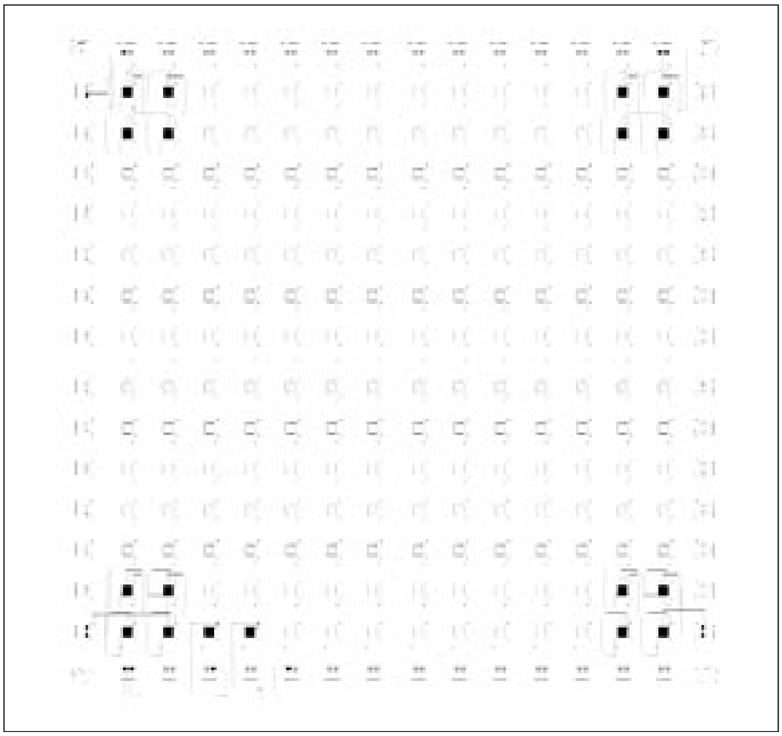

Figure 4. Array of identical sensors situated in the die corners, named counterclockwise ring5 (top left) to ring8. The relationship between chip area and sensor size can be observed.

plified structure of an I/O pad and the measurement scheme utilized in this work: A current sink circuit fixes 5 mA in the lower diode (the pad output buffer must be tristated). A refinement of this experiment should embrace different diode currents in order to select the biasing that produces the most linear response.[13]

Some test circuits

Ring-oscillators can be manually constructed or use a standard automatic partitioning, placement, and routing design flow. In the last case, the designers must include high-level directives to avoid the simplification of an even number of inverters during the compilation process. It is also useful to fit the inverters in distant LUTs to increase wiring delays. Note that unusually in digital design, the goal here is to decrease the operation frequency in order to minimize the problems related to self-heating, power consumption, and counter size.

In this article, we selected an array of four identical ring-oscillators to illustrate some aspects of thermal testing. Figure 3 depicts a detailed layout of one of them. The oscillators were manually placed and routed using four CLBs to increase their oscillation period. They have an overall loop delay of 35 ns: 23.2 ns corresponding to LUTs and 11.8 ns to wiring. The outputs were buffered (via another CLB) to prevent possible mismatching caused by different output paths. Figure 4 shows the final layout of the array (the picture includes the circuitry situated near the bottom left corner utilized to produce short circuits in pads and internal buffers).

Calibration hints

To perform an accurate sensor calibration, the FPGA samples must be introduced in a temperature-controlled oven (Figure 5). In our case, to save time, a configuration with all the transducers was downloaded, but just one was enabled during its characterization. We measured chip temperature by placing an iron–constantan (Fe–CuNi) thermocouple in the center of the package. A set of long cables (close to one meter) were necessary to externally configure and control the FPGA, as well as to carry the oscillator outputs outside the oven. To prevent excessive power consumption in the sensors due to these high off-chip loads, we inserted a driver (type 74HC125) near the FPGA to isolate the ring outputs from the cables.

A source of error in active thermal transducers is the own sensor dissipation. However, performing the measurements during a short enable window minimizes this problem. In our case, the oscillator was first left running during 0.2 ms to stabilize the output. Then, we measured the frequency during 4 ms (Figure 6) and stopped the oscillator. The procedure was repeated every 250 ms. Both parameters were obtained empirically, and they should be reviewed in future FPGAs, considering that self-heating effects will be more significant in the next generation of ICs.[14]

Figure 7 shows the efficacy of this strategy. The graph superposes the output frequency of ring5 for two different operation modes: windowed enabling and free-running operation. Even though the temperature was held constant to 22°C during the experiments, a frequency drift of more than 129 KHz (equivalent to 2.5°C) appeared in the free-running operation. This effect is negligible in the windowed–enabled mode.

