RFID Humidity Sensor Tag for Low-cost Applications

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Abstract **─** This article presents a low-cost, flexible, chipless Radio Frequency Identification (RFID) tag for humidity monitoring applications. The tag exhibits moisture sensing feature within a compact geometrical dimension of 20mm x 17.6mm. The design is loaded with 12 resonators, where each resonator represents 1 bit in the frequency domain. For the designed 12-bit tag, 11 inverted C-shaped resonators are dedicated for encoding 11-bit information in their spectral signature.

An integrated meandered-shaped resonator, covered with moisture sensitive Kapton® HN film, functions as a 1-bit moisture sensor. It is deployed for monitoring relative humidity (RH) levels, simultaneously. The passive RFID tag is realized on Taconic TLX-0 and has an operational bandwidth of 2.62 GHz. Furthermore, the design is modeled and analyzed for multiple substrates. The performance of the sensor tag for various humidity levels indicates that it is a potential solution for inexpensive sensing applications.

Index Terms **─** Moisture sensor, radar cross section, relative humidity, RFID.

I. INTRODUCTION

Radio Frequency Identification (RFID) is a wireless data collecting method deployed for automatic identification of distant targets. Billions of items are anticipated to use RFID tags for recognition in near future [1]. This technology has found its applications in identification [2], security and access control, health monitoring systems [3] and asset tracking [4].

Internet of Things (IoT) is an emerging technology which connects multiple smart objects to internet via wired or wireless networks [5]. Wireless sensor networks and RFID constitutes the IoT system. Recent advancements in RFID technology have facilitated their deployment in IoT [6].

The existing RFID technology is categorized as chip-based RFID and chipless RFID. The chip-based RFID tag consists of a silicon chip, used for data encoding, connected to a transceiver antenna. The presence of microelectronic chip makes the system costly and complex [7]. Therefore, research efforts are made to reduce the cost and complexity of individual tags. Passive RFID technique is the ultimate solution for low-cost system design. Integrating passive sensing feature makes RFID tags attractive for various application-specific utilities [8]. The sensing parameters may include temperature, pressure, methane sensing [9], moisture, crack, and strain sensing, etc. Relative humidity (RH) monitoring is an important physical parameter for drugs and food storage, water detection in damaged walls, archives, and buildings [10]. Therefore, the market has a demand for low-cost, reliable and robust RH sensors. Re-transmission based RFID tags perform moisture monitoring by detecting the change in the phase/amplitude of the retransmitted signal. However, limited coding capacity and restricted number of terminating sensors impose the restriction for sensing of multiples nodes simultaneously [11]. To overcome these limitations, frequency-signature based RFID tags with enhanced coding capacity and miniaturized structure are presented in [12-15]. RH monitoring is achieved by the variations resulted in electromagnetic footprint of the tag. Various moisture sensitive materials, e.g., polyvinyl alcohol, gelatin, dextrin and Kapton® HN film are deployed for RH sensing. These polymers show dielectric or conductive variations with humidity levels. Humidity sensor reported in [12] uses hygroscopic, polyvinyl alcohol (PVA), which absorbs moisture and a shift in the

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resonance frequency is observed. A sensor tag designed on paper substrate exhibits moisture sensitivity [13]. A stepped impedance resonator covered with Kapton® HN film polyamide for humidity monitoring in ubiquitous environment is proposed in [14]. A humidity sensor based on polyvinyl alcohol film polyamide as a sensing material is reported in [15].

In this paper, a miniaturized passive RFID tag is presented. Moisture sensing is integrated in the tag by deploying Kapton® HN film. Section II introduces the RFID tag design, followed by data encoding principal in Section III. The detailed sensing mechanism and results are presented in Section IV and Section V respectively. Section VI reflects the conclusion.

II. GEOMETRICAL CONFIGURATION

Based on the data encoding mechanism, the frequency signature tags can be categorized into 're-transmission' or 'backscattered' tags. The re-transmission tags consist of a transceiver antenna and resonators for ID encoding [16]. In the backscattered RFID tags, the structure is excited by an incident plane wave. Each tag generates a unique electromagnetic (EM) response when the plane wave is incident upon it. The information encoded in backscattered signal is evaluated as radar cross section (RCS). This mechanism is used in the presented sensor tag design.

