Wireless transducer based on split-ring resonator

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***Abstract*—In this paper we propose a wireless transducer, conceived as part of a wireless sensing tag working on the UHF RFID band. The transducer works both as antenna for wireless communication with a dedicated reader, and as sensing element. It is based on a small loop antenna loaded with a split-ring resonator in a complete single-layer design. Two proof-of-concept prototypes were fabricated, one on FR4 and the other on paper substrates. Both prototypes were easily adapted to work as humidity sensors, and measurements results showed the suitability of the transducer for low-cost wireless sensing applications.**

***Index Terms*—wireless sensor, metamaterials, split-ring resonator.**

I. Introduction

Wireless sensors allow a certain quantity to be measured in a non-intrusive way and thus they can be installed at places where intervention is preferably avoided such as harsh environments or difficult access spots [1]. Among the different types of wireless sensors used in industrial applications, solutions compatible with Radio-Frequency Identification (RFID) standard have rapidly gain adepts in last decades since they represent a low-cost implementation which requires no local battery in its passive mode. While RFID tags are mainly addressed for identification purposes, several studies have been published in which the tag is adapted for making sensors that respond to temperature, gas, humidity and strain, as recently reviewed in [2].

On the other hand, artificial metamaterials (MTM) have been proven to be useful for sensing applications [3], [4]. Moreover, metamaterials-inspired antennas have been reported in which dimensions of the antenna are effectively reduced [5]. These facts reveal the possibility of exploiting MTM for the design of compact wireless sensors, aiming to costs reduction and ubiquitous sensing. A well-known resonant particle that has been used for the implementation of artificial MTM media is the split-ring resonator (SRR) [6]. It is also known that this particle behave as a quasistatic resonator at its fundamental resonance, which depends on their distributed capacitance and inductance. Either one of them can be made sensitive to its surrounding environment and so the SRR can work as a sensor having its resonant frequency dependent on an external variable. This characteristic has been widely exploited for microwave [4], and wireless sensors [7]–[9].

In this paper, we present the design and implementation of a metamaterial-inspired wireless transducer, conceived as part of a wireless sensing tag composed by the transducer and a chip-load, as depicted in Fig. 1. The transducer serves both for the communication with a dedicated reader and for the sensing mechanism. It is composed of a small loop antenna loaded with a split-ring resonator with variable resonant frequency. The SRR interacts with its environment and changes the frequency in which the transducer impedance is matched to the chip-load. In this way, the chip should work as a load modulator which responds proportionally to the effective power received [10], hence one is able to decode in the reader the information carried by the transducer. The wireless transducer is fully compatible with printing fabrication processes such commercial RFID tag antennas due to its single-layer design. The operating frequency was set to the Ultra High Frequency (UHF) RFID band while keeping the physical dimensions of transducer small. Measurement results of two prototypes implemented in different substrates are presented. For illustrative purposes, they are adapted to work as humidity sensors by applying a Polyvinyl Alcohol (PVA) coating. The results show good sensitivity for the implementations, which demonstrates that the proposed design could serve as a transducer for a wireless sensing tag.

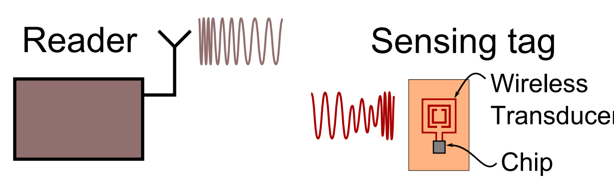

Fig. 1. Communication between reader and a wireless sensing tag. The tag includes the wireless transducer and a chip.

II. Wireless transducer

There are two direct effects of including the SRR inside of the small loop antenna. First, the matching condition with the load occurs without extra circuitry and at a lower frequency than the correspondant loop wavelength, allowing the reduction of the loop size and the tag as a whole. Second, the frequency of matching condition can be variable if the SRR resonant frequency is made dependent of an specific material, converting the tag in a wireless sensor. Therefore, accurate estimation of the SRR fundamental resonance frequency and evaluation of its electromagnetic interaction with the loop through the reflection coefficient are the main design issues.

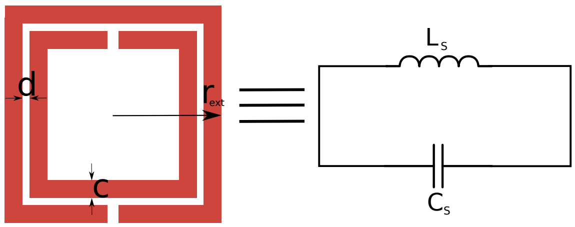

Fig. 2. Squared SRR structure and its simplified equivalent quasistatic model as an LC tank.

