

Giant Sensitivity through Fully-Passive and Chip-Less Parametric Temperature Sensors

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Abstract—In this work, we present a new passive and battery-less temperature (T) sensor, leveraging the unique dynamics of a varactor-based parametric frequency divider (PFD) to boost, by orders of magnitude, the temperature sensitivity attained by commercial and low-cost temperature sensitive components. We show that by including a ceramic thermistor in a PFD circuit made of off-the-shelf low-cost lumped components, the minimum PFD input power (P_{th}) triggering a sub-harmonic oscillation starts to depend on T . Such unexplored feature makes the generated PFD output power, at half of the driving frequency, exhibit a record-high sensitivity with respect to T that largely surpasses the maximum one attainable by operating the same thermistor in conventional read-out circuits. In order to demonstrate this unreported special operational feature, we built a PFD prototype on a Printed-Circuit-Board (PCB), operating at an input frequency of 886MHz (*i.e.* an output frequency of 443MHz) and strategically including a commercial thermistor in its network. Despite the fact that no supplied DC power was used, the output power of the built system showed a record-high sensitivity (up to 2.5dB/°C), thus offering exciting opportunities to attain low-cost chip-less temperature sensors for a variety of applications, ranging from smart manufacturing to environmental and agriculture monitoring.

Index Terms—Temperature Sensors, Parametric Nonlinearities, Nonlinear Dynamics, Parametric Frequency Dividers

I. INTRODUCTION

Recently, much attention has been paid to the development of temperature sensors, monitoring a steadily growing number of different kinds of goods and items [1]–[7]. Such effort has been driven by the urging need to protect specialized equipment, such as those used in manufacturing warehouses and data-centers, from undesired increases of their operational temperature (T). Similarly, the availability of such sensors can also be beneficial in applications where a prompt identification of any perishables, from food to medicine, suddenly exposed to incompatible temperatures is strongly required. Despite their large fabrication complexity, the continuous development of Micro- and Nano-ElectroMechanical systems (MEMS/NEMS [8], [9]) has provided means to achieve an ultra-sensitive temperature sensing. For instance, temperature sensors based on Aluminum Nitride (AlN) nano-plates acoustic resonators [10] have recently attracted much attention thanks to their CMOS-compatible fabrication process and to their significant Temperature Coefficient of Frequency (TCF = 50 ppm/ °C). However, for any given temperature range of interest, these devices exhibit sensitivities that are ultimately limited by their moderate quality factor ($Q < 1300$). Moreover, their integration with any available read-out circuits still represents a challenge that often comes with the risk of degrading even

more the Q of such resonators and, consequently, their temperature sensitivity. For this reason, there exists a strong need to build temperature sensors through low-cost components not requiring any heterogeneous integration, yet exhibiting sensitivities that surpass those attained by on-chip high- Q resonant sensors, like the previously reported MEMS/NEMS devices.

In this work, for the first time, we present a novel passive and battery-free temperature sensor, leveraging the unique dynamics exhibited by varactor-based parametric frequency dividers (PFDs) to boost, by orders of magnitude, the temperature sensitivity attained by a low-cost commercial thermistor. Such a unique operational feature, reported for the first time in this work, enables record-high temperature sensitivities exceeding those attained by the currently available state-of-the-art MEMS/NEMS temperature and thermal detectors [10]. Also the operational principles discussed and exploited for the first time in this work can be applied to achieve even other classes of physical sensors with unprecedented sensitivities.

II. PRINCIPLE OF OPERATION

The reported temperature sensor is formed by a varactor-based 2:1 PFD, including a network of lumped electrical components (*i.e.* inductors and capacitors), a commercial thermistor and a solid-state variable capacitor. PFDs are two-port RF circuits. They have the inherent ability to activate a 2:1 sub-harmonic oscillation for input power levels (P_{in}) exceeding a certain threshold (known as parametric threshold, P_{th}) through a super-critical bifurcation [11]. So, for P_{in} slightly higher than P_{th} , PFDs exhibit a steep but continuous P_{out} vs. P_{in} characteristic, being P_{out} the output power at the divided frequency delivered to the output load. Just recently, when studying the dynamics of such systems, we found that the P_{th} exhibited by any PFD depends on the impedance seen by its adopted varactor at both the input and output frequencies. Consequently, by adding a thermistor to the passive components included in PFDs and forming their stabilization network, any ambient temperature-induced change of the thermistor impedance results into a shift of P_{th} . Due to the large slope of the P_{out} vs. P_{in} characteristic exhibited by any PFD, in proximity of their super-critical bifurcation, such a shift in P_{th} produces a large variation of P_{out} that provides the mean to achieve the ultra-high temperature sensitivity reported in this work. The schematic of the temperature sensor circuit built in this work is reported in Fig. 1. This relies on off-the-shelf lumped components

(with low- Q not exceeding 80) and it does not require any DC supplied power or voltage to work. The core of the PFD circuit (including L_1, L_2, C_1, C_2, L_3) was designed for operation with an input frequency (f_{in}) of 886MHz (corresponding to an output frequency of 443MHz). This was done by following the design resonant conditions listed in [11]. Also, in order to keep a record-low P_{th} (lower than -16dBm) across the entire temperature range of interest (between 25°C and 60°C), the thermistor was connected to the circuit input port in a shunt configuration.