Main characteristics of thermal sensors on FPGAs

Figure 8 (next page) summarizes the main characteristics of the transducers. See our previous experiments on circuits with several LUT/wiring delay ratios as well as different implementation alternatives.[15,16]

The ring-oscillators exhibit the most linear response in the normal range of temperature operation. Their outputs are situated in an intermediate band of frequencies: between 21 MHz and 27 MHz (Figure 8a). So, their values can be easily managed by a low-cost microcontroller if a prescaler is used. All array sensors have the same temperature variation (–0.20% per °C), but each one runs at a different frequency for a given temperature. The maximum gap between them is about 0.8 MHz, although the outputs of rings 5 and 6 are almost identical.

Figure 8c summarizes an example of the second alternative: the use of the internal oscillator included in the XC4000 series FPGA.[17] In this case, to facilitate the comparison with the CLB-based rings, the 8-MHz output response of the OSC4 cell was calibrated in terms of temperature.

Finally, Figure 8e presents the result of the last option, the IOB diodes. From 20°C to 90°C, the voltage drop ranges between 0.63 mV and 0.55 mV. The average output sensitivity is –0.21% per °C. Similar results were obtained for 1-mA biasing. Diodes were less linear than ring-oscillators, but they have an interesting advantage as thermal sensors: Their response is almost independent of power supply variations. In effect, an important

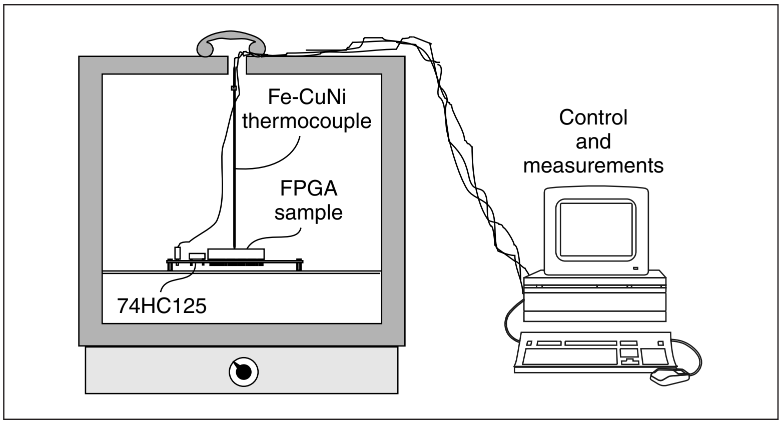

Figure 5. Sensor calibration setup.

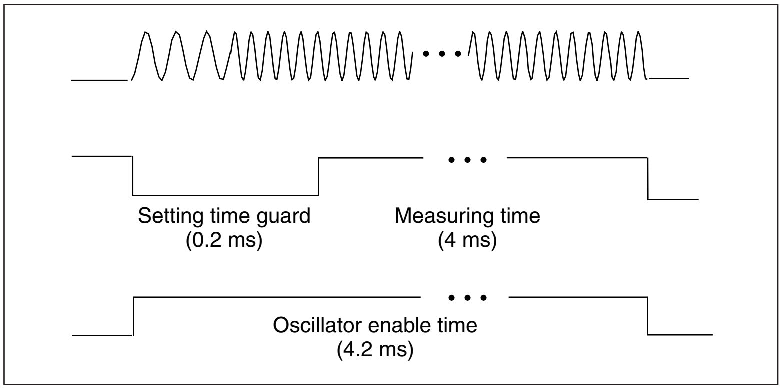

Figure 6. Windowed–enabled mode.

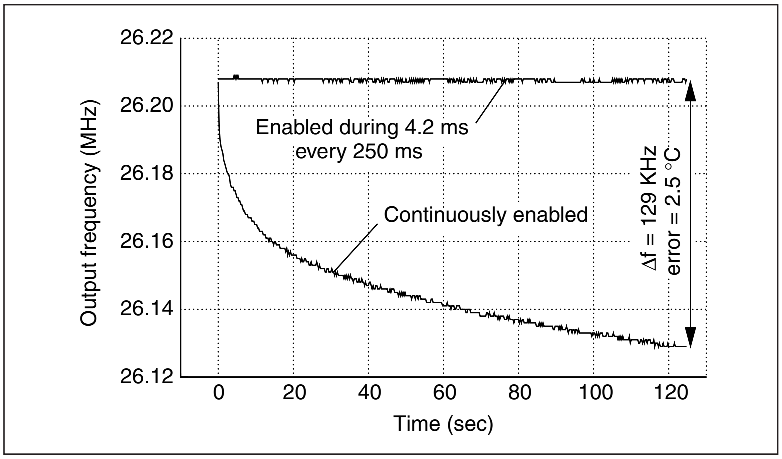

Figure 7. Self-heating error in ring5 calibration. Short enable window versus continuous operation.

