An Ising Tag with a $LiNbO_3$ Resonator For Temperature Threshold Sensing

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***Summary*— We present the first *Ising-Tag* (ITag) ever reported. This passive system implements a remote temperature threshold sensing functionality while using only a set of passive components including a $LiNbO_3$ microacoustic resonator fabricated in-house. Our ITag is formed by two battery-less RF parametric oscillators (POs) that operate as Ising spins. The POs are coupled by the $LiNbO_3$ device, and their output signals are combined with a power combiner to form the ITag's response signal (v_{out}). The reported ITag operates with an interrogation frequency of 904 MHz and an output frequency (f_{out}) of 452 MHz. Depending on whether the ITag's temperature (T_a) is lower or higher than a certain value (T_{th} = 40 °C), the two POs can exhibit an anti-ferromagnetic or ferromagnetic interaction. The spin interaction is set by the position of the resonance frequency of the coupling $LiNbO_3$ device with respect to f_{out}. Such a unique dynamical feature renders v_{out} negligible only for $T_a < T_{th}$, while turning v_{out} into an "alarm signal" for $T_a \geq T_{th}$. Excitingly this is achieved without requiring an operation near a point of marginal stability or the use of any batteries or integrated circuits.**

Keywords*— IoT, WSNs, Lithium Niobate, Acoustic Resonators, Nonlinear Dynamics, Parametric Oscillators

I. Introduction

Recent advancements involving the Internet of Things have produced significant growth and innovation in the design of wireless sensor nodes (WSNs). Yet, the unprecedented increase of the number of WSNs that will be deployed in the next few years is generating a strong interest towards developing new passive tags (PTs) able to implement smart functionalities without requiring batteries or any sets of integrated circuits [1]–[3]. In this regard, achieving PTs able to implement a threshold sensing functionality represents one of the strongest priorities. For instance, such PTs would be extremely useful along the cold chain to ensure a prompt identification of any foods or drugs exposed to inadequate temperatures. Similarly, the availability of long-lasting PTs with the ability to timely identify the start of a fire would be key to trigger immediate corrective actions.

In this work, we discuss the first Ising-Tag (ITag) ever reported. This ITag system operates with an input frequency (f_{in}) of *904 MHz* and an output frequency (f_{out}) of *452 MHz*. It uses a Lithium Niobate ($LiNbO_3$) resonator to couple two identical Radio-Frequency (RF) parametric oscillators (POs). The two POs are driven by a continuous-wave interrogation signal received by an off-the-shelf antenna. The POs' output signals are combined to form the ITag's response signal (v_{out}), which is radiated by using a second off-the-shelf antenna. The two POs emulate the behavior of two Ising spins, with interaction (ferromagnetic or anti-ferromagnetic) controlled by the temperature-dependent resonance frequency of the $LiNbO_3$ resonator. Consequently, v_{out} is strong only when the POs' output signals are in-phase (ferromagnetic interaction) and negligible when they are out-of-phase (anti-ferromagnetic

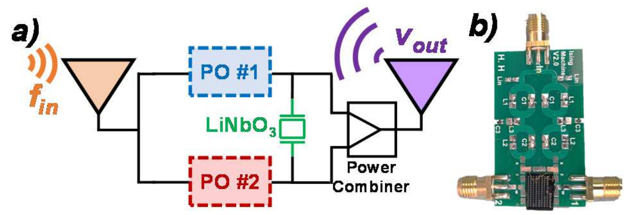

Fig. 1: a) Schematic view of the reported ITag that receives an input frequency f_{in} and transmits a response signal with strength v_{out} and frequency f_{out} equal to $f_{in}/2$. The ITag is constructed with two off-the-shelf antennas for interrogation and response, and with two RF POs coupled by using a $LiNbO_3$ microacoustic resonator. The POs' outputs are then power-combined; b) Top-view picture of the constructed PCB hosting the two POs and the $LiNbO_3$ device.

