A Novel Passive Wireless Ultrasensitive RF Temperature Transducer for Remote Sensing

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***Abstract* — A wireless passive ultrasensitive temperature transducer is presented in this paper. The transducer consists of micro bimorph cantilevers (Aluminum-Silicon) and split ring resonators, operating at millimeter wave frequencies around 30 GHz. As the temperature changes, the bilayer cantilevers deflect and thus alter the resonant frequencies of the resonators. The design achieves a sensitivity of 1.05 GHz/um with respect to cantilever deflection, corresponding to a sensitivity of 150 MHz/°C, three orders of magnitude higher than existing passive wireless temperature sensors. The sensor design has high Q factor, is ultra-compact, easily fabricated and integrated with other passive sensors in sensing networks. Depending on material choices, the proposed design can also be utilized in harsh environments. To demonstrate the proof-of-concept, scaled designs around 4 GHz are presented, utilizing Aluminum-PET (Polyethylene terephthalate) bilayer cantilevers, achieves a sensitivity of 2.14 MHz/°C.**

***Index Terms* — Temperature Sensor, Radio Frequency Transducer, Passive, Remote Sensing, Multiphysic sensing, Split Ring Resonators, MEMS Cantilevers.**

I. INTRODUCTION

Passive sensors are critical and highly desirable in remote sensing platforms, where long term environment controlling and monitoring can take place. Among the numerous essential physical parameters, temperature measurement is required for many automotive and industrial applications(such as engine operations), space shuttle and aircraft in-flight conditions, and road and bridge health. Some important necessities for the design of these sensors are that the sensor be wireless, battery-less, compact, and able to be easily integrated with other wireless passive sensors since multi-physical sensing is required for a complete environment monitoring. A wireless passive temperature transducer is a device without internal power placed at the monitored site that can transform the local temperature into an output signal that can be read wirelessly by a control system located remotely from the monitored site. Some techniques for temperature measurements include those based on thermoelectricity, temperature dependent variation of the resistance of electrical conductors, fluorescence and spectral characteristics [1]. However, most existing temperature sensors require a power source, and those with high sensitivity suffer from performance degradation above 130 °C [2-4]. A capacitively-loaded MEMS (micro-electromechanical systems) slot element for wireless temperature sensing of up to 300 °C was proposed in [5] but has very low sensitivity of about 500 Hz/°C.

A new wireless passive ultrasensitive temperature transducer is presented in this paper. The transducer consists of split ring resonators utilizing bilayer micro-cantilevers whose layers have different thermal expansive coefficients [6]. Utilizing MEMS allows devices to have low costs, small form factors, ease of fabrication and integration. The split ring resonators (SRRs) operate around 30-32 GHz, and have their slits covered with bimorph micro-cantilevers (Aluminum/Silicon) with an air gap. The cantilevers deflect as the temperature changes, thus alter the frequency response of the SRRs to an incident field. The bimorph material choices can be varied and adapted to application needs of temperature range without sensor structure modification, and may allow sensing of up to 300 °C or higher.

II. TEMPERATURE TRANSDUCER DESIGN AND OPERATION PRINCIPLES

The dimensions of the split rings are shown in Fig. 1a where r_{int} = 130 um, c = 120 um, d = 50 um, and s = 45 um. The SRRs are designed on a 150 um thick glass substrate with ε_r = 4.82. The bimorph cantilever, made up by a layer of Al and a layer of Si with equal thicknesses, is placed over the slit gap of the inner ring as shown in Fig. 1b, supported by anchor which is also Al. The thickness of the anchor determines the initial height of the cantilever. The lateral dimensions of the cantilever are 180 um x 120 um with its width the same as the ring width c, and those of the anchor are 50 um x 120 um.

