A Wireless Passive RCS-based Temperature Sensor using Liquid Metal and Microfluidics Technologies

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***Abstract*— A novel wireless and passive temperature sensor that utilizes microfluidic and liquid metal technologies for the temperature-dependent modification of the sensor's radar echo is introduced. Liquid metal is used to dynamically alter the number of antenna elements activated along a linear array configuration with respect to temperature. In this way, the sensed temperature value can be accurately quantified by the change in radar cross section (RCS) of the device. Simulation and measurements of the backscattered power of the temperature-reconfigurable array were performed to verify the concept and benchmark the sensitivity and temperature range of the sensor. This study is based on the number of elements activated by the short-circuiting of their gap through the temperature-expansion of liquid metal inside a bridging microfluidic channel. For the first time the remote measurement of temperature based on the RCS variability of a microfluidics-realized sensor is presented. It features an RCS range of 9 dBsm at 29.5 GHz corresponding to a tunable temperature range of at least 20°K and a resolution of 1.8 dBsm per element activated resulting in a temperature resolution around 4°K. It has to be noted that numerous major challenges encountered in the feeding and encapsulation of liquid metal inside microfluidic channels were addressed and preliminary guidelines for a novel generation of wireless sensors based on liquid metal and microfluidic technologies have been established for the first time.**

I. Introduction

Temperature monitoring is an important problem in electronic device maintenance, refrigerated food transport, agriculture and nuclear waste storage [1]. A low-cost solution for its wireless automation is important to monitor objects in real-time through unpredictable environments. A passive tag that can be read by a radar or illuminating reader would allow for the power/cost-efficient real-time temperature monitoring in agriculture and other mass-production scenarios, that require a large number of low-cost sensors, and where maintaining a stable temperature is critical for the health, safety and maintenance of the product.

The oldest and most common technique used to measure temperature has been to measure the volume expansion of liquids, such as water, or mercury, or solids along a length scale, which is determined by the dimensions of the enclosing container and is indirectly correlated to a specific temperature value [2]. This paper presents a novel sensor which extends this technique by using the thermal volume expansion of liquid metal to progressively short circuit a linear array of dipoles so that their aggregate radar cross section will effectively increase or decrease with respect to temperature. The novel sensor design and its electromagnetic simulation will be discussed first. The fabrication flow and benchmarking measurement results are then presented both for an ideal nonmicrofuilidic case of planar, solid metal scatterers and for the realistic 3D microfluidics liquid metal case.

II. Sensor Design

Without loss of generality, a dipole was chosen as the sensing element due to its wideband radiation characteristics. The operation principle, however, is not limited to dipoles, but can also be applied to other geometries like the bow-tie antenna or other scatterers whose RCS is highly sensitive to changes in dimension and/or number of elements.

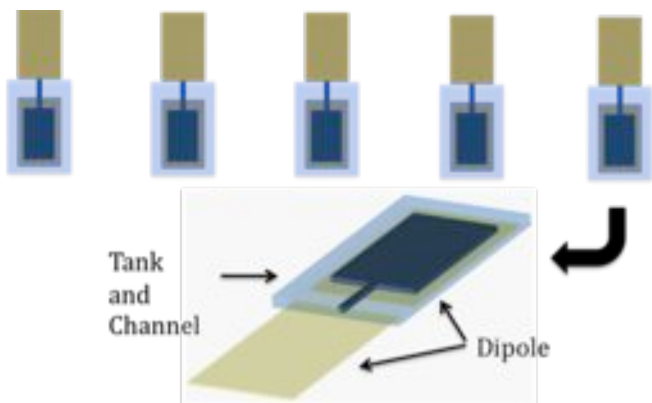

Fig. 1 Final microfluidics sensor on kapton substrate (9 x 23.4 x 0.127 mm3), dipole (length = 3.6mm, width = 1mm, thickness = 1µm), tank (interior dimensions: l = 1.3mm, w = 0.8mm, h = 50µm), galinstan channel (cross section: 50µm x 50µm).

For the presented novel microfluidic-based sensor, the temperature measurement input is realized with the progressive short circuiting of consecutive dipole(s) gaps by means of the incremental temperature-based volume expansion of a liquid metal, such as Galinstan, or mercury that is contained in (vertical) microfluidic channels bridging each gap similar to Fig.1. Although all gaps in this figure are shown to be the same for simplicity, in real sensors each gap should have a different length. In this way if the filling liquid is at the same temperature-controlled horizontal level (with respect to all dipoles) in all gap-bridging microfluidic channels, the electrical contact and short-circuiting of each dipole would occur at different temperatures as seen in Fig. 2. Using this concept, the sensor output is the value of the radar cross section of the array combination of open and shorted dipoles. Galinstan (Ga/In/Sn) is a eutectic alloy that exists in liquid form from -20° C to 1300° C[3]. It was chosen because of its high electrical conductivity (3.4 106 S/m)[4] and its ability to make electrical connections with other materials, making it useful to create reconfigurable liquid metal components for devices[5]. Also, its nontoxic property has made it useful in medical applications such as for flexible electrodes and thermometers[6], [7], [8].