A. SRR design

Split-ring resonators are composed by two concentric open rings, as shown in Fig. 2. When a time-varying magnetic field is applied perpendicular to the SRR surface, a current density is induced in a way that it is minimum at the gaps and maximum on the other side, accumulating opposite charges between the rings and hence producing a high distributed capacitance [11]. Therefore this structure can resonate at much lower frequency than the correspondant electrical wavelength of the structure. Based on this fact, its electromagnetic behavior can be considered to be quasistatic and thus it can be modeled with lumped-circuit elements, as illustrated on the right side of Fig. 2. This simplified model, represented by an LC tank, is useful for the SRR fundamental resonance. The resonant angular frequency of the tank, equal to $\omega_0 = 1/\sqrt{L_s C_s}$, depends on the geometry of the rings, i.e. the external equivalent radio of the SRR (r_{ext}), the trace width of the rings (c) and the gap between them (d). The total inductance and capacitance in this model can be expressed by [12]:

$$C_s = \left[2r_{ext} - \frac{3}{2}(c+d)\right] C_{pul}, \tag{1}$$

$$L_s = \frac{\mu_0}{2}\frac{l_{avg}}{4} 4.86 \left[\ln\left(\frac{0.98}{\rho}\right) + 1.84\rho\right], \tag{2}$$

ρ is the filling factor, l_{avg} is the average strip length calculated over the both rings, and C_{pul} is the capacitance per unit length between rings, given by

$$C_{pul} = \epsilon \frac{K(k')}{K(k)}, \tag{3}$$

where $k' = \sqrt{1-k^2}$, k is a function dependent on c and d, and $K(k)$ and $K(k')$ are the complete elliptic integrals of the first kind and is its complement, respectively. This capacitance is used as the main sensing mechanism of the transducer.

Through the equations presented above, it is possible to design a SRR with resonant frequency around the desired band. To validate the design, a simulation was performed using a $50\,\Omega$ characteristic impedance line coupled to the SRR [13]. In this configuration, the magnetic field is perpendicular to the ring plane, and a coupling is generated on the resonant frequency causing the insertion loss to have a profound dip. The structure was simulated in ADS from Agilent by using the Finite Element Method (FEM).

B. Transducer design

The complete tag structure and dimensions are shown in Fig. 3. The separation distances and gaps of the rings were chosen in order to facilitate the manual manufacturing of the prototype on paper substrate as shown in next section. The tag reflection coefficient was simulated with FEM. For the simulations, a FR4 substrate with relative permittivity of 4.37 and dielectric tangent loss of 0.02 was considered. Simulations showed that the frequency of impedance matching condition (minimum reflection with $50\,\Omega$ source) was slightly higher than UHF RFID band, located at approximately 1 GHz. This preliminary value was desired since a down shift on this frequency was expected after the PVA coating for the implementation of the humidity sensor, detailed in next section.

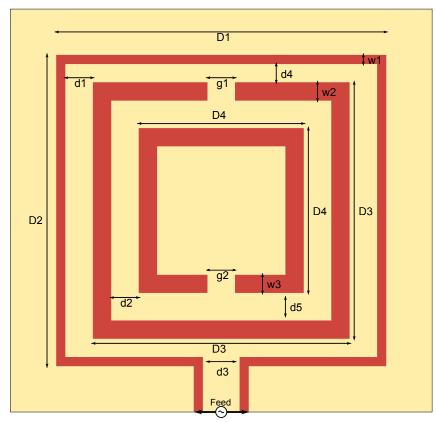

Fig. 3. Dimensions of the prototype on FR4 substrate in mm: D1 = 31.2 , D2 = 28.7 , D3 = 23.9, D4 = 17, d1 = 2.95 , d2 = 1.7, d3 = 3, d4 = 2.4 , d5 = 1.7 , g1 = g2 = 1, w1 = 0.7 , w2 = w3 = 1.75.

III. Implementation and Experimental Results

In this study, the capacitive sensing capability of the wireless transducer is demonstrated by adapting it to work as a humidity sensor and monitoring the change of the frequency at matching condition due to the relative humidity of the ambient. For instance there are different materials which can be used to enhance sensitivity on a wireless sensor [14]. In the case of humidity sensors, materials such as PEDOT [15], Kapton [16] and PVA [17] have been used satisfactorily. The latter has demonstrated higher sensitivity, therefore it was selected in order to prove the potentiality of the transducer as a humidity sensor.