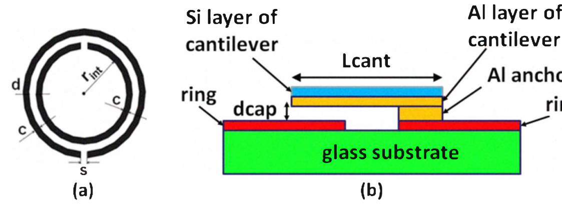

Fig. 1. Dimensions of a) split ring resonators without cantilever, and b) cross section view of cantilever with anchor implemented over the split gap of the inner ring.

SRRs were first theoretically proposed by Pendry et al. [6] and have attracted growing interests since. Many variations of SRRs have been proposed, mainly to realize a negative magnetic permeability material in a time-varying H-field component of a perpendicularly polarized wave incident on its surface. The metamaterial medium consisting of SRRs was shown to be highly frequency selective, suggesting the SRR elements have very high quality factor ($Q > 600$) [7-8]. 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, suggesting that by modifying the capacitance of these slots, the current on the rings is strongly influenced, and therefore, the resonant frequencies are shifted significantly. In our design, the Al layer of the cantilever is the lower layer of the bimorph cantilever and is shorted to one side of the split gap on the inner ring through the anchor, which is also made of Al. Thus, the deflection at the end of this cantilever effectively modifies the split gap capacitance. On the other hand, micro-cantilevers have been widely utilized in MEMS for various sensing applications. A bimorph cantilever consists of a metal and a dielectric, which is commonly fabricated in MEMS. Each material has a different thermal expansive coefficient, as the temperature changes their lengths change at different rate, thus causes the bimorph cantilever to bend [9]. Such a deflection (when implemented at the splits of SRRs) forms an ultrasensitive temperature sensor, and when based on MEMS, they are also robust, easily fabricated, and can be produced in high yield. It should be noted that 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. The operation of the first principle is well-known and has been utilized widely in numerous applications [1- 4, 9]. Thus, our simulations and proof-of-concept prototype are presented to mainly demonstrate the operation of the second principle in which the resonant frequency is shifted as a response to the cantilevers' deflection. Furthermore, at any given operating frequencies, the choice of materials is the factor that determines the upper and lower limit of temperature sensing range, rendering the design a highly broad applicability.

III. Simulations and Temperature versus Frequency response of the millimeter wave Transducer design

The deflection of the micro-cantilevers is approximated in simulations with a uniform deflection across the whole structure of cantilevers. A plane wave is incident on the infinite glass slab that supports the SRRs with a micro bimorph cantilever. The model is simulated in a 2-port set up in CST Microwave Studio 2009. In this model, only one cantilever is implemented, placed over the inner ring split. The S-parameters of two different h values (3 um and 5 um) are shown in Fig. 2, representing two different temperature states of the cantilever. The two resonances are observed at 29.87 GHz and 31.96 GHz showing a frequency shift of 2.09 GHz over 2 um difference in cantilever height. Hence, the sensitivity is 1.05 GHz/um with respect to the cantilever's deflection. Eq. 1 [9] is used to estimate the deflection of the cantilever whose parameters given in Sect. II, thus yields a sensitivity of 0.143 um/^{o}C in terms of deflection versus temperature. Therefore the sensitivity of the temperature sensor is approximately 150 MHz/^{o}C, three orders of magnitude higher than previously reported in [5]. In equation (1), d is the deflection of the free end, L is the length of the cantilever, α_1 and α_2 are the coefficients of thermal expansion of the low and high expansive material respectively, n is the ratio of E_1/E_2 which are the Young's moduli of low and high expansive materials respectively, m is the ratio of t_1/t_2 with t_1 and t_2 their respective thicknesses, and t is the total thickness of the cantilever.

$$d = L^2 \frac{3(1+m)^2}{t\left[3(1+m)^2 + (1+mn)\left(m^2 + 1/mn\right)\right]}(\alpha_2 - \alpha_1)(T - T_0) \qquad \text{Eq. (1)}$$