The proposed RFID tag is designed on substrate Taconic TLX-0 having relative permittivity ε_r=2.45 and loss tangent tan δ=0.0019 and a thickness of 0.5mm. The total dimension of the tag is 20mm x 17.6mm. Resonance at a particular frequency is achieved by etching a slot in copper sheet of thickness 0.035mm. The resonator length l corresponding to the desired frequency $\boldsymbol{f}$ is calculated by using the following set of equations:

$$c = f\,\lambda, \quad (1)$$

$$\lambda_g = \lambda\sqrt{\frac{2}{1+\varepsilon_r}}, \quad (2)$$

$$l = \frac{\lambda_g}{4}, \quad (3)$$

where λ indicates the calculated wavelength at central frequency, λ_g is guided wavelength, ε_r is relative permittivity and c is the speed of light in free space.

Initially, a single inverted C-shaped slot is designed and optimized by using Equations (1)–(3). The same design approach is followed to achieve 11-bit encoding RFID tag by using eleven inverted C-shaped slots. The outermost slot R_1 produces a resonance at the lowest frequency, whereas, the inner slot R_{11} resonates at highest frequency. For sensing purpose, a meandered S-shaped structure is incorporated inside the repetitive inverted C-shaped resonators as shown in Fig. 1. The width of individual slots is kept 0.3mm which allows ease of fabrication using the conventional PCB technology.

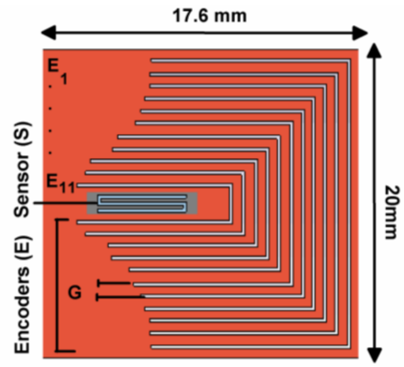

Fig. 1. The proposed RFID sensor tag.

It is observed that if two adjacent slots are placed in close vicinity, then the mutual coupling becomes significant and results in a distorted spectral signature. The effect of noise is minimized by introducing "guard bands" between consecutive resonances. A spectral separation of 200 MHz is maintained between all resonances to eliminate the impact of coupling. This can be controlled by the length l and the separation G between the adjacent slots. Each slot is of different length responsible to produce resonance at particular frequency. The optimized dimensions of RFID tag are summarized in Table 1.

Table 1: Dimensions of RFID tag

Resonator	Length l (mm)	Frequency f (GHz)	Gap	Gaps G (mm)
R_1	41.6	2.98	G_1	0.7
R_2	39.6	3.22	G_2	0.5
R_3	35.8	3.47	G_3	0.6
R_4	33.4	3.72	G_4	0.6
R_5	31.1	3.99	G_5	0.6
R_6	29	4.26	G_6	0.5
R_7	28	4.55	G_7	0.6
R_8	26.2	4.79	G_8	0.7
R_9	26	5.01	G_9	0.6
R_{10}	23.4	5.31	G_{10}	0.55
R_{11}	21.8	5.6	G_{11}	0.7
S	16.2	6.5		

III. DATA ENCODING MECHANISM

The simulations are carried out in commercially available EM software CST MICROWAVE STUDIO® (CST MWS). The tag is excited by using horizontally polarized plane wave. RCS probes are placed at a d = 50mm to observe the backscattered encoded signal. If D is the maximum dimension of the tag and λ is wavelength calculated at central frequency, then far-field distance is calculated by using Equation (4):

$$d = \frac{2D^2}{\lambda}. \quad (4)$$

The tag comprising of only C-shaped encoder slots is simulated and its RCS is studies. Eleven distinct bits, distributed over a frequency range of 2.62 GHz, ranging from 2.98 GHz to 5.60 GHz, are achieved.