The spatial expansion coefficient of galinstan is 11.5 10-5K-1 [6]. Due to this small expansion, a large tank (underlying the bottom half dipole) connected to each narrow microfluidic channel is needed to provide the maximum liquid displacement. The required volume of the tank is derived from the known relationship for volumetric expansion: , where V is the total volume, α V is the volumetric thermal expansion coefficient, Δ V is the fractional change in volume of liquid and Δ T is the change in temperature. The required tank dimensions can be obtained from relating linear to volumetric expansion: $\alpha_V = 3\alpha_L \Delta T \Rightarrow \Delta V = 3\alpha_L (LWH)\Delta T$

Given a fixed channel cross section of 50 μ m x 50 μ m that extends from a tank of height H = 50 μ m (normal to the dipole array plane), the tank length (tangent to the dipole), and tank width (transverse to the dipole) are optimized to W = 800um and L = 1.3mm respectively. This allows for an linear expansion resolution of 2.5 μ m/° K.

The range, sensitivity and resolution are all tunable considering the following relationship:

$$t[^\circ K] = d_i[\mathrm{m}] / \left(i \times r\left[\mathrm{m}/^\circ K\right]\right) \quad (1)$$

$$\textit{temperature Range}\left[^\circ \mathrm{K}\right] = N \times t\left[^\circ \mathrm{K}\right] \quad (2)$$

where i = {1…N} is the index of the dipole along the array, di is the gap size of the ith dipole [m], N is the total number of dipoles, t is the temperature resolution in °K and r is the resolution of linear expansion along the channel (2.5µm/°K in our case) determined by volumetric expansion relation and chosen tank dimensions.

In the final design shown in Fig. 1, a larger dipole width was used to fully overlap with the tank structure, which is positioned entirely within the projected area of the bottom half of the dipole. That aims in minimizing the influence of the tank on the sensor's RCS level and sensitivity (in RCS/number of shorts) around 29.5 GHz.

III. Simulation

The RCS is defined as *4 π times the ratio of power per unit solid angle scattered towards the receiver, to the power per unit area striking (incident) the target* [9] where the power per unit solid angle includes only *the component of the energy flux that is compatibly polarized with the receiving antenna* [9]. The RCS of a dipole is small in comparison to other antennas, and the maximum backscatter occurs when it is oriented parallel to electric field of the incident plane wave. For the case of a half wavelength dipole, where scattering occurs in the Rayleigh region, the amount of backscatter is proportional to frequency and reaches the peak at the resonant frequency of the dipole. As a result, theoretically, for an array of half wavelength dipoles, this RCS will increase with the number of shorted dipole elements as seen in Fig. 2.

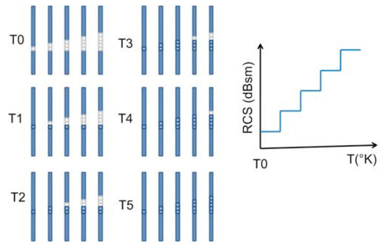

Fig. 2 Concept of sensor array. Six temperature states: T0 (Nshort = 0), T1 (Nshort = 1), T2 (Nshort = 2), T3 (Nshort = 3), T4 (Nshort = 4), T5 (Nshort = 5).

Electromagnetic simulations of the simplified "ideal" case were performed to verify this concept and observe the sensitivity of the structure. The frequency range of 29.1 – 29.9 GHz corresponded to the measurement setup available. Here, "Ideal" means that the bridging microfluidic channel containing liquid metal is replaced by a planar conductive strip of perfect electric conductor. Fig. 2 shows the RCS versus frequency of 5 thin copper dipoles on 100µm thick Kapton for 6 different temperature states: Nshort = 0, 1, 2, 3, 4, 5 as seen in Fig. 2 and Fig. 6-a.

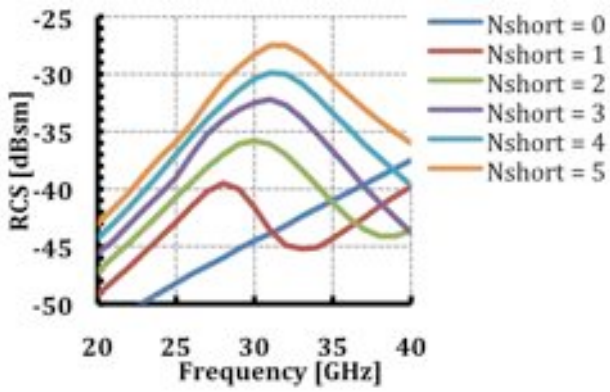

Fig. 3 Simulation results of the "ideal" sensor array.

