A low-cost passive wireless capacitive sensing tag based on split-ring resonator

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Abstract—**Wireless sensors technology have provided industry with an efficient tool for precise monitoring and automation control of any particular quantity. In situations in which many sensors need to be deployed, a low-cost solution plays a decisive role. Passive chipless sensing tags have been recently proposed in order to reduce the cost of the sensors significantly in comparison with traditional RFID tags. In this paper we propose a wireless capacitive sensing tag that works on the UHF RFID band based on a small antenna loaded with a metamaterial in a single-layer design. The proof-of-concept was shown with two implemented prototypes, one on FR4 and the other on paper substrates. Both prototypes were easily adapted to work as humidity sensors. Simulations and measurements results showed the suitability of the tags for low-cost sensing applications.**

Keywords*—*wireless sensor, capacitive sensing, chipless tag, small antennas, metamaterials, split-ring resonator, printed electronics.

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]. Within 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 responds with temperature, gas, humidity and strain, as recently reviewed in [2]. Nevertheless, for RFID-like solutions to be widely adopted, tag cost is still an obstacle because of the chip. Therefore, innovative approaches for chipless RFID tags solutions have been already presented for identification [3] and sensing [4]. While still in research stage since there are several constraints to be taken into account for this new technology [3], chipless tags have been indicated by the IDTechEx forecast [5] to have a promising market growth due to its potential cost of around 0.1 USD cent, compared to 15 USD cent of a traditional RFID tag.

Passive chipless sensor tags design depends on the data transfer principle used by the interrogator, which can be classified into time and frequency modes [3]. Frequency domain interrogation makes the design of the tag simpler, leaving most of the complexity and the data processing to the interrogator. In this mode, the information carried by the sensing tag can be extracted from the phase or amplitude of its frequency signature within certain bandwidth. Following the classification adopted in [3], the frequency-mode RFID-like chipless tags can be divided into three different approaches: The one that uses a set of symbols that owns a specific electromagnetic signature within a limited band, other that combines an antenna for the communication and an RF circuit which encodes the information, and lastly another that combines both approaches. Additionally, in order to add a sensing capability to the tag, a transducer must be included into the design, so the information is embedded in its frequency response.

On the other hand, metamaterials-inspired antennas have been proved to serve as chipless sensing tags [6] in which metamaterials (MTM) are useful for causing resonance and increasing sensitivity [7], [8]. MTMs have also proven to be useful for the design of electrically small antennas (ESAs) [9], which is interesting for cost reduction and ubiquitous sensing. Therefore, ESAs based on metamaterials are a convenient starting point for the design of wireless tags envisioning both miniaturization and sensing enhancement.

The wireless tag can be designed to be fully compatible with printing fabrication processes such as flexography, gravure or inkjet [10]. Printed electronics does not only allow low-temperature fabrication in large scale, using less energy consumption and with less reminiscences, but also makes possible to integrated electronics on flexible substrates, such as paper or plastic [11]. All these characteristics contribute to an even larger cost reduction of the tag.

In this paper we present a passive wireless tag with capacitive sensing capability based on the miniaturized antenna with MTM loading approach [9]. The sensor is build by a small loop antenna loaded with a Split-Ring Resonator (SRR) [12], which serves as the sensor transducer and to reduce the dimensions of the tag. The SRR acts as the unit cell of a negative permeability material which have been proven to modify the near-field region of an ESA, improving its radiation efficiency [13]. In our study, the tag is intended to work as a wireless sensor in which the information is obtained by the backscattered frequency response of the tag. In addition, the complete tag was conceived in a single-layer design and thus it is fully compatible with printing fabrication processes. The operating frequency was set to operate in the Ultra High Frequency (UHF) RFID band while keeping small the physical dimensions of the tag. Simulations and measurement results of the sensing tags prototypes on FR4 and paper substrate are presented. The sensing capability is demonstrated by coating the tags with Polyvinyl Alcohol (PVA) to make they work as humidity sensors. The results show good sensitivity for all tags implemented, which demonstrates that the proposed design could serve as a low-cost solution for wireless passive sensing.

The remainder of the paper is organized as follows: the tag design procedure and simulation results are described in Section II, the implementation and measurements on FR4 and paper substrates are presented in Section III and IV, respectively, and finally, conclusions are drawn in Section V.

