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# Flexible Passive Smart Skin Temperature Sensor for Remote Sensing in Structural Health Monitoring Applications

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***Abstract*—In this work, for the first time, the authors present a Smart Skin based temperature sensor for Structural Health Monitoring. The sensor topology employed is flexible, passive, form-factor, surface agnostic, sensor design enabling local temperature monitoring. The static operating frequency of this sensor is $23.26\,\mathrm{GHz}$ with a total foot print of $7.5\,\mathrm{cm}$ X $4.5\,\mathrm{cm}$ enabling a compact form factor solution to wireless passive sensing. The temperature response of the Smart-Skin based sensor is reported with an estimated sensitivity of $2.16\,\frac{\mathrm{MHz}}{^{\circ}\mathrm{C}}$ providing a highly sensitive, chip-less, flexible realization for Structural Health Monitoring applications.**

***Index Terms*—IoT, 5G, Remote Sensing, Flexible Electronics, Structural Health Monitoring**

## I. Introduction

With recent proliferation in Internet-of-Things (IoT) and 5G technology, there is a massive potential for building next generation systems that are based on ubiquitous, wireless remote sensing. Indeed, to meet the need of ubiquitous, wireless sensing, the solution of form-factor, fully passive sensors is highly desirable. Recent work to realize new passive sensors through chipless time-encoded Ultra-wide band (UWB) [1], radar cross-section (RCS) variation based on a split ring resonator (SRR) [2], RFID power-threshold sensing [3]. While these sensors provide passive solutions, they suffer from the either bulky sensor realizations, are limited in reading range, or require ICs to realize wireless monitoring. Smart-Skin (SS) based sensor topologies enable passive, chip-less, long-range, form-factor solution for the future of next generation wireless sensing networks. The authors in [4] demonstrate a SS based humidity sensor for low-cost, compact, long-range, passive through taking advantage of the high operational frequency of the sensor. Thus, SS-based topologies provide a cost-effective, simplistic, and form-factor solution for wireless sensing. In this work, the authors present a fully-passive, compact, flexible, Smart-Skin based that enables ubiquitous monitoring of temperature for Structural Health Monitoring (SHM) applications.

## II. Sensor Design

The flexible, passive sensor design consists of a cross-polarized Van-Atta array consisting of 5 single 5 x 1 linear antenna arrays. The substrate chosen was a low-loss, flexible Kapton HN ($\epsilon_r = 3.155, tan(\delta) = 0.003$) from Dupont with copper deposited with electroplating process for both the $5\,\mu\mathrm{m}$ thick array pattern and the ground layer of the sensor. By use of a high-gain, retro-directive structure enables long-range, off-angle interrogation of the fully passive sensor. Kapton HN has previously been utilized for local humidity sensing as the relative permittivity is highly correlated to changes in relative humidity as presented in [4]. Indeed, to decouple the effect of local humidity, the Van-Atta array was then laminated with a $0.254\,\mathrm{mm}$ thick film of Polycarbonate ($\epsilon_r = 2.78, tan(\delta) = 0.003$). Polycarbonate has been reported to display a change in relative permittivity -%2.6 from $25\,\mathrm{C}$ to $100\,\mathrm{C}$ [5]. This large dynamic range displays an excellent choice for SHM of local temperature. After the lamination process the static resonant frequency of the Van-Atta is $23.26\,\mathrm{GHz}$ at room temperature $25\,^{\circ}\mathrm{C}$. The entire dimensions of this flexible, passive sensor is only $4.5\,\mathrm{cm}$ x $7.5\,\mathrm{cm}$. With the simulation model and sensor stack-up displayed in Figure 1.

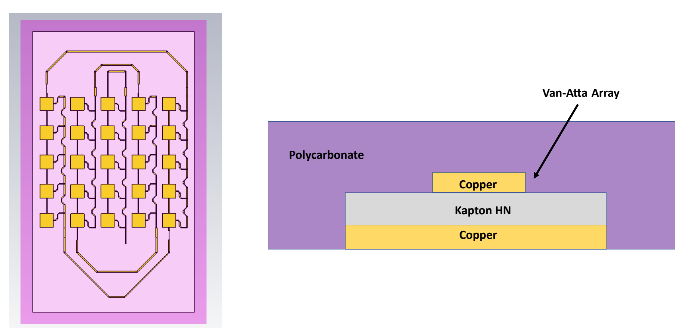


Fig. 1. Sensor simulation model and passive flexible sensor stack-up.