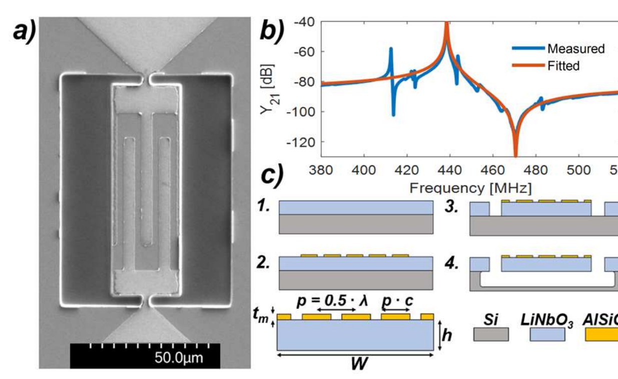

Fig. 2: a) Scanned-Electron-Microscope (SEM) picture of the fabricated $LiNbO_3$ microacoustic resonator; b) Measured and fitted Y_{21} response of the fabricated device with parameters: $f_s = 438.46$ MHz, $f_p = 470.58$ MHz, $R_s = 0\ \Omega$, $C_0 = 19.47$ fF, $R_0 = 0\ \Omega$, $R_m = 75.69\ \Omega$, $L_m = 44.55\ \mu H$, $C_m = 2.96$ fF, $k_t^2 = 16.84\%$, $Q_{slope} = 2213.92$; c) Fabrication flow we used to build the $LiNbO_3$ device used in this work. We started with 1. *1 μm* thin film $LiNbO_3$ bonded on Si using surface-activation bonding and chemical and mechanical polishing; 2. *200 nm* of AlSiCu patterned sputtering; 3. Ion Mill etch of $LiNbO_3$ with substrate angle of *72°* and 4. *18* cycles of XeF_2 release.

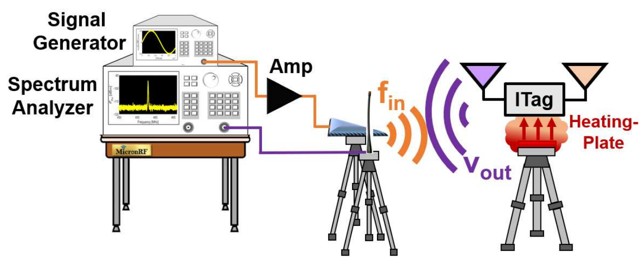

Fig. 3: Schematic view of the setup used to characterize our ITag. The emulated IoT-reader was made up of a signal generator delivering the interrogation signal at f_{in}, a power amplifier, transmitting antenna, receiving antenna, and a spectrum analyzer receiving the ITag's response signal at f_{out}. The ITag was placed onto a heating-plate *30 cm* from the measurement tools and was interrogated wirelessly for different applied temperatures.

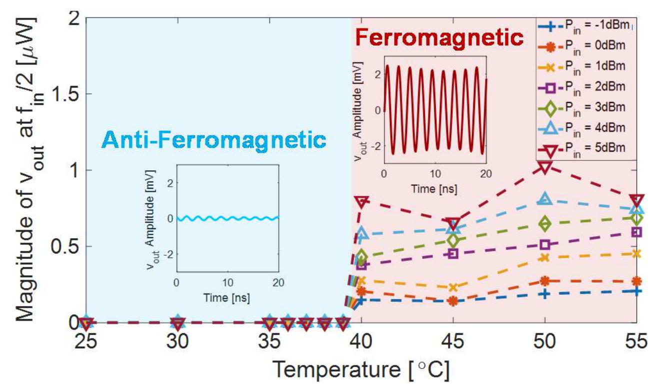

Fig. 4: Experimental results showing the transition between PO interactions from anti-ferromagnetic to ferromagnetic once T_{th} = *40 ˚C* has been exceeded. Below T_{th}, the magnitude of v_{out} is negligible due to the anti-ferromagnetic interaction between POs. Above T_{th}, when the interaction is ferromagnetic, v_{out} is much stronger and can act as an alarm signal, independently of received power, as shown above.

interaction). These interactions provide the means to implement a temperature threshold sensing functionality without requiring any batteries or any integrated circuits. Even more, the ITag's synchronization dynamics are power-independent. This makes our device insensitive to multipath and fading, differently from the prior passive tags for threshold sensing that must operate near a point of marginal stability [1], [2].