II. WIRELESS CAPACITIVE SENSING TAG

Metamaterials are sub-wavelength engineered artificial structures whose electromagnetic constitutive parameters are not readily found in conventional materials, like negative electric permittivity ($\epsilon_r < 0$) and magnetic permeability ($\mu_r < 0$). As a consequence, new and interesting properties arise, like negative refractive index (NRI), backward wave (anti-parallel phase and group velocities), reversed Snell's law, amongst others [8]. A known method to obtain negative permeability material from conductors is through the utilization of split-ring resonators, here referred as SRRs, which structure is shown on the left side of Fig. 1. 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 at the extremities of each ring and hence producing a high distributed capacitance [14]. Hence this structure can resonate at a wavelength larger than the diameter of the rings, and so several ESAs based on SRRs have been reported [9].

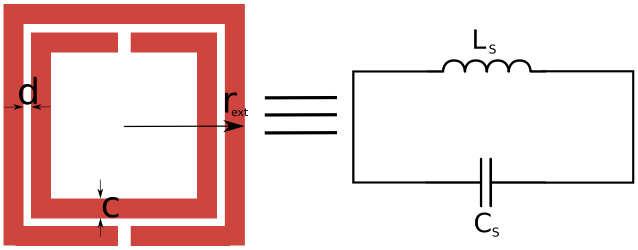


Fig. 1. Squared SRR structure and its simplified equivalent quasistatic model as an LC tank.

The SRR can be used as a transducer for sensing applications if its distributed capacitance is made to be dependent on the measured desired variable. This characteristic has been widely exploited for microwave sensors [8], however only few SRR-based wireless sensors have been reported: In [15], the idea of a capacitive sensor has been presented based on a bowtie antenna loaded with an SRR which operates between 1 and 2 GHz depending on the capacitor load located at the split of the inner ring. No results of the radiation efficiency of the device is given and the reflectance (S_{11}) measurement was made on its near field. In [16] and [17] a strain sensor was proposed based on a SRR array fabricated on silicon and Kapton substrates, operating at around 12 GHz. This array was fixed to a surface in which tension is applied and then the transmission coefficient (S_{21}) is measured by using two horn antennas. In [18], the idea of using a double-sided SRR for temperature or humidity sensor operating around 10 GHz was proposed, and verified by S_{21} simulations. In [19] and [20], the authors proposed a temperature sensor operating around 30 GHz based on a SRR array loaded with a cantilever on the split of the inner ring. For the proof-of-concept, they fabricated a scaled prototype which operates around 4.7 GHz on Rogers RT5870 substrate. The measurement was carried on with a horn antenna and thus obtaining its reflection coefficient, however no further details on the efficiency of radiation of the structure is given. In the next sections we present the design procedure and simulation results of the proposed wireless tag operating at UHF RFID band in which the SRR serves as a miniaturization technique and as the sensor transducer.

A. SRR design

Based on the fact that the SRR is smaller than the free space wavelength resonance, 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. 1. This is a simplified model, represented by an LC tank which resonant angular frequency is given by $\omega_0 = 1/\sqrt{L_s C_s}$, where [21]:

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

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

$$\rho = \frac{c+d}{2r_{ext} - c - d}, \tag{3}$$

$$l_{avg} = 8\left[r_{ext} - \frac{1}{2}(c+d)\right]. \tag{4}$$

Note that 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

$$C_{pul} = \epsilon\frac{K(k')}{K(k)}, \tag{5}$$

where k is

$$k = \frac{\frac{d}{2}}{c + \frac{d}{2}}, \tag{6}$$

$K(k)$ is the complete elliptic integral of the first kind, $K(k')$ is its complement, and $k' = \sqrt{1-k^2}$. This expression can be accurately calculated as

$$\frac{K(k')}{K(k)} = \frac{1}{\pi}\ln\left[\frac{2(1+\sqrt{k'})}{1-\sqrt{k'}}\right], \tag{7}$$

for $0 \leq k^2 \leq 0.5$.

Through the equations presented above, it is possible to design a SRR resonating around the desired band. The gaps were made small to guarantee a high quality factor Q as proven in [22], which is convenient for sensing applications in the frequency mode. To validate the design, a simulation was performed using a $50\,\Omega$ characteristic impedance line coupled to the SRR [23]. 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). The main resonant frequency was generated at 1 GHz.