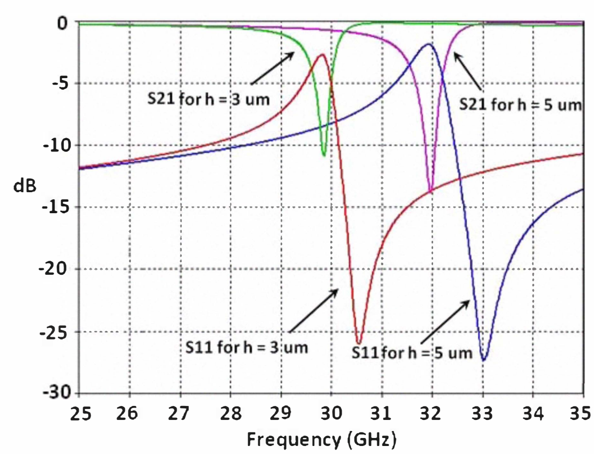

Fig. 2. S11 and S21 of the passive temperature transducer based on SRRs and a bimorph cantilever.

IV. Design, fabrications, and Measurements of the Transducer Scaled Prototypes around 4 GHz range

A. *Designs and Fabrications of Cantilevers and prototypes of different SRR temperature sensor models operating around 4 GHz*

Two scaled model of the design proposed in Sect. III are fabricated. 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 SRRs are excited by a coplanar line (CPW) from the back side of the substrate as shown in Fig. 3 with the prototype is shown on the right. The cantilevers were made of only a layer of Al (100 um) but have different PET (Polyethylene terephthalate) anchor thicknesses of 150 um and 50 um. However due to fabrication variation, the actual heights of the cantilevers' end are measured with an optical scanner to be approximately around 165 um and 65 um. The resonant frequencies of the SRRs thus can be investigated and the principle of frequency shift with respect to cantilever heights can be validated. One of the ground-signal separation gap lines of the coplanar line is aligned with the virtual line connecting both SRR split gaps at their middles. The width of the signal line is 4 mm and the ground-signal separation is 150 um.

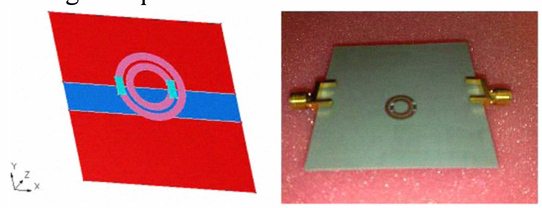

Fig. 3. Coplanar line scaled model of the SRRs with 2 cantilevers covering 2 SRR split gaps.

The second prototype design is fabricated on Rogers RT5870 substrate (ε_r = 2.33, substrate thickness = 787 um). The dimensions of the SRRs are as follows: r_{int} = 3.5 mm, c = 1.0 mm, d = 0.5 mm, and s = 1.0 mm. The bimorph cantilevers have lateral dimensions of 1.0 mm x 3.0 mm. These were fabricated on a 100 um thick layer of PET laminated on one side of the Al sheet (which is also 100 um thick). Another 100 um sheet of PET is glued to the other side of the Al sheet but only covers half of the Al sheet. Then, the sheet is diced 1mm into the side of the 3-layer PET-Al-PET formation, and 2 mm into the side of 2-layer Al-PET formation to produce the cantilevers with the PET anchor attached as shown in Fig. 4. These cantilevers are then placed over the split gap of the SRR prototype with conductive epoxy and annealed. The final scaled prototype of the temperature transducer is shown in Fig. 5. The air gap h (Fig. 1b) between the cantilever and the ring surface is characterized with an optical device and estimated to be approximately around 150 um (Fig. 6).

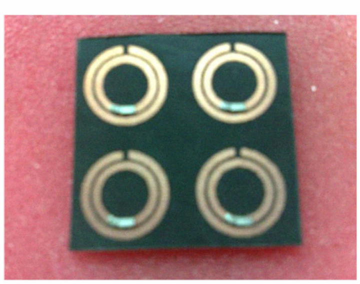

Fig. 4. SRR scattering model sample on RT5870 with bimorph cantilevers.