The PVA polymer was diluted in 1:3 water-ethanol solvent with a 1:10 proportion (1 g of PVA to 10 ml solution). This solution was left to magnetic stirring during 3 hours at ambient temperature. Then, the solution was poured over the conductors face of the fabricated prototype on FR4 substrate and left it to dry at ambient temperature. The frequency at impedance matching condition (from now on referred as f_m) with PVA coating resulted in approximately 980 MHz, which represented a 3 % variation from the case without it.

The test setup used for the measurement of the humidity sensor is illustrated in Fig. 4. Measurements were done at 23 °C ambient temperature and 60 % relative humidity (RH). A closed container ($12 \times 13 \times 15\,\mathrm{cm}^3$) with non-conducting walls was used to recreate an varying RH environment. This container was filled with 200 ml of water and then closed. A small hole was left on the upper face for inserting the measurement cable, so the transducer was connected to this side of the cable, without water contact, and the other side was connected to a Vector Network Analyzer (0.3 MHz - 8 GHz). The reflection coefficient (S_{11}) was monitored during 1 hour. In this period, the internal environment of the container reached approximately 100 % of RH. The plot of S_{11} vs time is shown in Fig. 5. The repeatability of the sensor was also verified by taking the transducer out of the container. A change in the quality (Q) factor around resonance is observed, which is due to the dielectric loss increment at higher level of water absorption. This result is consistent with the measurements reported in [17]. The evolution of the frequency at impedance matching condition in time is plotted in Fig. 6. A maximum variation of 25 MHz range was observed, which gives a 2.5 % variation from its initial value.

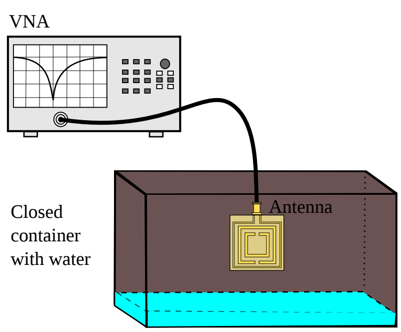

Fig. 4. Measurement setup for the humidity sensor.

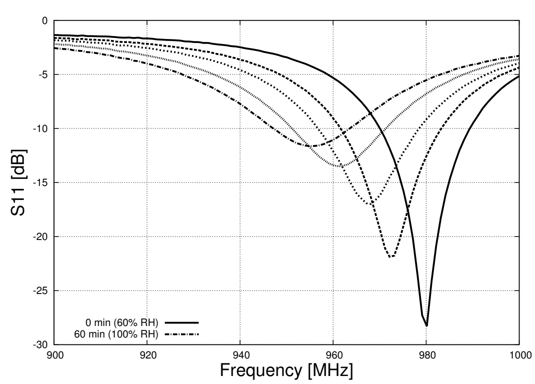

Fig. 5. Reflection coefficient variation of the FR4 prototype in response to relative humidity.

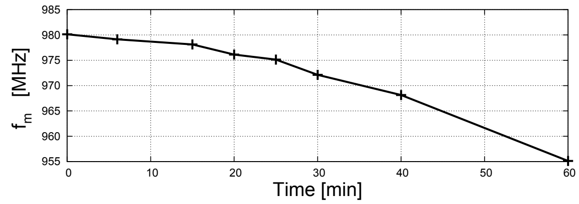

Fig. 6. Frequency at impedance matching condition of the FR4 prototype versus time due to variation of the relative humidity.

For the proof-of-concept aiming a low-cost wireless sensing tag, a prototype was fabricated on photo-quality paper with a 220 μm thickness and a relative permittivity of 2.36. The conductive traces were applied manually on the glossy face (as it would be in a printed implementation) using conductive copper tape and tinning the joins as shown in Fig. 7. Since the non-glossy face of the paper is also sensitive to humidity due to its porous conformation, a humidity sensing response of the prototype without PVA was first analyzed, by using the same setup of the FR4 implementation. As it was expected, the prototype on paper responds without the need of PVA coating, resulting in a variation of 77 MHz during one hour of experiment.

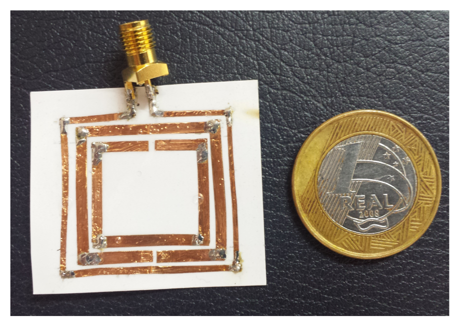

Fig. 7. Physical implementation of the wireless transducer on paper.

