Miniaturized Elliptical Slot Based Chipless RFID Tag for Moisture Sensing

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Abstract **─** This paper presents a compact 10-bit chipless radio frequency identification (RFID) sensor tag. The proposed structure has overall size of 22.8 mm×16 mm and possesses the capability of identification of data as well as moisture sensing of the tagged objects. The resonating structure comprises of elliptically shaped slots in a nested loop manner, investigated for three substrates that are Rogers RT/duroid®/5880, Taconic (TLX-0) and Rogers RT/duroid ®/5870. The prototype is fabricated by using Rogers RT/duroid®/5880, and moisture sensing is realized by deploying heat-resistant sheet of Kapton®HN (DuPontTM) on the smallest slot considered as sensing slot over the aspired frequency spectrum of 3.5 GHz-15.5 GHz. The proposed tag is quite suitable for cost effective applications and can be deployed on the conformal surfaces for identification and sensing purposes.

Index Terms **─** Chipless tag, moisture sensor, Radio Frequency Identification (RFID).

I. INTRODUCTION

The chipless RFID as contactless identification technique plays a vital role in RF sensing of low-cost item-level tagging along with identification. In the literature, different smart materials have been explored for temperature, moisture, strain and gas sensing in various chipless RFID tags [1]. Chip based RFID tags require silicon chip or integrated circuit for operation which makes the tag economically less viable [2]. In contrast with conventional RFID systems, chipless tags require neither an integrated chip, battery or power source nor a complex mechanism needed for interrogation of binary data between transmitter and receiver. Various flexible substrates such as paper and printing techniques like flexography have been analyzed to make the tag robust and less expensive [3]. Data-dense, compact and humidity sensor tag incorporating moisture absorbing polyvinyl-alcohol is used to monitor real-time humidity in the environment of tagged objects [4]. In the modern technological era, ceaseless development of internet of things (IoT) [5-6] facilitates the task automation by inclusion of wireless sensors and efficient home monitoring system using different internet protocols [7]. Application specific RFID tag fabricated on a low-cost paper substrate for efficient frequency band allocation and applications focusing on time and data identification using frequency shift encoding technique has been reported in [8]. Deposition of various moisture sensitive materials on the resonators/slots to make the tag capable of monitoring humidity has also been explored in recent works. Fully passive chipless RFID tag can be deployed on curved surfaces by using organic and flexible substrates such as paper-based tags [9-10].

Inductor-capacitor based humidity sensor tag provides a less expensive solution for tagging of millions of objects [11]. Multi-resonator chipless RFID tag optimized using Taconic substrate within the small size can be used for many industrial and IoT based applications [12]. The change in permittivity of the superstrate above the substrate using backscattering phenomenon is another approach to investigate the humidity sensing in chipless tags [13-14]. The reliable system of measurement is designed to monitor the read range of tag and humidity sensing behavior presented in [15]. The parameters of interest while designing the resonant element include shape, dimensions, and structure like ring-shaped tag structure using paper substrate [16], FSS based square shaped concentric loop tag design [17] and C-shaped chipless RFID tag [18]. Researchers are focused on achieving high data capacity and compactness in smart tags by introducing novel structures capable to perform sensing.

This research work presents a symmetric, moisture

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sensitive and data-dense fully passive chipless RFID tag. A novel elliptically shaped slot resonator is designed to store massive data within a small size of 3.648 cm^2. While maintaining the bit density of 2.74 bits/cm^2, the proposed structure is geometrically optimized and comparatively investigated for three distinct substrates. Using Rogers RT/duroid®/5880 as a substrate, flexibility is accomplished over the operational RF band of 3.5 GHz-15.5 GHz. Furthermore, the most attractive feature of the presented tag is moisture sensor integration using Kapton® HN tape on the smallest slot along with being compact and flexible, in comparison with the recently published research work.

