A Novel Passive Ultrasensitive RF Temperature Transducer for Remote Sensing and Identification utilizing Radar Cross Sections Variability

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Introduction

Temperature sensing is critical in many automotive, medical, and industrial systems for applications such as engine operations, space shuttle and aircraft in-flight conditions, and road and bridge health. A passive wireless temperature sensor would enable remote sensing and long term monitoring for those applications. Most existing temperature sensors require a power source, and ones with high sensitivity suffer from performance degradation above 130 ^{o}C [1]. A capacitively-loaded MEMS slot element for wireless temperature sensing was proposed in [2] but has very low sensitivity of about 500 kHz/ ^{o}C. In this work, the authors introduce a new wireless passive ultrasensitive temperature transducer based on split ring resonators (SRR) that can be integrated into wireless multi-physical sensing platforms. The new temperature transducer achieves an ultrahigh sensitivity of about 780 MHz/ ^{o}C. Furthermore, improving the technique reported recently in [3], the authors also propose a new micro-sensor identification technique based on loaded multi-band scatterers whose radar cross section (RCS) read by a frequency modulated continuous wave (FMCW) radar. In this paper, a prototype of the novel SRR temperature sensor integrated into the passive multi-sensor identification sensing system is demonstrated as well as RCS measurements.

Design and Operation Principles of the Wireless Temperature Transducer

The temperature transducer consists of split ring resonators excited by a coplanar transmission line. The cantilevers are bilayer micro-cantilevers in which the two layers have different thermal expansive coefficients [4]. The split ring resonators operate in the sensing band of 28-34 GHz with dimensions shown in Fig. 1a. The SRR have their slits covered on top with bimorph micro-cantilevers (Aluminum/Silicon Dioxide) as shown in Fig. 1b. The cantilevers deflect as the temperature changes, thus alter the frequency response of the SRR. The bimorph material choices can be varied and adapted to application needs of temperature range without modifying the sensor structure, and may allow sensing of up to 300 ^{o}C or higher. Top view of the whole transducer with SRR, cantilevers, and CPW is shown in Fig. 2 with signal line width of 300 um designed to have 50 Ω of impedance. The SRR with cantilevers are positioned on one side of the substrate (150 um thick glass, ε_r= 4.82), and the CPW is implemented on the other side. The dimensions of the split rings are follows: r_{int} = 230 um, c = 120 um, d = 50 um, and s = 45 um. The cantilevers have total length of 180 um, and the anchor has length of 50 um. The thicknesses of Al and SiO_2 layers are the same, which is 0.5 um.

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SRRs were first theoretically proposed by Pendry et al. [5]. 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. In our design, due to the topology of the cantilevers, they become factors determine split gap capacitance, which influences the current flow on the rings. Thus the deflection of the cantilevers can effectively induce a large shift of the resonant frequencies. It should be noted that the RF temperature transducer presented here operates based on two uncoupled principles: the direct relationship between temperature and deflection of cantilevers, and the direct relationship between cantilevers heights and the resonant frequencies of the SRRs.

Simulations and Measurements of the Temperature Sensor

The simulation results of the CPW SRR temperature transducer are shown in Fig. 3. The plots show the magnitude of S21 of two different values of cantilever height denoted dcap in Fig. 1b. The simulations are performed in CST Microwave Studio 2009. The results show a shift of 5.24 GHz as the cantilever height changed from 3 um to 5 um, resulting in a sensitivity of about 2.6 GHz /um. The deflection of the cantilevers with respect to temperature is estimated to be about 0.3 um/ ^{o}C [4]. Thus, the proposed sensor has a sensitivity of 780 MHz/ ^{o}C, three order of magnitude more sensitive than existing sensors in terms of frequency shift versus temperature change. With the choices of materials presented here optimized for high precision of small temperature change, the best deflection range is between 2 um to 10 um, corresponding to a temperature dynamic range of about 27 temperature units. This range allows the linear response of frequency to deflection, while the response of deflection to temperature change has a much greater dynamic range.