For the ideal case, shown in Fig. 3, the offset value (RCS when all dipole are open for the lowest temperature) of the sensor is -44.5 dBsm and the RCS range is 16 dBsm for a realistic temperature range of approximately 20°K. Simulation were performed for the final design where the dipole width increased to contain the microfluidic tank (fig.1), taking into account the finite conductivity of galinstan. The results show an increased offset value of up to -31.1 dBsm with a range around 6 dBsm (@29.5GHz) due to the contribution of the tank filled with galinstan.

IV. Fabrication of the Wireless Microfluidic Temperature Sensor

The fabricated microfluidic sensing structure is shown in Fig. 4 (3 masks). During this technological process, the Kapton substrate (127µm thick) is attached to a Silicon wafer (525µm thick), where the silicon functions as a removable support. First, Ti/Cu (0.1µm/0.9µm) seed layer was sputtered on the top side of a 127 µ m thick Kapton substrate using the lift-off method. An 800nm thick SU-8 negative resist layer is spin coated to protect the copper dipoles.

Fig. 4 Final structure after fabrication process flow.

Afterwards, channels and tanks were micromachined using photolithography on 50 µ m SU-8. In order to minimize the stress on the wafer, the SU-8 was localized just around the microfluidic structure. Finally, a photosensitive SU-8 dry film, of 25 µm in thickness, was laminated and patterned on top of the channel to close the structure and realize the fluidic access [10]. In that way, two holes were perforated in the cover, one over the tank to fill with liquid metal and the second at the end of the channel to evacuate air. Second step is to fill the tank and channel with Galinstan liquid metal. Injecting galinstan into microsized channels is extremely difficult.

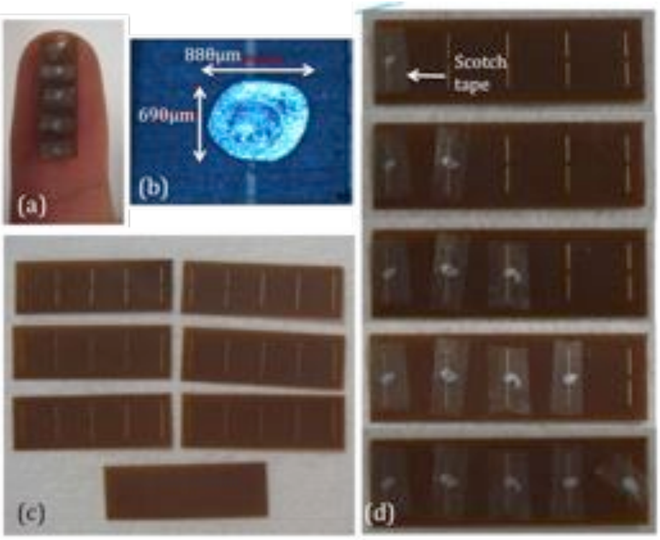

Fig. 5 Array size (a), short circuit with galinstan drop (b), ideal dipole arrays on Kapton (c) and with galinstan drop (d).

The challenge of handling galinstan is due to its fast oxidation when exposed to as little as 0.2% oxygen [3]. In addition, the repeatability of the technological process is critical to develop a structure where the performance is consistent. Several studies [5], [6], [11] and [12] were performed in the last years working around this problem which is still slowing the progress in RF MEMS research today. We choose silver gel (with a resistivity between 0.001mΩ and 0.004mΩ) as a temporary liquid metal in place of Galinstan to demonstrate the progressive element short-circuiting proof of concept.

V. RCS Measurements

Various sets of arrays were fabricated to represent the “ideal” temperature states (dipoles shorted using copper or liquid metal planar strips as shown in Fig. 5). Each array set had different (but constant for all array elements) gap sizes (50um, 100um, and 300um) along the array for each temperature state (Nshort = 0, 1, 2, 3, 4, 5). The objective of this experiment was to verify that different numbers of shorted dipoles show a measurable difference in the overall RCS. The results from these simplified experiments are valid to characterize the final sensor. The radar cross section of each dipole array was measured at 29.5 GHz by using an FMCW radar with a radar-to-target separation distance of 160cm. Calibration was performed with a metallic sphere of radius 3.5cm.

A. *Planar dipole arrays including open and short circuit*

The ideal case (for which liquid metal is replaced by copper) was measured using planar dipoles that were already short circuited in fabrication. Each array was mounted vertically and measured one at a time. The RCS data can be seen in Fig. 7, starting with an offset value of -44 dBsm and covering a range of 14 dBsm. These results verify the concept of the RCS linearly increasing as the number of dipôle elements increases at the fixed frequency of 29.5 GHz.