II. OPERATION MECHANISM

The proposed chipless RFID tag works on backscattering technique. The backscattering principle works with RFID reader (transceiver with antenna) and the chipless tag. The two main components of the RFID measurement system which play a vital role in the generation and reception of a signal from the chipless tag are VNA (vector network analyzer) and antenna subsystem. The function of VNA is to analyze the transmitted signals impinged on the tag and the backscattered signals that are reflected towards the reader. The antenna subsystem is responsible for transmission and reception of signals.

Incident plane EM waves are used to energize the RFID tag when placed in the vicinity of the reader. The chipless RFID tag absorbs electromagnetic waves transmitted by the reader. These EM waves when impinged on the tag, stimulate the current on the conductive layer of the resonating structure. In response to this, the modulated backscattered signals are returned towards the reader. This technique is called "backscattering" in which encoded data from the tag containing the exclusive tag IDs are used for tracking of tagged objects as illustrated in Fig. 1.

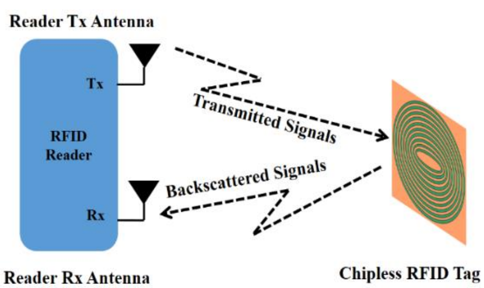

Fig. 1. Backscattering mechanism.

The proposed chipless tag design presented in this research article consists of elliptical slotted structures in a nested loop manner. The realized tag is placed at far field distance for the efficient measurement of RCS response. The Fraunhofer distance can be precisely calculated from (1):

$$R = 2D^2/\lambda, \tag{1}$$

here R represents far field distance, D signifies the longest dimension of the tag and λ denotes wavelength. There is an inverse relation of frequency with the wavelength. Hence, wavelength can be found from (2):

$$\lambda = c/f, \tag{2}$$

where, c indicates speed of light and its value is 3×10^8 m/s and f symbolizes centre frequency.

III. CHIPLESS TAG DESIGN

The design and analysis of chipless RFID tag is highly focused on maximizing the bit capacity to size ratio. The in-depth analysis of areas consumed by different shapes helped us to reach a compact structure. The proposed elliptic tag provides enhanced performance in comparison with conventional circular slot-based tag and Fig. 2 is provided to signify the choice of the structure. The resonance frequency of a particular slot can be calculated using (3):

$$f_r = \frac{c}{2A}\sqrt{\frac{2}{\epsilon_r + 1}}, \tag{3}$$

here, c represents speed of light, A symbolizes the dimension of the largest slot and ϵ_r is the relative permittivity. As per this equation, the larger slot produces resonance at smaller frequency. It is worth noticeable in Fig. 2 that the elliptical slot consumes less area and is able to produce resonance at smaller frequency in comparison with the circular configuration. This can be explained by carefully evaluating the design parameters of circle and ellipse. The area of circle is defined by only one parameter, i.e., radius. The overall area of the ellipse is controlled by major and minor axis. The two design parameters provide space for further optimization and hence, prove the elliptical structure a finest choice for the tag design.

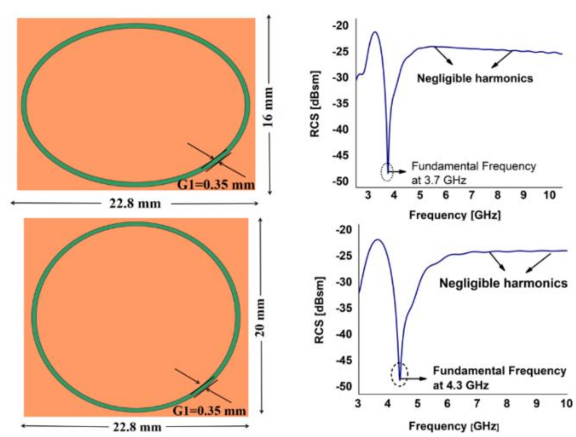

Fig. 2. Comparison between circular and elliptical slot.