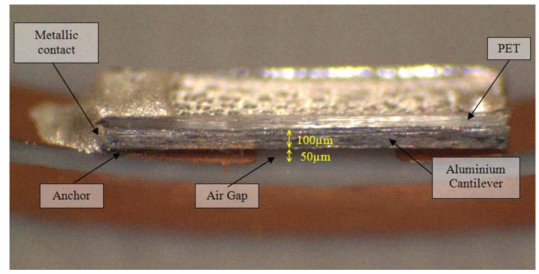

Fig. 5. The microscopic view of the bimorph cantilever.

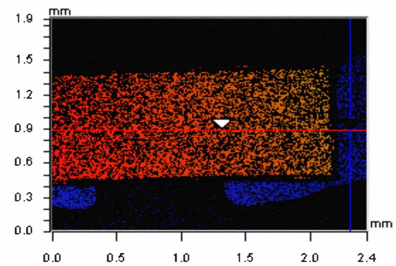

Fig. 6. Cantilever under optical scan.

B. Measurements of the Scaled Temperature Sensor Prototypes

For the measurements of the CPW SRR model samples (Fig.3), S-parameters of the CPW model are shown in Fig. 7. A frequency shift of 800 MHz from 4.8 GHz to 4.0 GHz is observed. This shift is corresponding to a different in cantilever height of approximately 100 um, which gives a sensitivity of 8.0 MHz/ um with respect to cantilever deflection.

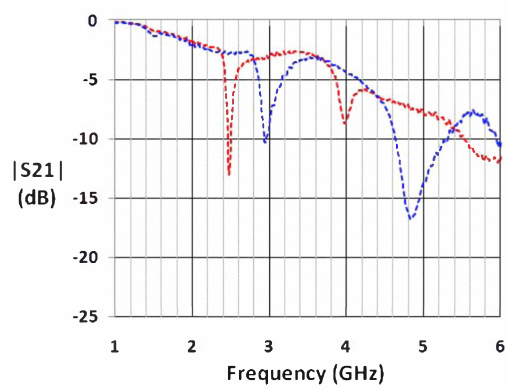

Fig. 7. S21 magnitude of the two CPW SRR sensor prototypes each implemented with two cantilevers with different average height of 65 um (red curve), and 165 um (blue curve).

For the measurements of the second prototype model, the SRR scattering model (Fig. 4), the measurements were performed with a horn antenna and a vector network analyzer (Fig. 8). A reflection only calibration was done using short, open, and load standards. A lamp was used as a heat source, and a thermometer was used to monitor the temperature in proximity of the sensor prototype. First, the sample is heated by the lamp in close proximity to 100 °C, then is allowed to cool down for stable frequency reading. Due to limitation of the measurement set up, heat is not confined but dissipates quickly, and the system only becomes more stable as it cooled down to around 60 °C. The temperature and frequency response of the sensor prototype are recorded. The plot of two temperature points of 60 °C and 32 °C are shown in Fig. 9.

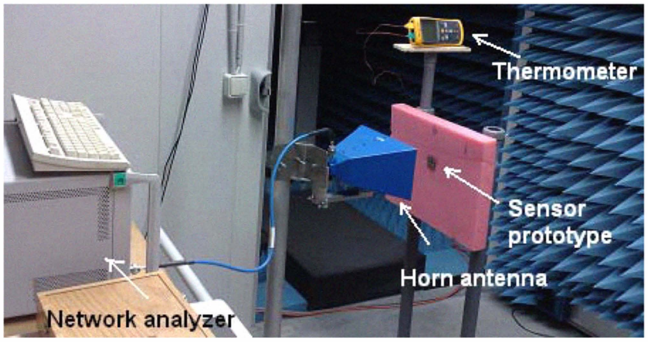

Fig. 8. The temperature measurement set up.

