Design and Development of a Millimetre-wave Novel Passive Ultrasensitive Temperature Transducer for Remote Sensing and Identification

Trang T. Thai[1], Franck Chebila[2], Jatlaoui M. Mehdi[2], Patrick Pons[2], Herve Aubert[3], Gerald R. DeJean[4], Manos M. Tentzeris[1], Robert Plana[2]

[1]*School of ECE, Georgia Institute of Technology*
85 5th St., TSRB, Atlanta, GA 30332, U.S.A.
trang.thai@gatech.edu
etentze@ece.gatech.edu

[2]*CNRS; LAAS*
7, avenue du Colonel Roche, F-31077 Toulouse, FRANCE
{fchebila, mjatlaou, ppons, plana}@laas.fr

[3]*University of Toulouse; UPS, INSA, INP, ISAE, LAAS*
7, avenue du Colonel Roche, F-31077 Toulouse, FRANCE
Herve.Aubert@enseeiht.fr

[4]*Microsoft Research, Microsoft Corporation*
One Microsoft Way, Redmond, WA 98052, U.S.A.
dejean@microsoft.com

Abstract— **The millimetre-wave passive temperature transducer consists of micro bimorph cantilevers (Au-Silicon) and split ring resonators, operating around 30 GHz. The temperature change causes a deflection on the bimorph cantilevers, thus results in a shift of resonant frequencies of the split ring structure. The design achieves sensitivity of 2.62 GHz/um in terms of frequency shift response to cantilever deflection, corresponding to a sensitivity of 498 MHz/ºC, three order of magnitude higher than existing sensors. In terms of deflection versus temperature, the material choices for the bimorph cantilevers can be varied and adapted to different applications including those operating in harsh environments. To demonstrate proof-of-concept, a scaled prototype operating around 3 GHz is presented with Radar Cross Section measurements for remote identification.**

I. INTRODUCTION

Passive sensing is important in many applications that operate in remote sensing systems. Among many physical parameters, temperature sensing is critical in many applications utilized in automotive, medical, and industrial field. Typical applications include monitor systems for engine operations, space shuttle, aircraft in-flight conditions, and roads and bridges. Therefore, a passive wireless temperature sensor is desired to enable remote sensing and long term monitoring for those applications. It eliminates the use of a battery, reduces replacement and maintenance work, and allows integration with other wireless passive sensors to form a multi-physic remote sensing system. Most existing temperature sensors require a power source and/or do not have high sensitivity [1-3]. Recently, a new class of passive wireless sensors was introduced operating based on the correspondence between the physical parameters and shifts in resonant frequencies of a resonating structure [3-5]. In this work, a newly designed wireless passive temperature transducer is presented, whose sensitivity is three order of magnitude higher than that reported in [3]. The transducer consists of split ring resonators (SRR) and micro bimorph cantilevers. The sensor's operation is based on the deflection of the cantilevers corresponding to the temperature change, from which a shift in resonant frequencies of the SRR is induced. In a sensing system, a sensor node should not only provide information about the physical conditions of the surrounding environment, but also provide its position in the network of multiple sensor nodes. Therefore, based on the technique recently reported in [6-7], the authors also propose a newly improved micro-sensor identification technique that allows efficient communication between a network of many passive sensor nodes with a central monitoring station. The communication is based on radar cross section (RCS) level of loaded multi-band scatterers read by a frequency modulated continuous wave (FMCW) radar.

II. DESIGN AND OPERATION PRINCIPLES OF THE TEMPERATURE TRANSDUCER

The transducer consists of double split rings positioned on a dielectric substrate. The slits of the rings are covered with bimorph micro-cantilevers whose layers are made from two different materials, gold and silicon, with different thermal expansion coefficients. The design and dimensions of the SRRs and cantilevers are shown in Fig. 1. The dimensions of the split rings are follows: rint = 230 um, c = 120 um, d = 50 um, and s = 45 um. The substrate is made of glass with dielectric constant $e_r = 4.82$, and its thickness is 150 um. The cantilevers have length of 180 um, and the anchor has length of 50 um. Both thicknesses of Au and Si layers are 0.5 um.

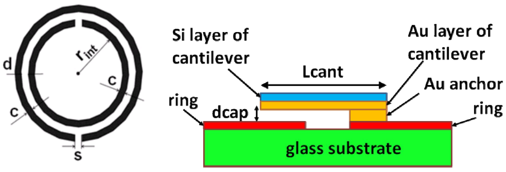

Fig. 1 Topology of the SRRs and bimorph cantilevers

The SRRs of the sensor can be excited in two different approaches. In the first approach, a plane wave is incident on the face of the SRRs as illustrated in Fig. 2. In the second approach, a coplanar waveguide is placed on the other side of the substrate, and the SRR slits are aligned to a gap between the signal line and the ground plane as illustrated in Fig. 3. Thus, the SRRs can be excited by the fringing field that travels along the CPW. The CPW is designed to have 50 Ω of impedance.