A compact, miniaturized and passive chipless RFID tag structure loaded with slots in nested loop fashion with its geometric parameters is shown in Fig. 3. Rogers

RT/ duroid®/5880 having thickness of 0.508 mm, Rogers RT/duroid®/5870 with the thickness of 0.787 mm, and Taconic TLX-0 having thickness 0.635 mm are three substrates used for tag optimization. The area consumed by the compact tag design in all cases is 22.8 mm×16 mm. The length of minor axis is labelled as *M1*=11 mm, while the length of the major axis from the origin is represented as *M2*=7 mm. Slots are etched out from copper cladding with the thickness of 35µm. There are ten slots corresponding to ten bits generating 2^{10}=1024 multiple unique tag IDs. The tag is optimized in such a way that sharp resonances are produced at different frequencies in RF band of 3.5 GHz-15.5 GHz. The uniform width of slot *G1* is 0.35 mm, while the space between two neighboring slots is denoted by *G2* = 0.4 mm. The length of the minor axis of the innermost slot *E* and the height of the outer most ellipse *A* are 1.1 mm and 15.4 mm, respectively. Furthermore, *S2*=0.4 mm and *S1*=0.3 mm are the perpendicular and horizontal distances of the tag from the outermost slot, respectively. Incident plane wave is used for exciting the RFID tag and the presence of slot produces logic state "1" while a shorted slot generates logic state "0" which results in absence of that particular resonance in the RCS curve. After the successful optimization and analysis of single elliptical slot, additional number of resonators are added in the structure in a similar way. The proposed design is simulated, geometrically analyzed and optimized using CST Microwave Studio Suit®.

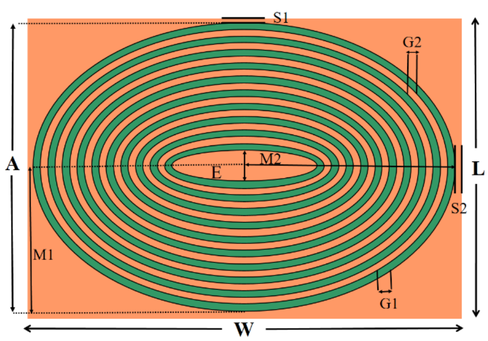

Fig. 3. Layout of proposed chipless RFID tag.

IV. RESULTS AND DISCUSSION

This section demonstrates the measured and computed RCS response of the proposed flexible, robust and ten-bit chipless RIFD tag. The presented tag design is examined for three dissimilar substrates, Rogers RT/duroid®/5880, Taconic TLX-0 and Rogers RT/duroid®/5870. The results are recorded in terms of different data encoding combinations for identification of tagged objects. It is observed from the results that changing the electrical properties of the substrate shifts the RCS graph on the frequency axis. The comparative analysis of the tag examined using different substrates is also discussed in this section and given in Table 1. The experimental arrangement consists of transmitting and receiving antennas and vector network analyzer (VNA) model R&S ZVL-13 for testing the fabricated sample of the proposed tag in the standard environment. The tag is positioned at the far-field distance of 32 mm to observe the RCS response. The fabricated prototype of the proposed chipless tag in comparison with euro coin is presented in Fig. 4.

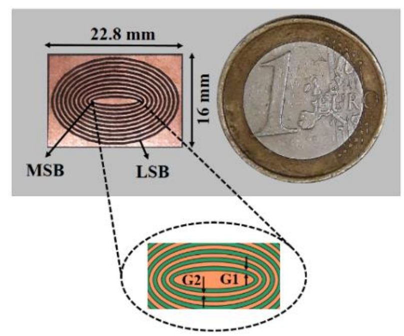

Fig. 4. Fabricated prototype of chipless tag.