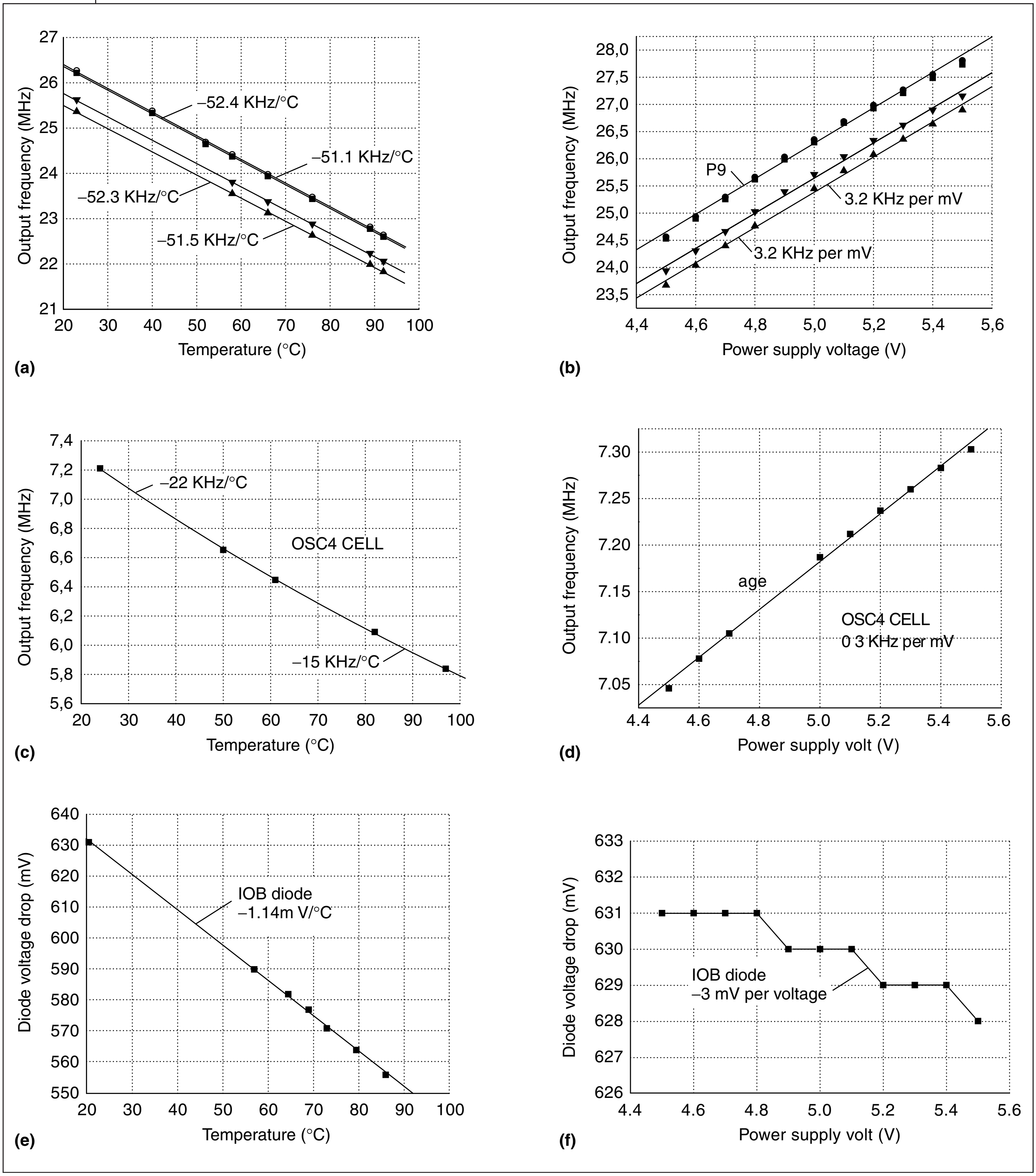

Figure 8. (a), (c), and (e) Thermal response of ring-oscillators, OSC4 cell, and IOB diodes and (b), (d), and (f) their corresponding power supply sensitivity.

parameter of the transducers is the error caused by power supply variations (see Figure 8b, Figure 8d, and Figure 8f). Ring-oscillators exhibit a linear response in the operation range, but their frequency drift (in percentage of output variation per volt) is important: near 15% per volt (Figure 8b).

The OSC4 cell and the IOB diodes have a lower power supply sensitivity: 3.6% per °C and less than 1%, respectively (see Figure 8d and Figure 8f).