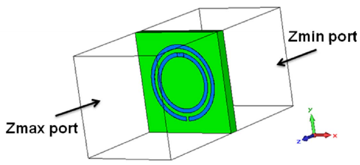

Fig. 2 The set up of the first approach to excite the SRRs.

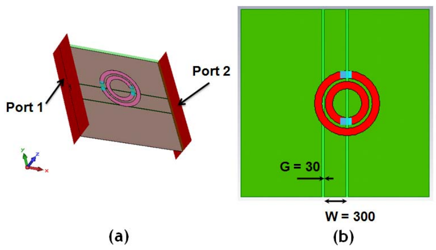

Fig. 3 The set up of the second approach to excite the SRRs with a) the three dimension view and b) the top view of the circuit with substrate not shown and dimensions indicated in micron.

The temperature sensing of the transducer is based on two uncoupled principles: 1) the deflection of the bimorph cantilevers in response to the temperature change, and 2) the resonant frequency shifts in response to the deflection of the cantilevers.

In the first principle, the deflection is due to the difference in thermal expansion coefficients of the two materials that constitute different layers of the cantilevers. As the temperature changes, the length of each cantilever layer expands differently. Since the two layers are bonded together, the cantilevers are bent into a curvature in order to accommodate different lengths of their layers. The deflection can be estimated according to (1), where d denotes the deflection, α_1 and α_2 denote thermal expansion coefficients of the two layers, t_1 and t_2 denote the thickness of the two layers, L denote the length of the cantilevers, and ΔT denotes the temperature change. The bimorph cantilevers have many operating ranges depending on the material choices. Despite extended thermal cycling, the bimorph cantilevers are robust and reliably returns to the same position at a given temperature as long as they are operated within their range limits for a particular material choice [10].

$$\delta = \frac{\Delta T(\alpha_1 - \alpha_2)(1 + t_1/t_2)L^2}{2(t_1 + t_2)} \qquad (1)$$

In the second principle, the structure of split rings was first proposed by Pendry et al. [8] and many variations of SRRs have been introduced since then mostly to obtain a metamaterial medium in which the permittivity or the permeability or both can be realized with negative values. When the SRRs are excited, the slits on each ring force the current to flow from one ring to another across the slot between them, which behaves effectively as a distributed capacitance. Thus, the field at the slit on each ring is highly concentrated. The positions of the cantilevers right above the ring slits as shown in Fig. 1 allow the cantilevers to influence the capacitance of the split gap directly, which in turn influence the amount of current flow between the two rings. As the air gap between the cantilevers and ring changes, the capacitance of the SRRs is altered, thus the resonant frequencies of the SRRs are shifted accordingly.

It should be noted that the operation of the first principle is independent from that of the second principle. Meanwhile, the first principle is well-known and has been utilized widely in numerous applications [9-10]. Therefore, the simulations and proof-of-concept prototypes presented in this work are dedicated to show the operation of the second principle. That is for any given deflection caused by a temperature change the sensitivity of frequency shifts in response to deflection is demonstrated. As a result, the upper and lower limits of temperature sensing range are determined mostly by the choice of materials utilized in the bimorph cantilevers.

III. Simulation Results of the Temperature Transducer Presented in Two Approaches of Excitation

Due to the fact the field at the cantilevers is mostly concentrated in the air region sandwiched between the cantilevers and the metal rings, in simulations and measurements the deflection of the micro-cantilevers is approximated with a uniform deflection across the whole length of cantilevers. Based on Eq. 1, the design of cantilevers presented in Fig. 1 is estimated to have a sensitivity of 0.19 um/^{o}C. The simulation results of the first approach of excitation (Fig. 2) are shown in Fig. 4. In the model of the first excitation approach, only one cantilever is implemented, which is placed over the inner ring split. The two resonances observed in this frequency range of 20-40 GHz are constituted by two rings in the structure. Observed from Fig. 4, the highest sensitivity is shown to be 1.41 GHz/um, corresponding to 268 MHz/^{o}C.

The simulation results of the second approach of excitation (Fig. 3) are shown in Fig. 5. In this model, two cantilevers are implemented, one is placed over the inner ring split, and the other is placed over the outer ring split. The resonances are different from those observed in Fig. 4 because the effective impedance in this structure is changed. In this structure, the sensitivity is shown to be 2.62 GHz/um, corresponding to 498 MHz/^{o}C. This is three order of magnitude higher than that reported in [3] where a slot resonator operating at 19 GHz is introduced with bimorph micro-cantilevers yielding a sensitivity of about 700 kHz/um. In [3], the cantilevers deflect from 200 um to flat position corresponding to temperature range of 25°C to 300°C.