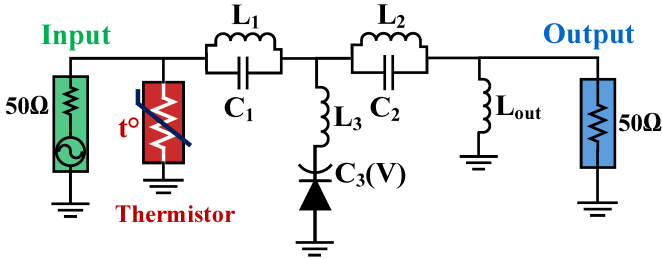


Fig. 1: Circuit schematic of the reported parametric temperature sensor. The values of the inductors L_1, L_2, L_3 and L_{out} are 39nH, 22nH, 22nH and 1.8nH, respectively. The values of the capacitors C_1 and C_2 are 1.5pF and 1.4pF, respectively. The varactor model is Skyworks SMV1430 and the thermistor model is TDK B59810C0120A070.

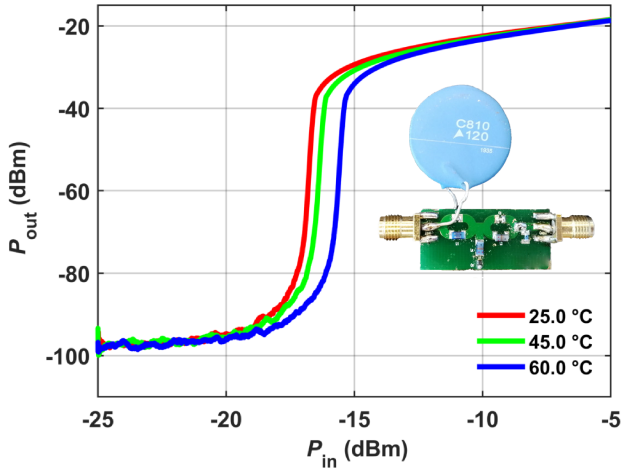


Fig. 2: Measured P_{out} vs. P_{in} characteristic exhibited for three different temperatures by the temperature sensor reported in this work, when this is driven by an input signal at 886MHz and with a power level swept between -25dBm and -5dBm. A picture of the fabricated PCB used to assemble the reported temperature sensor circuit is also shown in the inset.

The emergence of the the divided signal for $P_{in} > P_{th}$ and the sensitivity of P_{th} with respect to temperature (enabled by the inclusion of the thermistor) were analyzed by extracting the P_{out} vs. P_{in} characteristic for the reported sensor (see Fig. 2)

at three different temperatures. In order to do so, a signal at 886MHz, with power level swept from -25dBm to -5dBm, was injected in the circuit from its input port (Fig. 1), while monitoring the output power at 443MHz delivered from the output port to a 50Ω load. As evident, the reported temperature sensor exhibited a P_{th} that is always lower than -16dBm. Also, as expected, due to the fact that the thermistor is embedded in the PFD network, any ambient temperature shift altering the at-ambient temperature impedance of the thermistor results into a significant change of P_{th} . Ultimately, from Fig. 2, it is evident how the measured P_{out} vs. P_{in} characteristic exhibits a large slope that provides the means to achieve giant changes of P_{out} for even smaller variations of P_{in} . Thus, by fixing the P_{in} at an operational input power value (P_{op}) that is slightly higher than P_{th} , we can obtain a dramatic change of P_{out} with respect to the slightest temperature change, hence providing the means to achieve the ultra-high sensitivities reported in this work.

III. RESULTS AND DISCUSSION

The reported temperature sensor was assembled on a printed circuit board (PCB) using an FR-4 substrate (see the inset of Fig. 2). In order to characterize its performance and sensitivity, we used two synchronized vector network analyzers (VNAs), providing the 886MHz input power while simultaneously monitoring the P_{out} value at 443MHz. The sensor was then placed on a digitally controlled hotplate to allow the extraction of P_{out} , at different temperatures and for a fixed P_{in} equal to P_{op} (-16.6dBm). Such a value was chosen as it corresponds to the input power giving the highest slope of the P_{out} vs. P_{in} characteristic. The P_{out} value was then extracted for temperatures ranging from 25°C to 60°C, with steps of 2.5°C. As evident from Fig. 3, where the measured normalized output power ($\hat{P}_{out}$) is plotted vs. temperature, the reported temperature sensor shows an extraordinary high contrast, exceeding 45dB, between the measured $\hat{P}_{out}$ values at 25°C and 60°C, respectively. In addition, it exhibits a maximum sensitivity of 2.5dB/°C which is defined as the steepest slope of the $\hat{P}_{out}$ vs. temperature trend as shown in Fig. 3. It is important to point out that both these measured contrast and sensitivity values are orders of magnitude higher than what would be attained by simply monitoring the power flow through the same thermistor used in our sensor (see Fig. 3). Such a unique feature demonstrates how the unique dynamics of the reported sensor architecture allows to surpass the fundamental limits exerted by any adopted temperature sensitive component (a thermistor in this case) and enable unprecedented sensing capabilities, without requiring any advanced manufacturing of on-chip devices and systems. In order to further demonstrate this unique operational characteristic, we also compared the maximum sensitivity attained by our reported sensor with the one that would be attained by monitoring the power flow through a state-of-the-art AlN nano-plate thermal detector [10], engineered to operate across the same temperature range explored in this work. In order to do so, an AlN device was modelled by using a modified Butterworth-Van Dyke model