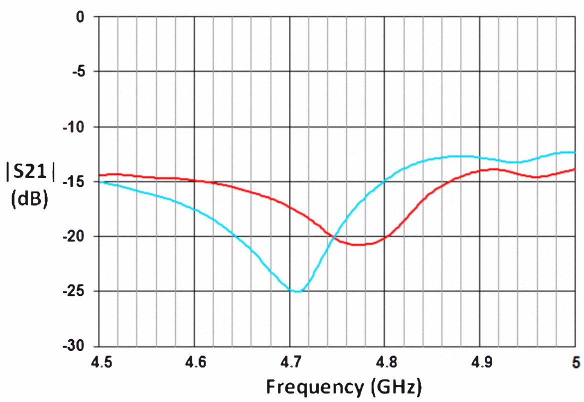

Fig. 9. Plots of frequency response (S11) of the sensor prototyped at 60°C (in red) and 32°C (in blue).

The frequency response in Fig. 7 shows a resonant frequency shift of 70 MHz, from 4.77 GHz to 4.70 GHz, corresponding to a sensitivity of 2.5 MHz/°C. In comparison to the sensitivity of 500 kHz/ °C as reported in [5], this transducer design yields 5 times more sensitive. It should also be noted that the wireless passive temperature sensor in [5] operates around 19 GHz, whereas the scaled prototyped demonstrated here is operating at 4.7 GHz. Due to limitation of fabrication and measurements, the linearity response of the sensor is not addressed in the proof-of-concept prototypes.

V. Conclusions

A new wireless passive ultrasensitive temperature RF transducer operating around 31 GHz based on split ring resonators and bimorph micro-cantilevers has been designed to have a high sensitivity of 1.05 GHz/um with respect to the cantilever deflection. With the choice of materials for the bilayer cantilevers presented in this work, the transducer achieves a sensitivity of 150 MHz/°C. The transducer is completely passive and miniaturized, has high quality factor that allows high resolution of sensing which may enable integration of different types of sensors without saturating the operating frequency band of the sensing system, thus achieve multiphysic sensing in a single passive network. A scaled model of the design was also designed, fabricated, and presented in this paper to illustrate the proof-of-concept of the sensor. The scaled model operates around 4 GHz and was performed measurements with a heat source to give a sensitivity of 2.5 MHz/°C. This low sensitivity of our scaled model also out performs previously proposed wireless passive temperature sensors. In future work, we will fabricate the micro temperature transducer that operates around 31 GHz and develop the multiphysic passive sensing by integrating together temperature and pressure transducers on a single unit of passive device.

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References

[1] P. R. N. Childs, J. R. Greenwood, and C. A. Long, “Review of temperature measurement,” Rev. Sci. Instrum., vol. 71, No. 8, pp. 2959-2978, Aug. 2000.

[2] J. Goetz, “Sensors that can take the heat”, *Sensors*, pp. 20–38, June 2000.

[3] O.J. Gregory, T. You,“Ceramic Temperature Sensors for Harsh Environments”, *IEEE Sensor J.,* vol.5,Oct. 2005, pp.833-838.

[4] Lemi Toygur, “Interface Circuits in SOI-CMOS for High-temperature Wireless Micro Sensors,” Ph.D. Dissertation, Case Western Reserve University, OH, January 2004.

[5] S. Scott, and D. Peroulis, “A capacitively-loaded MEMS slot element for wireless temperature sensing of up to 300 °C,” IEEE Intl. Microwave Symp., pp.1161-1164, Boston, MA, June 2009.

[6] 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.

[7] D. Smith, W. J. Padilla, D. C. Vier, S. C. Nemat-Nasser, and S. Schultz, “Composite Medium with Simultaneously Negative Permeability and Permittivity,” Phys. Rev. Lett., vol. 84, no. 18, pp. 4184-4187, May 2000.

[8] R. Marques, F. Mesa, J. Martel, and F. Medina, “Comparative analysis of edge- and broadside-coupled split ring resonators for metamaterial design- theory and experiments,” IEEE Trans. Antennas and Propagation, vol. 51, no. 10, Oct. 2003.

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