Due to limitation of measurements and fabrication, a scaled model is fabricated operating around 3 GHz in order to validate the proof-of-concept of the design. The first one is fabricated 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 cantilevers were made of only a layer of Al (100 um) but have different PET (Polyethylene terephthalate) anchor thicknesses of 140 um and 65 um. The resonant frequencies of the SRR thus can be investigated and the principle of frequency shift in response to different cantilever heights can be validated, since the principle of bimorph cantilever deflection in response to temperature is well-known [4]. The width of the signal line is 4 mm and the ground-signal separation is 150 um. The measurements of the scaled model are shown in Fig. 5. A maximum frequency shift of 750 MHz is observed. This shift is corresponding to the difference in cantilever height of approximately 75 um, which gives a sensitivity of 10 MHz /um with respect to cantilever deflection. Notice that each of the two resonant frequencies observed in this band around 3 GHz is mainly due to each of the two rings in the SRR.

RCS Measurements of the Temperature transducer

The technique of remote identification and data acquisition is based on the use of FMCW radar reader operating in the band of 1-12 GHz, functions as an interrogation device. 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. In the new technique proposed here, the temperature sensor is treated as a load and is connected to a horn antenna through a 13 m long cable. The loaded horn antenna operates in the band of 1.8 GHz to 3.4 GHz with a gain of 15 dBi that is located 3.5 m away from the terminal of radar system. The temperature sensor is terminated with a 50 Ω load. The carrier frequency of the radar is 3 GHz, thus based on the total travel distance of the signals, each object gives a different beat frequency with different RCS level. Therefore, by adjusting the cable length for different sensors, a scheme of multi-sensor remote sensing and identification is achieved. As illustrated in Fig. 6, the signal sent from the radar is received by the loaded horn antenna travels a total distance of 33 m before reaching the temperature sensor. Thus, the beat frequency of the sensor is determined to be 22 kHz. The RCS measurements of the two CPW SRR sensor samples with different cantilever heights operating around 3 GHz described in previous section is shown in Fig. 7. A difference of 3dBm is observed indicating the response of the temperature transducer can be quantitatively identified in this remote sensing radar system.

Conclusions

A new wireless passive ultrasensitive temperature RF transducer based on SRR and bimorph micro-cantilevers has been designed, operating in the band of 28-34 GHz. The sensor achieves a sensitivity of 2.6 GHz /um in terms of frequency shift versus deflection, and a sensitivity of 780 MHz/ ^{o}C, three orders of magnitude higher than existing sensors. The bimorph material choices can be varied and adapted to application needs of different temperature ranges without sensor structure modification, and may allow sensing of up to 300 ^{o}C or higher. The transducer is completely passive and miniaturized, has high quality factor that allows high resolution of sensing which enables integration of different multiple sensors in proximity. The scaled model, operating around 3 GHz, successfully illustrates the proof-of-concept for the new sensing principle based on SRR. The RCS measurements of the sensor implemented in the new technique of remote sensing and identification demonstrate the correlation between the deflection of the cantilevers of the sensor and the measured RCS, indicating that temperature sensing can be detected and different sensor nodes can be identified passively and wirelessly.

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References

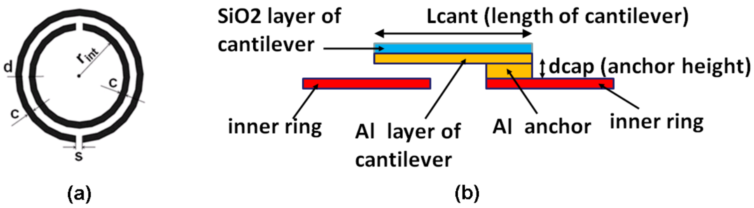
[1] Otto J. Gregory and Tao You, “Ceramic Temperature Sensors for Harsh Environments”, *IEEE Sensor Journal,* vol. 5, October 2005, pp. 833-838.

[2] S. Scott, and D. Peroulis, “A capacitively-loaded MEMS slot element for wireless temperature sensing of up to 300 ^{o}C,” *IEEE International Microwave Symposium*, pp. 1161-1164, Boston, MA, June 2009.

[3] M.M.Jatlaoui, F.Chebila, P.Pons, H. Aubert , “New Micro-sensors Identification Techniques Based on Reconfigurable Multi-band Scatterers,” *APMC 2009*, Singapore, Dec 7-10, 2009.