II. METHODS/RESULTS

Our ITag (Fig. 1) is formed by two identical POs simultaneously driven by the same wirelessly received signal. The POs leverage the nonlinear dynamics of varactor-based passive circuits to enter a period-doubling regime [4]. The POs' output signals are combined by using a power combiner, thus generating v_{out}. v_{out} is then wirelessly transmitted by using an off-the-shelf antenna. As mentioned, a thin-film $LiNbO_3$ resonator is used to couple the two POs prior to being combined. Fig. 2 shows a SEM image of the $LiNbO_3$ device together with its measured admittance curve and its fabrication flow [5]. The spins-coupling renders the POs able to instinctually set their spin-interaction based on the $LiNbO_3$ device's resonance frequency value and, consequently, based on the ITag's temperature (T_a). In fact, for T_a-values lower than a certain threshold (T_{th}) set by f_{in}, the two POs exhibit an anti-ferromagnetic interaction, resulting in output signals with equal magnitudes but opposite phases. In such a scenario, v_{out} is negligible. Contrarily, when T_a reaches or exceeds T_{th}, the POs exhibit a ferromagnetic interaction, thus showing equal and in-phase output signals that lead to strong, remotely detectable v_{out}-levels that can be used as alarm signals. We validated the operation of our ITag by placing it on a remote-controlled heated surface and by remotely interrogating it at *904 MHz* for different set T_a-values ranging from *25 ˚C* to *55 ˚C*. The temperature of the resonator was simultaneously measured by using an IR temperature sensor to ensure that each data-point was extracted after reaching the preset steady-state temperature value. At each T_a-step, our ITag was interrogated by different signals with incident power-values between *-1 dBm* and *+5 dBm* and the ITag was deactivated following each interrogation. This procedure was repeated three times to validate consistency in performance. The output of the ITag was measured wirelessly using an emulated IoT-reader comprised of a spectrum analyzer placed almost on top of the interrogating antenna, as shown in Figure 3. As the ITag's temperature increased above *40 ˚C*, we noticed a sharp increase in the magnitude of v_{out} due to a temperature-driven transition to a ferromagnetic interaction between the two POs. Nevertheless, v_{out} returned to exhibit a negligible magnitude once the temperature of the $LiNbO_3$ device was set back to below T_{th}, as shown in Fig. 4. It is important to emphasize the power-independent synchronization dynamics of ITag, which make its accuracy resilient to multipath and channel-fading.

III. CONCLUSIONS

In this article, we presented the first ITag ever reported. This remote sensing tag can implement a temperature threshold sensing functionality without relying on batteries or integrated circuits. The reported ITag uses a $LiNbO_3$ resonator to instinctually control the Ising interaction between two un-biased RF parametric oscillators according to the ambient temperature. Even more, owing to its frequency dividing characteristics, our ITag is immune to multipath, reader's self-interference, and clutter, which adversely affect the electromagnetic performance of other existing remote sensors.

REFERENCES

[1] H. M. E. Hussein, M. Rinaldi, M. Onabajo, and C. Cassella, "A chip-less and battery-less subharmonic tag for wireless sensing with parametrically enhanced sensitivity and dynamic range," *Sci. Rep.*, vol. 11, no. 1, p. 3782, Feb. 2021, doi: 10.1038/s41598-021-82894-x.

[2] H. M. E. Hussein, M. Rinaldi, M. Onabajo, and C. Cassella, "Capturing and recording cold chain temperature violations through parametric alarm-sensor tags," *Appl. Phys. Lett.*, vol. 119, no. 1, p. 014101, Jul. 2021, doi: 10.1063/5.0054022.

[3] M. Abdulkarem, K. Samsudin, F. Z. Rokhani, and M. F. A Rasid, "Wireless sensor network for structural health monitoring: A contemporary review of technologies, challenges, and future direction," *Struct. Health Monit.*, vol. 19, no. 3, pp. 693–735, May 2020, doi: 10.1177/1475921719854528.

[4] H. M. E. Hussein, M. A. A. Ibrahim, G. Michetti, M. Rinaldi, M. Onabajo, and C. Cassella, "Systematic Synthesis and Design of Ultralow Threshold 2:1 Parametric Frequency Dividers," *IEEE Trans. Microw. Theory Tech.*, vol. 68, no. 8, pp. 3497–3509, Aug. 2020, doi: 10.1109/TMTT.2020.2999790.

[5] L. Colombo, A. Kochhar, G. Vidal-Alvarez, and G. Piazza, "X-Cut Lithium Niobate Laterally Vibrating MEMS Resonator With Figure of Merit of 1560," *J. Microelectromechanical Syst.*, vol. 27, no. 4, pp. 602–604, Aug. 2018, doi: 10.1109/JMEMS.2018.2847310.