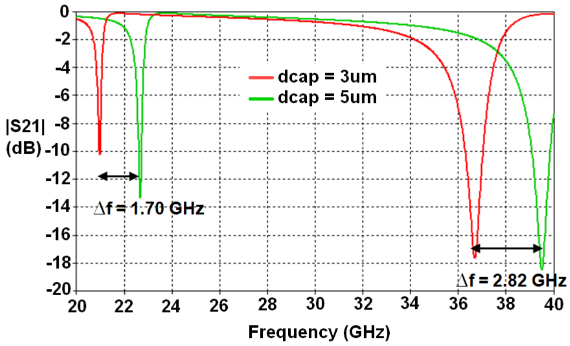

Fig. 4 Magnitude of S21 of the first excitation.

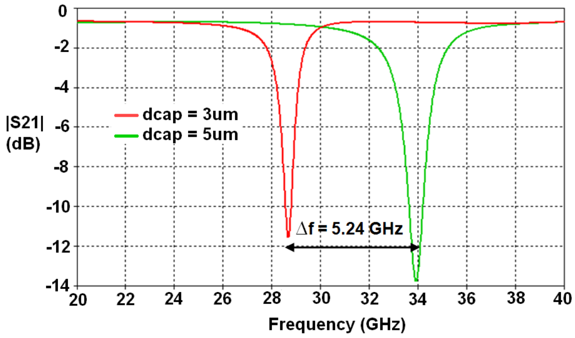

Fig. 5 Magnitude of S21 of the second excitation.

IV. Simulation Results of the Temperature Transducer Presented in Two Approaches of Excitation

A low frequency prototype is designed and fabricated utilizing CPW for excitation to demonstrate the proof-of-concept of the proposed temperature transducer. Due to limitation of fabrication and measurements, the prototype is scaled up in size and is operating around 3 GHz range. The prototype is realized on Neltec N9217 substrate (ε_r = 2.17, substrate thickness = 787 um). The dimensions of the SRRs in this model are as follows: r_{int} = 2.5 mm, c = 1.0 mm, d = 0.5 mm, and s = 1.0 mm. The width of the signal line is 4 mm (50 Ω of impedance) and the ground-signal separation is 150 um. The cantilevers were made from a 100 um thick Al sheet. A smaller sheet of PET (Polyethylene terephthalate) is laminated on top of the Al sheet. Then the two sheets are diced 1mm into the side of the Al-PET, and 1.5 mm into the side of PET to form cantilevers with attached anchor. In this formation, PET is the anchor's material. The cantilevers are then placed over the split gaps of the SRRs with conductive epoxy. The air gaps between the cantilevers and rings, denoted as dcap in Fig. 1, are measured with an optical scanner after the assembly. Two samples with different anchor height values are fabricated to emulate the uniform deflection of the cantilevers. Each sample has two cantilevers as shown in Fig. 6. The cantilever heights, i.e. dcap values, on the prototypes are measured with a profilometer. The average heights of the cantilevers are approximately 128 um and 101 um for each pair of the cantilevers assembled on two different prototypes.

A. Simulations and Measurements of Transmission parameter of the Sensor Prototype

The simulated and measured results of this design show excellent agreement with respect to resonant frequencies as indicated in Fig. 7. The low value of S21 in measured results reflect a high insertion loss due to the transition between CPW and coaxial cable, however it has little significance concerning proof-of-concept. A frequency shift of about 800 MHz from 4 GHz of 101 um dcap sample to about 4.8 GHz of 128 um dcap sample is observed in Fig. 7, resulting in a sensitivity of about 30 MHz/um that is two magnitude higher than 700 kHz/um of the sensor reported in [3] which is based on a 19 GHz resonating slot.

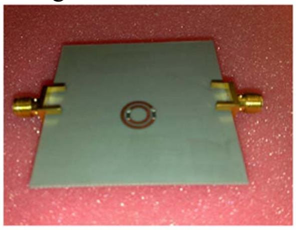

Fig. 6 The low frequency prototype of SRR sensor.

B. Measurements of Radar Cross Section of the Sensor Prototype

A FMCW radar (frequency modulated continuous wave) operating at 3 GHz is utilized as an interrogation device in the communication network illustrated in Fig. 8.