The PVA coating was then applied to the paper prototype. The resultant frequency shift caused by the coating application was of 10 %, which effect was already expected to be higher than with the FR4 substrate because of the thinner thickness of the paper. The results of the variation on f_m is shown in Fig. 8 and compared with the no-PVA case. This is also illustrated in Fig. 9 by its percent variation normalized with its value at the start point of the measurement (0 min) in each case. The sensitivity definition used for comparing the transducers is:

$$S = \frac{(f_{res}|_{60min} - f_{res}|_{0min})}{(RH|_{60min} - RH|_{0min})} \tag{4}$$

Considering a RH at the start and end of the 1-hour experiment of 60 % and 100 %, respectively, the sensitivity for the case of the paper implementation without PVA resulted in 1.9 MHz/%RH and, for the case with PVA, in 4.4 MHz/%RH. The results showed that paper prototype with PVA has a higher sensitivity than without it, and at the same time both paper prototypes showed higher sensitivity than the FR4 prototype.

The results for all implemented transducers are summarized in Table I. Sensitivity values obtained are on the order of the results reported in [2] and [17]. These experimental results also demonstrate that both implementations in paper could be used as low-cost wireless sensors, which can be also fabricated with printing techniques.

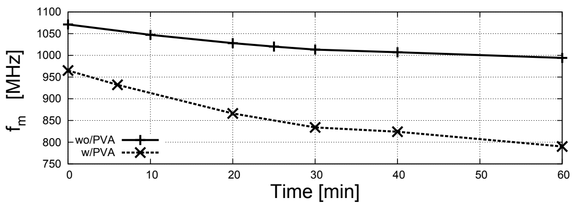

Fig. 8. Frequency at impedance matching condition of the paper prototype vs time (with and without PVA coating).

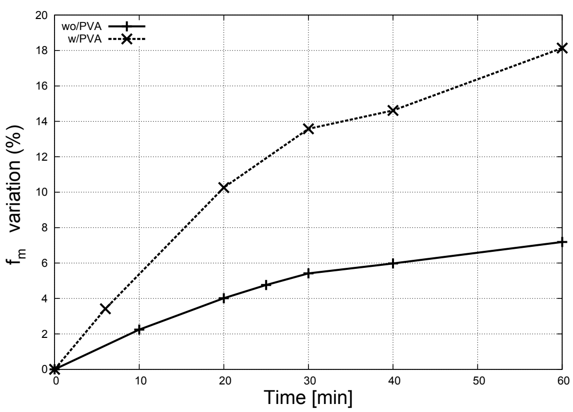

Fig. 9. Normalized percent variation of the frequency at impedance matching condition of the paper prototype vs time (with and without PVA coating).

TABLE I
WIRELESS TRANSDUCER MEASUREMENT RESULTS: VARIATION OF THE FREQUENCY AT IMPEDANCE MATCHING CONDITION DURING ONE HOUR OF EXPERIMENT AND EQUIVALENT SENSITIVITY TO RELATIVE HUMIDITY.

Substrate	Δf_m [MHz]	Δf_m [%]	S [MHz/%RH]
FR4 + PVA	25	2.5	0.6
Paper	77	7.2	1.9
Paper + PVA	175	18	4.4

IV. CONCLUSIONS

Wireless sensors are very useful for control and monitoring applications in industrial environments, however, in order to construct an intelligent sensor network, the sensors must be low cost. In this paper we proposed a wireless transducer as part of a wireless sensing tag working in the UHF RFID band. The tag design was inspired on small antennas techniques based on metamaterials loading. The selected metamaterial particle was the split-ring resonator, which allowed the miniaturization of the tag and boosted the sensitivity of the transducer due to its high distributed capacitance. The transducer follows a single-layer structure, which makes it compatible with printing fabrication processes. Two prototypes on different substrates, FR4 and paper, were fabricated. The sensitivity was characterized by coating the transducers with PVA, so they work as a humidity sensors. The FR4 prototype showed a measured sensitivity of 0.6 MHz/%RH and in the case of the paper, it showed a sensitivity of 4.4 MHz/%RH. In this way, the transducers proved to be suitable for wireless sensing.

ACKNOWLEDGMENT

The authors would like to thank CNPq and CAPES for financial support of this research.

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