B. Tag design

The tag concept is related to the small antenna approach with MTM loading, so-called near-field resonant parasitic elements [9]. Thus, in our tag, a SRR is coupled to an electrically-small loop antenna. The coupling among these two structures is the mechanism that increases the radiation efficiency by enhancing the loop magnetic near field [13]. In order to be considered small, the practical rule of thumb is that the perimeter of the loop should be less than $\lambda/3$ (or area $< \lambda^2/100$) [24].

The SRR was fit entirely inside the loop antenna area, so some simulation refinements were done in the SRR position for setting the final resonant frequency. The complete tag structure and dimensions are shown in Fig. 2. As the width of the loop increases also the bandwidth, and as a high Q factor improves the sensitivity of the sensor, the loop was made thin. Note that the feed is only for characterization purposes, while in a real environment, the tag operates based on backscattering i.e. whith the feed short-circuited. The separation distances and gaps of the rings were chosen in order to facilitate the manual manufacturing of the paper prototype.

The tag was simulated also by using FEM. For the simulations, a FR4 substrate with relative permittivity of 4.37 and tangent loss of 0.02 was considered. The simulated resonant frequency of the tag was in accordance to the previously SRR simulation, at 1 GHz. This frequency was selected to be slightly higher than UHF RFID band due to the expected shift with the PVA coating for the humidity sensor, detailed in next section. Following the criteria of an ESA, which states that the wave number β times the minimum radius a of a sphere enclosing the maximum dimension of the antenna must respect $\beta a < 1$, the βa resulted in 0.48 at 1 GHz. The simulated quasi-omni directional radiation pattern is shown in Fig. 3(b). As can be observed, the maximum directivity was achieved at the horizontal plane with 35.55 % efficiency at 1 GHz. This is equivalent to a -1.89 dBi gain. The approximated formula for an uplink/downlink communication range (r) with a chipless tag is described in (8), where P_r is the backscattered received power, G_{TX} is the gain of the reader's antenna, and α is a factor that takes into consideration the tag communication performance which includes the equivalent RCS (radar cross section), antenna aperture, polarization mismatch, among others.

$$r \approx \left(\frac{\lambda_0}{4\pi}\right) \sqrt{G_{TX} G_{TAG}} \sqrt[4]{\frac{\alpha P_{TX}}{P_r}}, \tag{8}$$

According to the Brazilian agency of communications (ANATEL) the EIRP (equivalent isotropic radiated power) is limited to 30 dBm. Therefore, considering a commercial RFID reader with -80 dBm sensitivity and a factor alpha of 10 %, the interrogation distance is estimated to be around 7 meters.

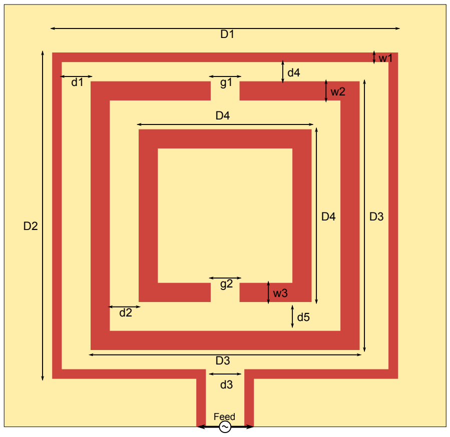
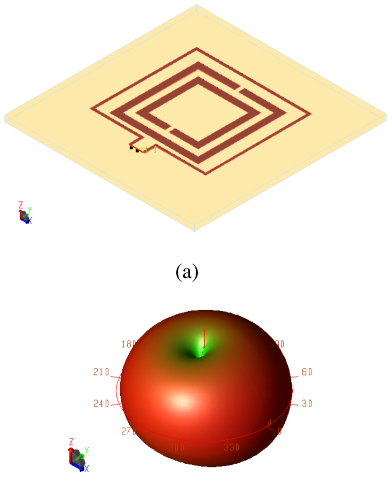


Fig. 2. Dimensions of the tag on FR4 substrate in mm: D1 = 31.2 , D2 = 28.7 , D3 = 23.9, D4 = 17, d1 = 2.95 , d2 = 1.7, d3 = 3, d4 = 2.4 , d5 = 1.7 , g1 = g2 = 1, w1 = 0.7 , w2 = w3 = 1.75.