A. Multiple ID combinations

The proposed 11-bit ID encoder tag can produce 2^{11} different combinations using logic '1' and '0' which corresponds to presence or absence of a data bit respectively. Figure 2 shows the spectral signature of RFID tag sending all '1'.

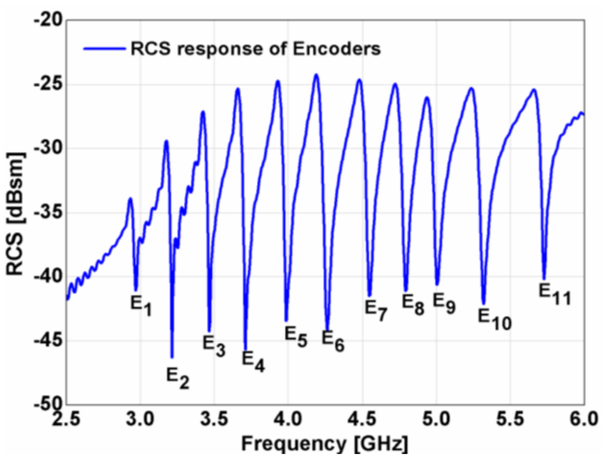

Fig. 2. The RCS response of 11-bit encoder tag.

Different data combinations can be achieved by altering the physical structure of the tag. Figure 3 shows three independent tag IDs '101111111111', '11101111111' and '11111111111'. The RCS comparison in Fig. 3 shows when a slot from a particular position is removed then only the logic state corresponding to that resonator is changed from '1' to '0'. The remaining resonators continue to resonate on the same frequencies.

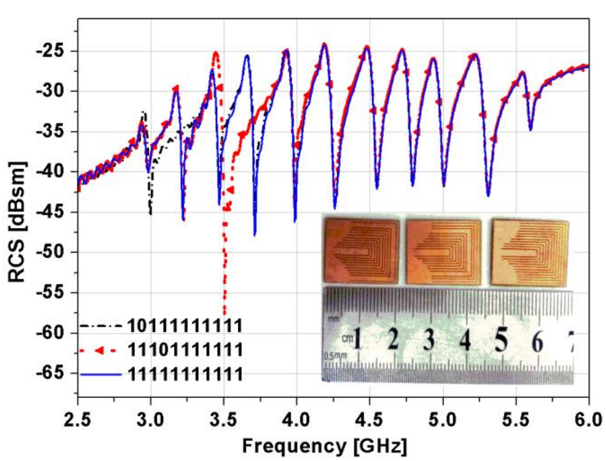

Fig. 3. Shorted tag structures and their RCS.

B. Performance analysis of different tags

Initially, the tag is designed on Taconic TLX-0 substrate with copper as a radiating material having thickness 0.035mm. Furthermore, the tag is designed and analyzed on low-cost substrates, Rogers RT Duroid 5880 and Polyethylene Terephthalate (PET). The comparison for multiple substrates is presented in Fig. 4, without altering the geometrical parameters of the designed tag presented in Table. 1.

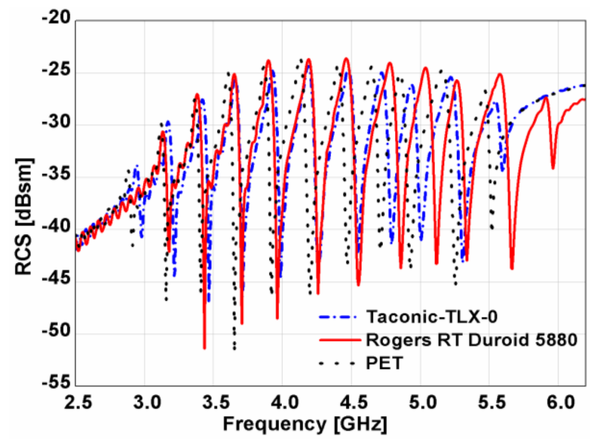

Fig. 4. RCS response for different substrates.