A. Rogers RT/duroid®/5880 substrate

The frequency signatures of the articulated tag in terms of computed and measured RCS response with flexible laminate Rogers RT/duroid®/5880 is illustrated in Fig. 5 (a). The RFID tag design covers the operational RF spectrum from 3.5 GHz to 15.5 GHz and yields ten bits with unique tag ID: 1111111111. Sharp and clear resonances are observed, and every single resonance corresponds to one data bit. Figure 5(b) illustrates the arbitrary data encoding sequences that can be accomplished by adding and subtracting slots in the proposed structure generating two unique tag IDs: 0101111111 and 0000000000. Here "0" represents shorted slot and omission of a dip in the RCS graph. The proposed tag demonstrates acceptable agreement with measured and computed results.

Table 1: Comparison of proposed tag with various substrates

Characteristics	Rogers RT/duroid®/5870	Taconic TLX-0	Rogers RT/duroid®/5880
Thickness (mm)	0.787	0.635	0.508
Loss Tangent	0.0009	0.0019	0.0009
Permittivity	2.2	2.45	2.2
Radiator	Copper	Copper	Copper
Flexibility	×	×	✓
Freq. Band (GHz)	3.7-15	3.5-14.9	3.5-15.5

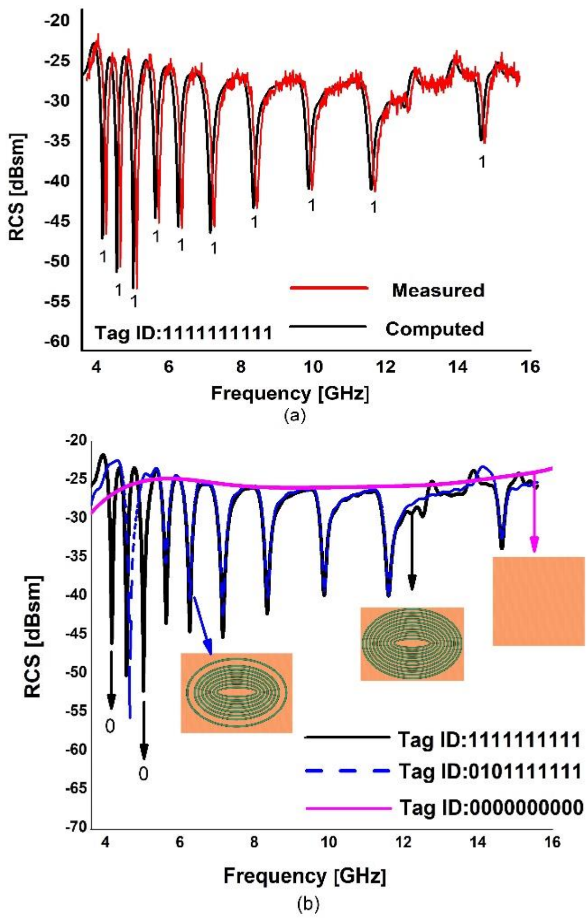

Fig. 5. (a) Simulated and measured results, and (b) RCS response with different bit sequences.

B. Taconic TLX-0 substrate

The optimized tag design by using the Taconic TLX-0 substrate with thickness 0.635 mm (∊r = 2.45) has ten bits as shown in Fig. 6. The RCS response of the tag illustrates ten resonance dips and covers the bandwidth of 11.4 GHz. It is observed from results that the most significant bit appears at 3.5 GHz, and the least significant bit is produced at 14.9 GHz.

C. Rogers RT/duroid®/ 5870 substrate

The proposed symmetric geometric structure is analyzed for Rogers RT/duroid®/5870 with the thickness 0.787 mm and loss tangent tan δ=0.0009. Figure 6 depicts the RCS magnitude response of the proposed structure in the squeezed frequency spectrum of 3.7 GHz -15 GHz.

The surface current distribution of the formulated slotted structure by using Rogers RT/duroid®/5880 laminate at the lowest frequency of 3.5 GHz is presented in Fig. 7 (a). The metallic portion acts as capacitive part while the non-metallic part behaves as an inductive element. The maximum concentration of current represents the inductive effects. The low intensity of the current indicates the capacitive effects. Figure 7 (b) indicates the surface current intensity at the highest frequency of 15.5 GHz.