Two examples of thermal testing

To illustrate the sensitivity of the on-chip sensors, we fixed pins 35 and 36 of a XC4005 FPGA to opposite logic levels. Both pins are situated in the bottom left corner, close to ring6. Then, we produced an intentional short circuit between these pins and monitored the array response. The results are summarized in Figure 9a. It shows the normalized frequency of the sensors (with respect to their values at room temperature). In $t = 0$, the short circuit begins, finishing at $t = 25$ sec. An analysis of the data indicates that all frequencies decrease following a second-order exponential; however, the decay is different for each sensor. A peak temperature is detected by ring6: almost 3°C higher than that measured in the opposite corner. The temperatures in the equidistant corners (ring5 and ring7) were almost equivalent. The above experiment was repeated for a short circuit produced in two internal tristate buffers situated near ring6. Even considering the small magnitudes involved in this case, the behavior is similar to that obtained in the previous test (Figure 9b).

Taking into account that chip failures depend on not only the steady-state junction temperature but also the temperature gradients,[18] this experiment also illustrated that the ring-oscillators can be utilized to determine if a significant difference of temperature exists in the die during the operation.

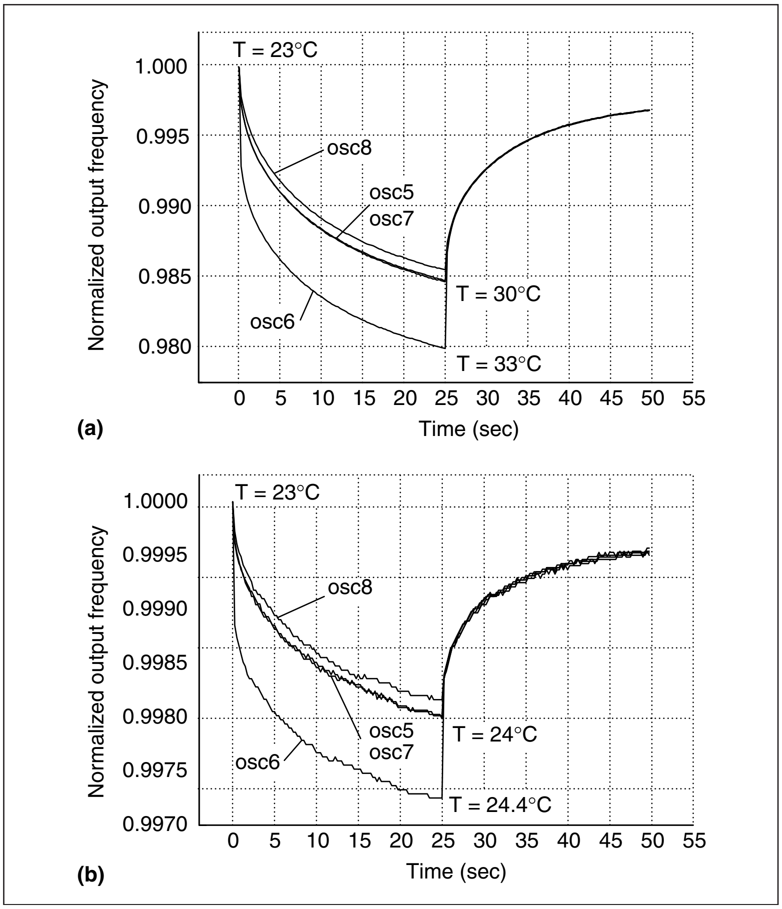

Figure 9. Normalized response of each sensor (with respect to their frequencies at room temperature) for (a) pad and (b) internal-buffer contentions.

THIS ARTICLE SUGGESTS some ideas to implement an online thermal monitoring strategy on reconfigurable systems. The three alternatives show different advantages. The best results in frequency range, resource occupation, and power supply sensitivity correspond to the built-in XC4000 series oscillator. Meanwhile, CLB-based ring-oscillators can be situated in virtually any position of the chip. Pad diodes are also interesting due to their lower power supply sensitivity.

The sensor calibration procedure can be dropped if the goal is just to detect peak power values. In this case, the adjustment can be done in terms of power consumption by measuring both chip input current and sensor output frequency for each computer configuration and for normal operation. Thus, the correct thermal status of the machine can be described by a range of expected frequency values in each FPGA.

These methods also facilitate the construction of highly reliable systems based on FPGAs. Even considering that the advantages of the thermal deration technique (the lowering of the operating temperature to get an extra margin of safety) is being reviewed,[18,19] the proposed transducers allow the designers to know the junction temperature *Tj* for the actual operation conditions. Thus, aspects like the thermal effects of the printed circuit board,[20] the chip positioning, the heat produced by neighboring devices, the interferences in the air flow, the humidity, or the details related to the heat sink utilized can be incorporated into the deration strategy.

Finally, this work opens a new field of application for FPGAs. The reconfiguration capability transforms these devices into a powerful tool for the study of thermal aspects of ICs and packaging, allowing researchers to perform an unlimited number of new experiments. Just the possibility of "moving" the sensors along the die is unthinkable in other VLSI technologies.

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