1) Taconic TLX-0

The properties and analysis for Taconic TLX-0 substrate are presented in Section A. It can be seen in Fig. 4 that the overall bandwidth of designed tag is 2.62 GHz, where most significant bit (MSB) produces a resonance at 2.98 GHz, and least significant bit (LSB) resonates at 5.6 GHz.

2) Rogers RT Duroid 5880

The same prototype is designed on Rogers RT Duroid 5880 substrate with a dielectric constant ε_r=2.33, loss tangent tan δ=0.0002 and thickness 0.254mm. The complete band of operation is 2.77 GHz, where MSB resonates at 3.19 GHz, and LSB resonates at 5.96 GHz depicted by Fig. 4.

3) Polyethylene Terephthalate (PET)

The presented RFID tag is designed on a thin, low-cost substrate, PET, to incorporate the flexibility feature. The substrate has a thickness of 0.255mm, dielectric constant εr=3.2 and loss tangent tan δ=0.022. The analysis presented in Fig. 4 shows that the tag designed on PET requires the minimum frequency band for data encoding. In this case, the MSB is observed at 2.91 GHz, and LSB is present at 5.52 GHz.

The comparison of multiple substrates proves that the tag designed on PET substrate provides the best solution in term of flexibility and cost. Another prominent feature of the PET-based tag is the efficient band utilization. It uses a spectrum of 2.61 GHz to data.

IV. HUMIDITY MONITORING

The integration of a sensing mechanism in RFID tag enables it to provide information about the state of identified object. Relative humidity *RH* is an important parameter for various moisture sensitive applications such as drugs storage, cold storage for a large quantity of food, etc. For this purpose Kapton® HN film with loss tangent tan δ=0.0026, dielectric constant ε_r=3.5 and thickness 0.1mm is used as a hygroscopic sensitive polymer. Its relative permittivity varies with the slight variations in humidity level. Kapton® HN film possesses linear dielectric change with humidity [17] given by Equation (5):

$$\varepsilon_r = 3.05 + 0.008 \times RH. \quad (5)$$

For sensing purpose, a meandered S-shaped structure has been proposed inside the repetitive inverted C-shaped resonators. The S-shaped structure is covered with an adhesive tape of Kapton® HN dielectric film of thickness 0.1mm. The presented sensor tag has compact size and efficient band utilization.

The moisture sensitive nature of the film introduces drift in the resonance frequency of the slot, as indicated in Fig. 5. The sensing trend of the moisture tag in an ambient environment is investigated for different humidity levels. The resonance frequency is shifted to lower values with the increase in %RH. When the humidity level is incremented from 30% to 100%, the resonance is drifted from 6.7 GHz to 6.55 GHz. An overall shift of 150 MHz in the frequency spectrum is observed for the variations in %RH. However, the bits generated by the encoder slots remain unaffected by the change in the sensor resonance frequency.

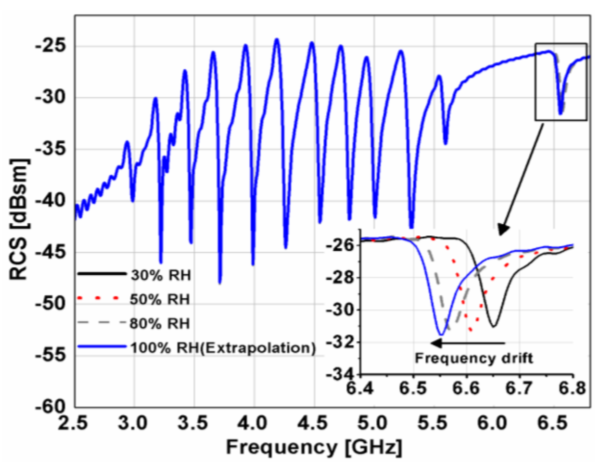

Fig. 5. RCS response of the sensor tag.