III. TAG IMPLEMENTATION AND MEASUREMENTS

The sensing characteristics of the implemented tag was further explored. For instance, there are different materials which can be used to enhance sensitivity on a wireless sensor [4]. In this study we decided to demonstrate the capacitive sensing capability of the tag by adapting it to work as a humidity sensor. In the case of humidity sensors, materials such as PEDOT [25], Kapton [26] and PVA [27] have been used satisfactorily. The latter has demonstrated a great sensitivity response, therefore it was selected in order to prove the potentiality of our tag 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 tag on FR4 substrate and left it to dry. The resonant frequency after 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 tag 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 resonant frequency of the tag was monitored during 1 hour. In this period, the internal environment of the container reached approximately 100 % of RH. The variation of the



(a)

(b)

Fig. 3. FEM electromagnetic simulation: (a) 3D structure of the tag and (b) simulated radiation pattern results.

resonant frequency vs time is shown in Fig. 5. The repeatability of the sensor was also verified by taking the tag out of the container, leaving it at ambient environment. The change in Q factor is due to the higher dielectric loss due to water absorption, which is consistent with the results reported in [27]. The evolution of the resonant frequency 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 resonance.

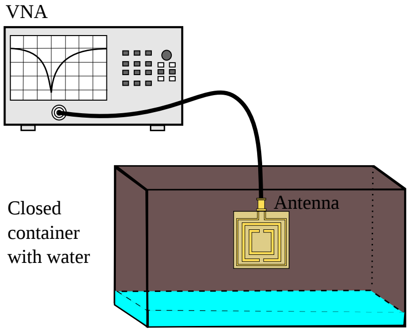


Fig. 4. Measurement setup for the humidity sensor.

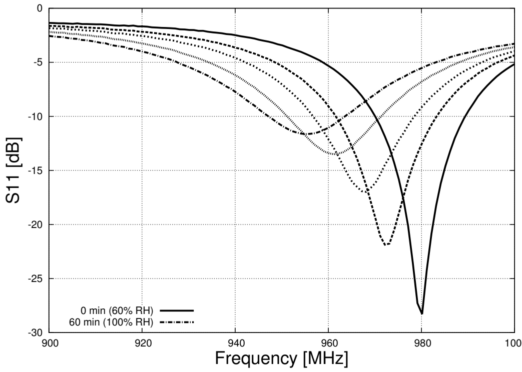


Fig. 5. Reflection coefficient variation of the FR4 tag in response to relative humidity.

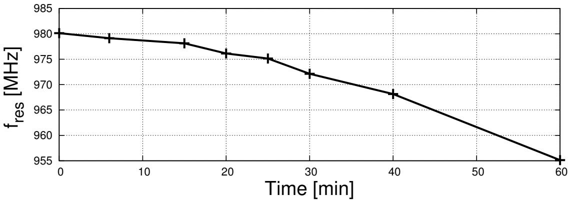


Fig. 6. Resonant frequency of the FR4 tag versus time due to variation of the relative humidity.

IV. LOW-COST IMPLEMENTATION ON PAPER

For the proof-of-concept of a low-cost wireless sensing tag, a prototype was fabricated on paper. This was first simulated to verify its radiation pattern, which resulted in a maximum gain of -3.9 dBi, or equivalently a distance range of interrogation higher than 5 meters, calculated with (8) with the same parameters as the FR4 prototype. The substrate used is a 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 tag without PVA was first analysed, by using the same setup of the FR4 prototype. The measured reflection coefficient variation vs time is shown in Fig. 8. As it was expected, the paper tag responds without the need of PVA coating, resulting in a variation of 77 MHz during one hour of experiment.

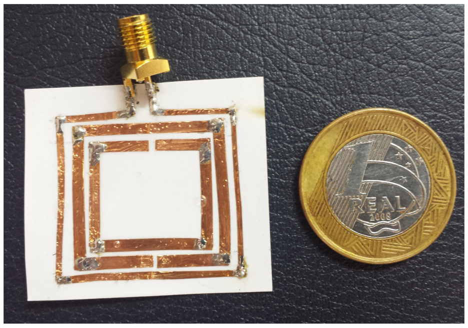


Fig. 7. Physical implementation of the sensing tag on paper.

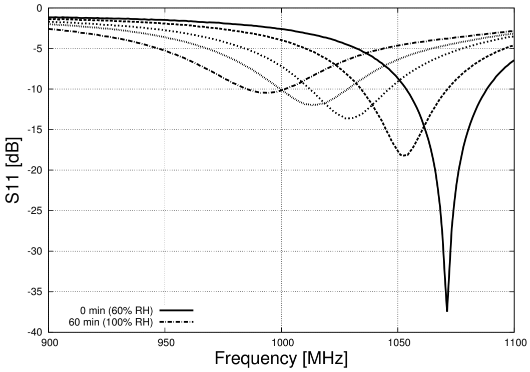


Fig. 8. Reflection coefficient variation of the tag paper without PVA coating in response to relative humidity.