B. *Planar dipole arrays short-circuited with galinstan drops*

In the next experiment, microsized drops of galinstan were placed onto the open gaps of the dipoles to short them as seen in fig. 5-b and -d. Each array was measured and the RCS data can be seen in Fig. 7. The offset value is at -45.5 dBsm, the range is around 12 dBsm, and the resolution comes out to 2.4 dBsm. From three repeated measurements uncertainty of 0.4 dBsm was observed and stays within resolution value. These results, in fact, verified that galinstan could be used for effective electrical contacts required to short circuit the dipoles at 29.5 GHz and increase the RCS of the antenna array.

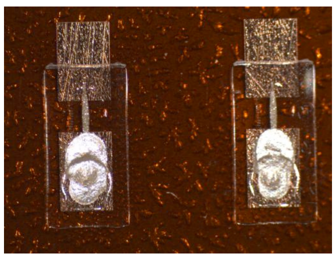

Fig. 6 Microfluidics sensor (tank+channel filled with liquid metal).

C. *Microfluidic structure with liquid metal*

As it was discussed before, the filling of galistan into the microfluidic channel was a major challenge. After a thorough effort, we manage to fill the microfluidic structure (Fig 6) with liquid metal to emulate each temperature statse by filling the tank and channel of one dipole for a single array, two dipoles for a second array, three dipoles and so fourth. The same type of RCS radar measurements, as previously discussed, were performed and the results are presented in Fig. 7. An offset value of around -38 dBsm was obtained, a range of 9dBsm was observed, an uncertainty of 0.3 dBsm and a resolution of 1.8 dBsm. From these results, the discretization of the temperature values in relation to RCS for a microfluidics structure was confirmed. The microfluidics structure exhibits a smaller range and resolution due to the larger dipole width that supports the tank geometry however a measurable difference in RCS versus number of short circuits is still seen (fig.7). Based on the smallest gap size chosen the designed sensor (d1=10µm), the temperature range is theoretically 20°K.

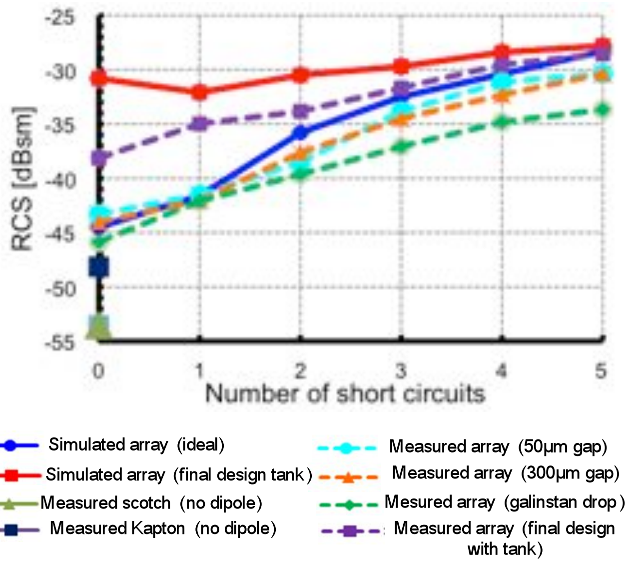

Fig. 7 Simulation and measurement results.

The primary focus of the next step was to solve the problem of filling the microfluidic structure with galinstan. To do this, a new technique for injecting galinstan into a microfluidics test structure was optimized. It allows for the galinstan to flow easily into the channel in a controlled manner without oxidation and to remain intact. Upon filling the channel, temperature measurements were performed showing measurable expansion of the galinstan within the channel. RCS versus temperature measurements on the final galinstan microfluidic structure will be presented at the conference.

VI. Conclusions

In this paper, the new concept of a wireless passive temperature sensor based on microfluidics and liquid metal technologies is presented. Liquid metal is used to alter the number of antenna elements activated along a linear array configuration with respect to temperature. The discrete RCS variation versus number of short circuited dipoles along the antenna array is verified. For a 5-element prototype including, microfluidic structures, a range of 9 dBsm was observed with a resolution of 1.8 dBsm. The corresponding temperature behavior of a resolution of 4°K was theoretically calculated using the thermal expansion coefficient of galinstan. Experiments using liquid metal were performed to validate the sensor performance with microfluidics technology included. Various technological challenges, including injecting galinstan into complex microsized structures have been addressed setting the foundation for a new type of conformal wireless sensors.

Acknowledgment

The authors would like to acknowledge IFC/SRC and NSF for their support and contribution towards this work.

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