The additional sensing functionality in the designed RFID tag equips a conventional package with intelligence to monitor environmental humidity variations and inform the customer about product condition. Henceforth, the sensor integration enables the deployment of the proposed design for various Internet of Things (IoT) and smart sensing applications. A comparison of presented research and previously proposed work [12-14] is shown in Table 2.

Table 2: Comparison of designed tag

Feature	Ref. [12]	Ref. [13]	Ref. [14]	Present Work
Substrate	Taconic TLX-0	Taconic TLX-0	Taconic TLX-0	PET, Roger 5880, Taconic TLX-0
Size (mm)	17x7.5	15x6.8	50x3.45	17.6x20
Trans. bits	4	6	4	12
Flexibility	No	No	No	Yes
Sensing	Yes	Yes	Yes	Yes

V. RESULTS AND DISCUSSION

The proof of concept RFID tag is fabricated on Taconic TLX-0 substrate. The experimental setup deployed, is shown in Fig. 6.

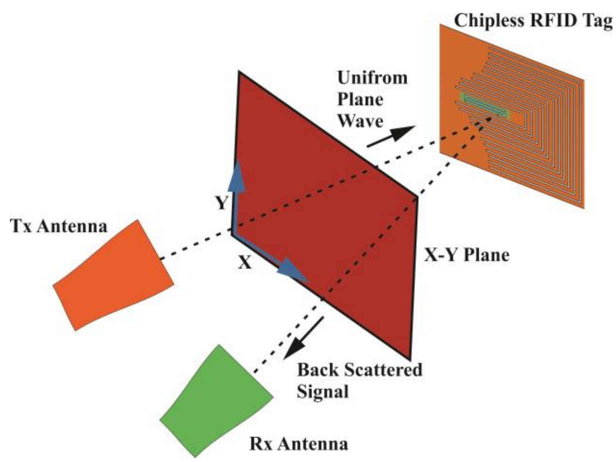

Fig. 6. Experimental setup.

It consists of two horn antennas; Tx is used to illuminate the chipless RFID tag with an incident plane wave, whereas the backscattered response observed by the antenna Rx. The two port vector network analyzer (VNA) R&S®ZVL13is used inside the climate chamber Weiss Technik WK11-180 to investigate the variations in the frequency response of the sensor tag for various humidity levels.

The experimental setup represented by the block diagram in Fig. 6 is used to calibrate the results. A comparison between the computed and measured results is shown in Fig. 7. It can be seen that the measured results are in good agreement with the simulated results.

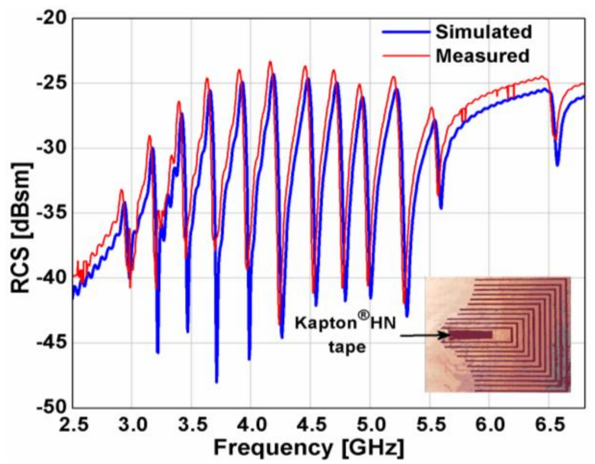

Fig. 7. Computed and measured results.

V. CONCLUSION

A passive RFID tag for 12-bit information encoding is proposed. It provides an inexpensive solution for RH monitoring in wireless communication. The prototype is designed and analyzed on Taconic TLX-0, Rogers RT Duroid 5880 and flexible Polyethylene Terephthalate (PET). In the proposed design, the slots are arrayed so that mutual coupling can be avoided among the resonators and optimized lengths of slots yield the resonances in a squeezed band. Kapton® HN adhesive film is used as sensing material. A shift in resonant frequency is observed with the variation in humidity levels. Therefore, the proposed tag is a potential candidate for data encoding and humidity monitoring for low-cost applications.

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