(MBVD [12]) and the same TCF reported in [10]. Also, the electromechanical coupling coefficient of this piezoelectric device (K_t^2) was chosen to be 0.34% to enable the highest contrast in the power flow across the device and a monotonic behavior of $\hat{P}_{out}$ across the same temperature range explored in this work. Finally, the Q of the resonator was swept so as to find its minimum value ensuring a maximum sensitivity level matching the one attained by our reported parametric temperature sensor. As evident from Fig. 4, despite the fact that the reported temperature sensor only relies on low- Q lumped components, its maximum sensitivity (2.5dB/°C) could only be achieved by the analyzed AlN nano-plate resonator if this piezoelectric device was exhibiting a Q approaching 4000 (hence nearly four times higher than what previously demonstrated in [10]).

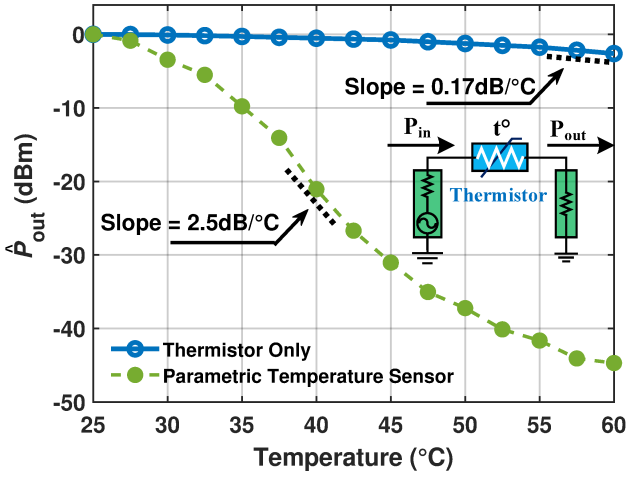


Fig. 3: Measured $\hat{P}_{out}$ at 443MHz (green dashed line) vs. temperature, for P_{in} equal to P_{Op} . For comparison, a corresponding trend was also extracted (blue curve) when considering the power flow across the same thermistor used by the reported parametric sensor. The circuit schematic used for this second evaluation is reported in the inset.

IV. CONCLUSION

In this work, we presented a novel battery- and chip-less temperature sensor. By leveraging the unique dynamics of parametric frequency dividers, such sensor allows to exhibit record-high contrast and temperature sensitivity (up to 2.5dB/°C), exceeding by orders of magnitude what attained through other available sensing schemes and through the adoption of the same temperature sensitive component (a commercial thermistor). The novel sensing technique exploited by this reported temperature sensor can be applied to achieve even other classes of low-cost physical sensors not relying on any micro-fabricated devices, yet exhibiting extraordinary sensitivities.

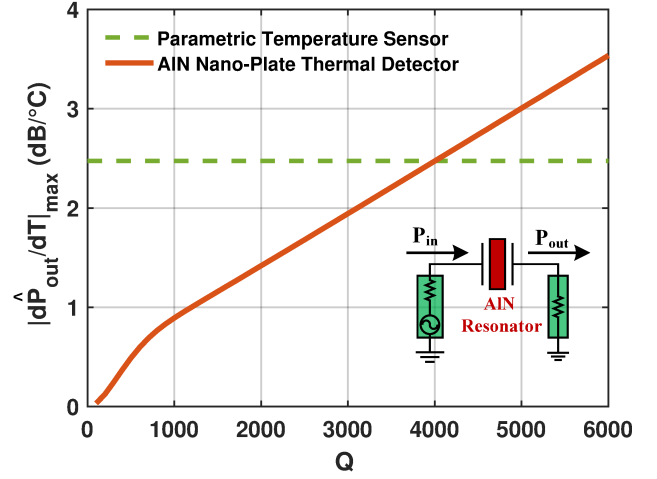


Fig. 4: A comparison of the maximum sensitivity of $\hat{P}_{out}$ vs. temperature achieved by the reported temperature sensor (green line) with the one attained by a state-of-the-art AlN nano-plate resonator with Q varying between 10 and 6000 and with a TCF value extracted from [10]. The circuit schematic used during the evaluation of the maximum sensitivity attained by the AlN nano-plate temperature sensor is also reported in the inset.

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