## III. Measurement

Wireless interrogation of the sticker-like form-factor, flexible, passive sensor was conducted utilizing an Anritsu 37369A Vector Network Analyzer (VNA) with two 15 broadband horn antennas in a cross-polarized configuration over a frequency range of $20\,\mathrm{GHz}$ to $30\,\mathrm{GHz}$ to track the peak resonant frequency of the sensor with changes to local temperature. To invoke local temperature gradient, a heat lamp was shined on the passive sensor located at a reading range of $1.3\,\mathrm{m}$ from the interrogating horn antennas. Local temperature measurements were recorded with a thermometer placed next to the sensor and the measurement setup can be viewed in Figure 2. Two

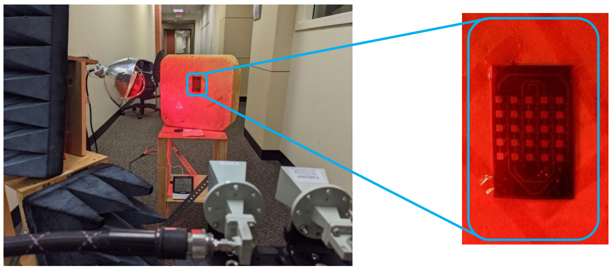

Fig. 2. Measurement setup of temperature sensor.

types of measurements were conducted to extract temperature response of the flexible wireless temperature sensor. First the temperature sensor was thermally cycled from $23.89\,^{\circ}\mathrm{C}$ to $51.66\,^{\circ}\mathrm{C}$ with the heating lamp and let to cool back down to $23.89\,^{\circ}\mathrm{C}$. Then a reference measurement was taken to remove the reflections in the environment. An inverse Fast-Fourier Transform (IFFT) of the $S_{21}$ measurement of both temperature response and reference measurement was taken and a subtraction of the reference measurement was done. The maximum of this resulting measurement was selected and a window in the time-domain response of the temperature sensor was conducted to monitor the spectral content of the temperature sensor. Finally, a Fast-Fourier Transform (FFT) was taken on this windowed response and the peak frequency of the sensor was tracked throughout this thermal cycling experiment is displayed in Figure 3. The sensor displays

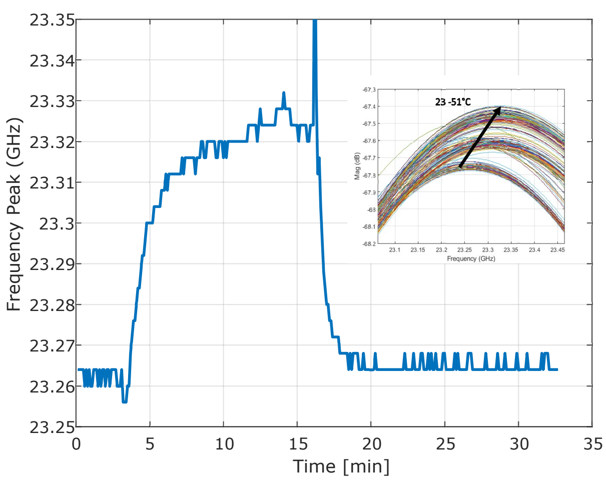


Fig. 3. Heat cycling measurement of temperature sensor.

rapid response to local temperature variation and the ability to recover to the initial frequency of the sensor. A linear-fit of the temperature sensor can be shown in Figure 4 with an estimated sensitivity of the sensor is reported to be $2.16\,\frac{\mathrm{MHz}}{^{\circ}\mathrm{C}}$. This estimated sensitivity is better by 1-2 orders of magnitude when compared to alternative wireless temperature sensors and presents the same sensitivity as the measured prototype in [2] with the added benefits of a flexible, Additively Manufactured realization, a larger linear dynamic range of the sensor, and the potential for long-range SHM applications.

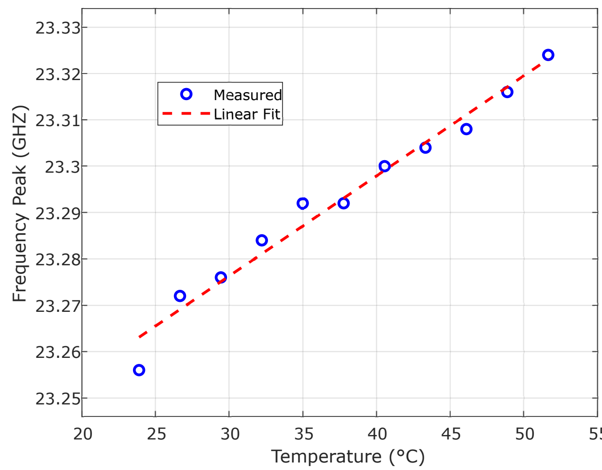


Fig. 4. Estimated temperature sensitivity of the passive wireless sensor.

## IV. Conclusion

In this work, a flexible, fully passive low-cost temperature Smart-Skin sensor is presented. The sensor displayed a quick and highly sensitive response with local temperature changes at close ranges. However, with utilization of a phase-array based interrogation, providing a high-gain and narrow beam of illumination of these sensors, the theoretical reading range is estimated to be in excess of x10 with potential for densely distributed, long-range remote sensing of temperature in next generation SHM.

## Acknowledgement

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