The PVA coating was then applied to the paper tag. 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 frequency variation are shown in Fig. 9 and compared with the no-PVA case. This is also illustrated in Fig. 10 by the percent variation of the resonant frequency normalized at the start point of the measurement (0 min) in each case. The sensitivity definition used for comparing the tags is shown in (9):

$$S = \frac{(f_{res}|_{60min} - f_{res}|_{0min})}{(RH|_{60min} - RH|_{0min})} \tag{9}$$

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 tag without PVA resulted in 1.9 MHz/%RH and, for the case with PVA, in 4.4 MHz/%RH. The results showed that paper tag with PVA has a higher sensitivity than without it, and at the same time both paper tags showed higher sensitivity than the FR4 prototype. The results for all implemented sensing tags are summarized in Table I. As can be observed, experimental results showed that both implemented tags in paper could be used as low-cost wireless sensors, which can be also fabricated with printing techniques.

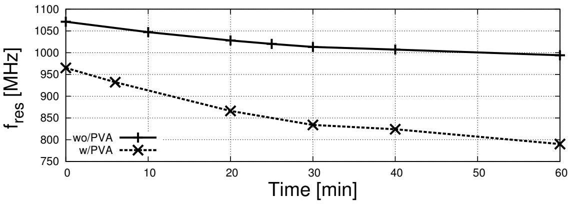


Fig. 9. Resonant frequency of the paper tag vs time (with and without PVA coating).

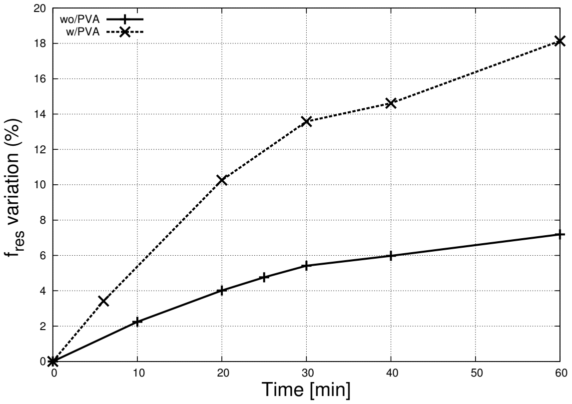


Fig. 10. Normalized percentual variation of the resonant frequency of the paper tag vs time (with and without PVA coating).

TABLE I. SENSING TAGS MEASUREMENT RESULTS: RESONANT FREQUENCY VARIATION DURING ONE HOUR OF EXPERIMENT AND EQUIVALENT SENSITIVITY TO RELATIVE HUMITY.

Tag	Δf_{res} [MHz]	Δf_{res} [%]	S [MHz/%RH]
FR4 + PVA	25	2.5	0.6
Paper	77	7.2	1.9
Paper + PVA	175	18	4.4

V. 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. Passive RFID tags with sensing capabilities have been reported, although the chip of the tag still represents a considerable cost for massive sensor deployment. In the last years, chipless tags have been proposed in order to supply a ultra-low-cost solution for RFID-like tags for identification and sensing. In this paper we proposed a wireless passive sensing tag that works in the frequency mode and is intended for UHF RFID band. The tag design was inspired on small antennas techniques based on metamaterials loading. The metamaterial structure selected was the split-ring resonator, which allowed the miniaturization of the tag and permitted a great sensitivity for the sensor by controlling its distributed capacitance. In addition, the design uses only a single-layer structure, which makes it compatible with printing fabrication processes. Two prototypes on different substrates, FR4 and paper, were fabricated. The simulated radiation efficiency results show the tag could be interrogated wirelessly. The sensitivity was characterized by adapting the tags in order to function as a humidity sensor. This was made by applying a PVA coating. The FR4 prototype showed a measured sensitivity of 0.6 MHz/%RH and in the case of the paper tag, it showed a sensitivity of 4.4 MHz/%RH. Also the paper tag was demonstrated to have a sensitivity of 1.9 MHz/%RH even without the use of the PVA coating due to the porosity of the paper alone. In this way, the tags proved to be suitable for wireless passive sensing and also a low-cost solution fully compatible with printing fabrication processes.

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