[4] R. J. Stephenson, A. M. Moulin, and M. E. Welland, “Bimaterials thermometers,” *The Measurement Instrumentation and Sensors Hanbook*, Chemical Rubber, Boca Raten, FL, 1999.

[5] J. B. Pendry, A. J. Holden, D. J. Ribbins, and W. J. Stewart, “Magnetism from conductors and enhanced nonlinear phenomena,” IEEE Trans. Microwave Theory Tech., vol. 47, pp. 2075-2084, Nov. 1999.



(a) (b)

Fig. 1. Dimensions of a) split ring resonators without cantilevers, and b) cross section view of a cantilever implemented on a ring split.

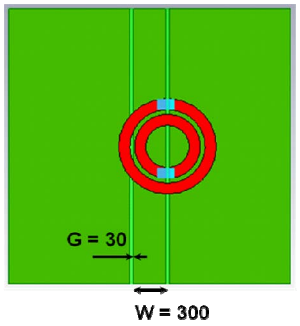


Fig. 2 Top view of the whole transducer (indicated dimensions are in um).

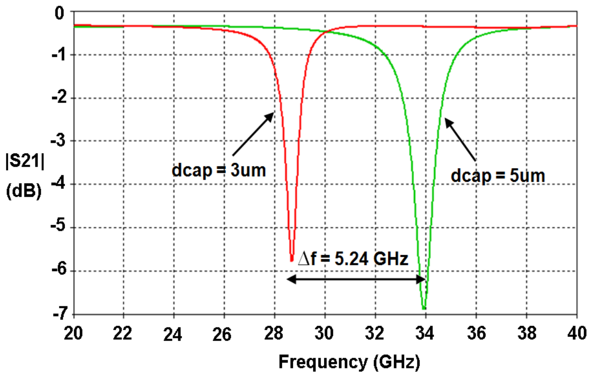


Fig. 3 Simulation results of the temperature transducer (millimeter-wave model).

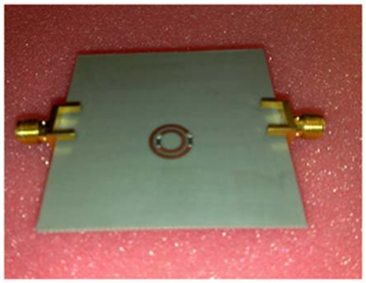


Fig. 4. The scaled prototype of the temperature sensor that operates around 3 GHz.

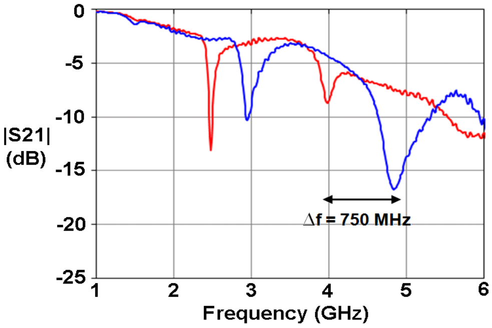


Fig. 5. Magnitude of S21 of the CPW lines with SRRs utilizing 2 cantilevers for cantilever height of 50 um (red curve), and 100 um (blue curve).

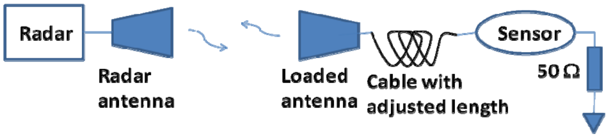


Fig. 6. Diagram illustrating the new remote sensing and identification technique.

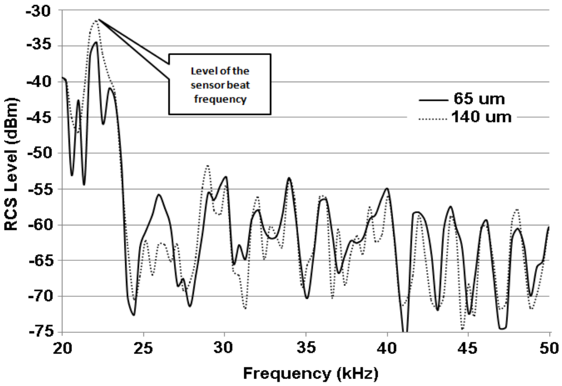


Fig. 7 Measured RCS of the scaled prototype of the termperature sensor with different cantilever heights.