A Novel Wireless Passive Temperature Sensor Utilizing Microfluidic Principles in Millimeter-Wave Frequencies

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***Abstract*—An RCS temperature sensor using microfluidics technology for millimeter-wave frequencies is presented An example using a shorting dipole array shows the potential for the development of a temperature sensitive liquid scatterer as a low cost solution for environmentally friendly, automated, easily deployable temperature monitoring.**

I. INTRODUCTION

A new miniaturized passive and wireless sensing tag is presented, which is based on microfluidic and liquid metal technology. When polled by a reader in Millimeter-Wave frequencies, the temperature value gets quantified through the temperature-sensitive modification of the tag's backscattered power. The tag consists of an array of solid and liquid-metal scattering elements designed to have a temperature dependent RCS (Radar Cross Section). Specifically, an array of open circuited dipole-like elements with a liquid metal shorting switch – realized using microfluidics principles - per element is progressively (element-by-element) short circuited via the volume expansion of the liquid metal with temperature. Simulations have been performed to benchmark the sensitivity, range and resolution aiming in the fine tuning of the design parameters for specific applications. Measurements have been also performed to verify a measurable difference in radar echo (reflected power) received as each successive element in the array is short-circuited due to increase in temperature. The preliminary prototype of the presented miniaturized sensor [3.6mmx1mmx1um] 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. The temperature-reconfigurable structure is fabricated using microfluidics technology to allow for proper sealing, feeding, encapsulation and easy deployment of the liquid metal tag. Preliminary guidelines for a novel generation of wearable, implantable and conformal "smart house"/"smart skin" wireless sensors based on liquid metal and microfluidic technologies have been established for the first time.

II. MOTIVATION

Temperature monitoring is an important problem in "smart house" power saving systems, electronic machinery monitoring, perishable material (e.g. food/milk) storage and transport, chemical and explosive material, agriculture and nuclear waste storage [1]. A low-cost solution for its wireless automation is crucial to monitor objects in real-time through "rugged" 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 mass inventory/mass-production scenarios, that require a large number of low-cost sensors, and where maintaining a stable temperature is critical for the health and safety of the product. In addition, item level monitoring necessitates miniaturized form factors of the sensing devices. 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.

III. PREPARE YOUR PAPER BEFORE STYLING

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 [3], 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

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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 Figure 2. Using this concept, the sensor output is the value of the radar cross section (proportional to the reflected power) of the array combination of open-circuit and short-circuit dipoles. Electromagnetic simulations of a 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 millimeter-wave measurement setup available. Here, "Ideal" means that the bridging microfluidic channel containing liquid metal is replaced by a planar conductive strip with perfect electric conductor, while the dipole gaps have approximately the same width. Fig. 2 also shows the simulated RCS (reflected power) versus frequency of 5 thin copper dipoles on 100μm thick Kapton for 6 different temperature states: Nshort = 0 (no shorts), Nshort = 1, Nshort = 2, Nshort = 3, Nshort = 4, Nshort = 5 (all 5 gaps are shorted). Fig.3 reports a very good agreement between simulation and measurement for different channel and material choices for the sensor topology shown in Fig.1. A corresponding resolution of 4K for measurement range of 20K was theoretically calculated for a 5-element prototype with ultraminiaturized size (3.6mmx1mmx1um).

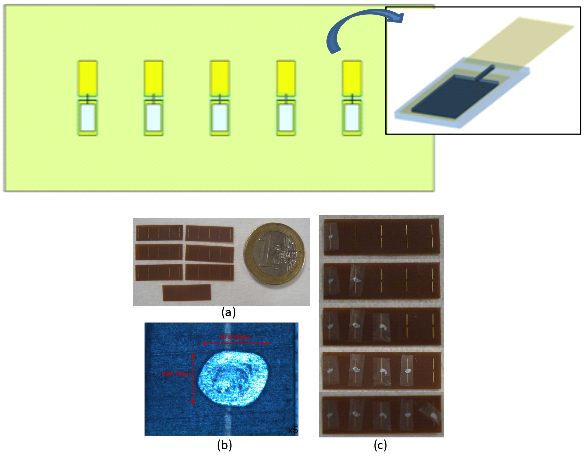
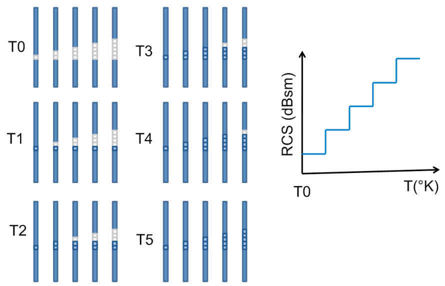


Figure 1. Final microfluidics sensor on kapton substrate (9 x 23.4 x .127 mm^3), dipole (length = 3.6mm, width = 1mm, thickness = 1μm), tank (interior dimensions: l = 1.3mm, w = 0.8mm, h=50um); galistan channel (cross section 50um x 50um)



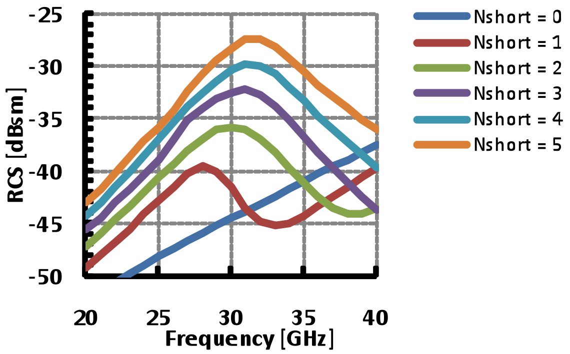


Figure 2. Concept of RCS temperature sensor. Dipole array at 6 different temperature states: T0 (Nshort = 0), T1 (Nshort = 1), T2 (Nshort = 2), T3 (Nshort = 3), T4 (Nshort = 4), T5 (Nshort = 5).

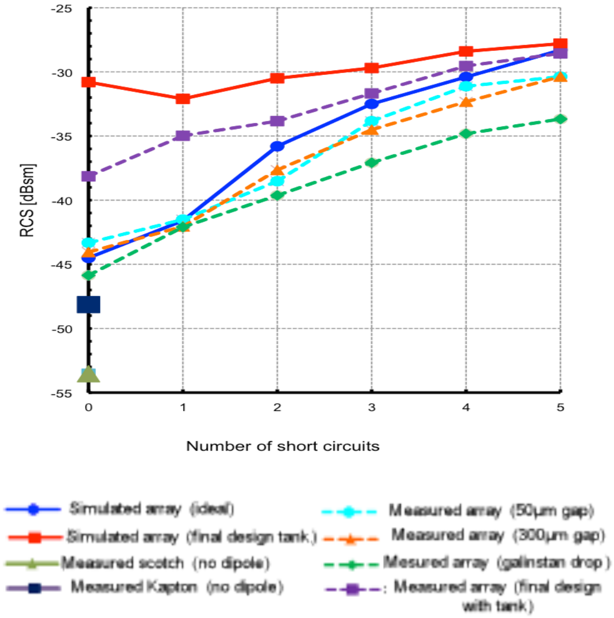


Figure 3. RCS variation for different sensor experimental implementations and for different temperature states

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