In this technique of remote identification and data acquisition, the radar sends off RF signals and receives a modified response from the sensors while signals scattered from the rest of the environment remain unmodified. The loaded horn antenna, located 3.5 m away from the terminal of

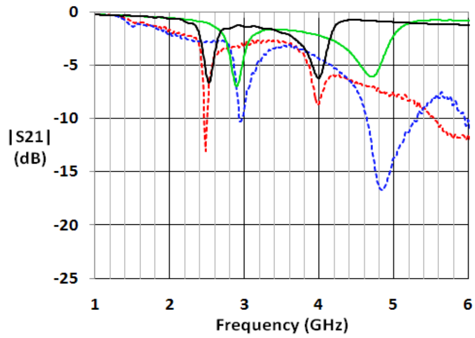

Fig. 7 Magnitude of S21 for the SRR sensor prototype with solid black curve is simulated results of dcap = 101 um model, solid green curve is simulated results of dcap = 128 um model, dash red curve is measured results of dcap = 101 um sample, dash blue curve is measured results of dcap = 128 um sample.

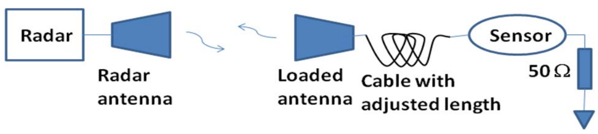

Fig. 8 RCS measurement system for remote sensing and identification.

the radar system, operates in the band of 1.8 GHz to 3.4 GHz with a gain of 15 dBi. The sensor prototype is treated as a load of the horn antenna, and is terminated with a 50 W load at the end of a 13 m long cable. The capture of the RCS measurement system is shown in Fig. 9. Based on the total travel distance of the signals, each object gives a different beat frequency with different RCS level. The corresponding beat frequency for the sensor prototype in the described set up is 22 GHz as indicated in Fig. 10. At this frequency, the fluctuation of the RCS level between two average dcap values (101 um and 128 um) of the two prototypes is observed to be about 3dBm. Thus, with different lengths of the transmission lines connecting the sensor nodes with the communicating antenna, i.e. the loaded horn antenna in this set up (Fig. 8), the positions of different sensor nodes in this passive sensing network can be identified (indicated by beat frequencies) along with its sensing information (indicated by RCS levels). The measurements were repeated twice one day apart, the same RCS fluctuation was observed. Thus, RCS reading corresponding to the two dcap values is shown to be capable of reliable sensing.

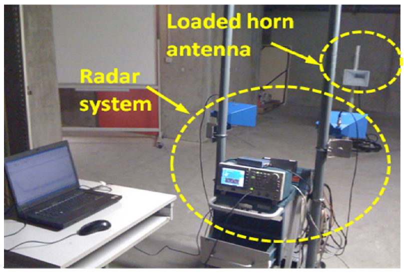

Fig. 9 Capture of RCS measurement system.

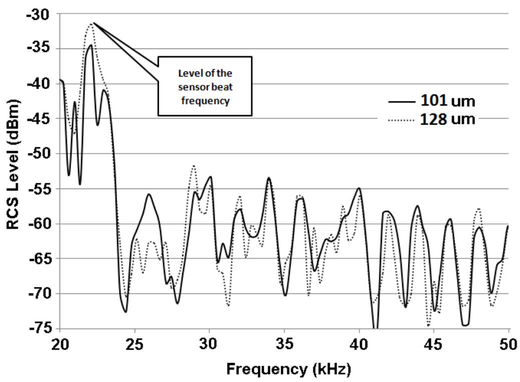

Fig. 10 RCS measurements of the low frequency prototypes for sample with dcap of 101 um (solid line) and sample with dcap of 128 um (dash line).

V. Conclusions

A new wireless passive ultrasensitive temperature transducer based on SRRs and bimorph micro-cantilevers is developed. The transducer operates in the millimeter-wave frequency band around 30 GHz based on two principles: the well-known cantilever deflection induced by temperature change, and the newly introduced principle of SRR resonant frequency shifts induced by deflection of cantilevers. The newly designed sensor is shown to have a high sensitivity of 2.6 GHz/um regarding frequency shift in response to cantilever deflection, corresponding to 498 MHz/^{o}C. A low frequency prototype is designed at larger size is demonstrated to achieve sensitivity of 30 MHz/um, regarding frequency shift in response to cantilever deflection, one order of magnitude higher than previously reported temperature sensors also operated based on frequency shifts in response to cantilever deflection. Thus the prototype successfully illustrates proof-of-concept for the new sensing principle based on SRRs and bimorph micro-cantilevers. The bimorph material choices can be varied to accommodate different temperature ranges, and may allow sensing of up to 300 ^{o}C or higher. The wireless temperature transducer is completely passive and highly compact, has high quality factor that allows high resolution of sensing, enabling integration of different multiple sensors in proximity. In addition, the RCS measurements of the temperature sensor prototype, implemented in the new technique of remote sensing and identification, demonstrate the correlation between the deflection of the cantilevers of the sensor and the observable RCS at a particular beat frequency. As a result, this system is capable of remote sensing and identification obtained from a completely passive sensor network.

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