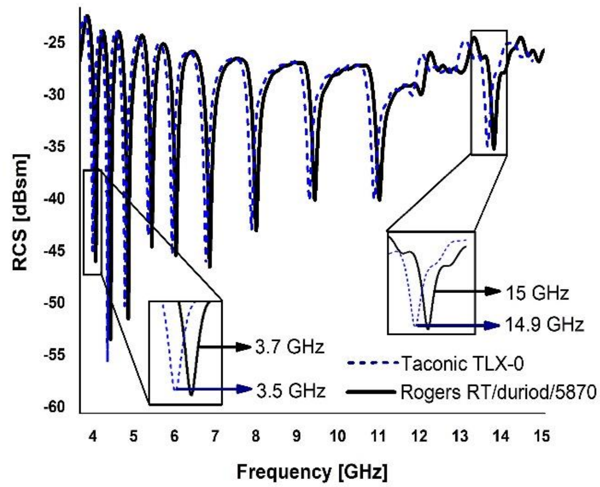

Fig. 6. RCS response with various substrates.

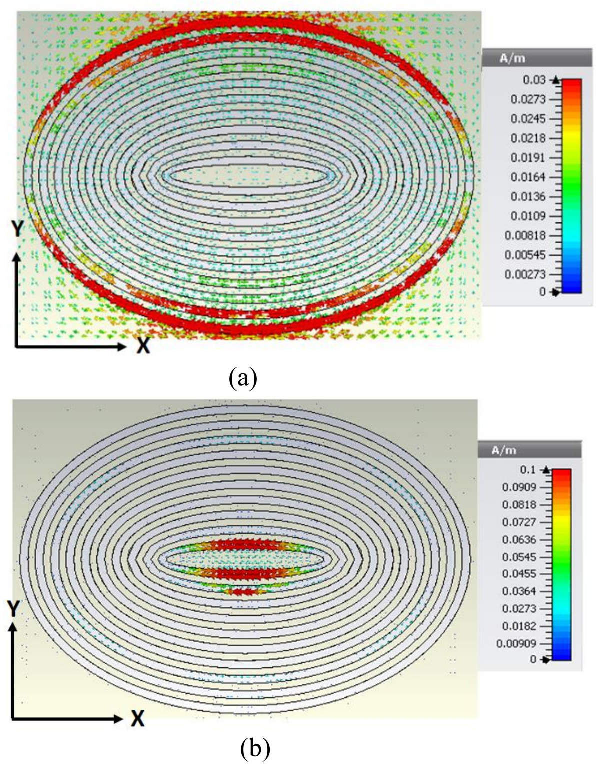

Fig. 7. (a) Current density at minimum frequency, and (b) current density at maximum frequency.

V. MOISTURE SENSOR

The proposed RFID tag holds an additional feature of moisture sensing when the heat-resistant polyamide sheet of Kapton® HN is incorporated into the structure. For this purpose, multiple steps are performed for the proposed symmetric tag. We use Rogers RT/duroid®/5880 as substrate, and place thin sheet of the Kapton® HN with the thickness of 0.125 mm on the smallest slot. Here, Kapton HN tape is used for sensing purpose and absorbs moisture from the surroundings. This feature of Kapton enhances its usage for the moisture sensitive applications such as the food industry (cold storage eatables) and drug storage [14].

The change in the percentage of relative humidity level will alter the permittivity (∈r = 3.5) of Kapton film which results in the shifting of resonances associated with sensing slot towards the left side in the RCS curve [11]. The linear change in permittivity level with relative humidity [20-21] of Kapton® HN is demonstrated in (4):

$$\epsilon_r = 3.05 + 0.008 \times RH. \quad (4)$$

To experimentally analyze the moisture sensing performance of proposed chipless tag, climatic chamber by Weiss Technik WK11-180 is used to investigate the sensor response of the tag for numerous humidity levels. As shown in Fig. 8, every 20% increase in moisture level shifts the resonance frequency of the sensing slot towards the lower side.

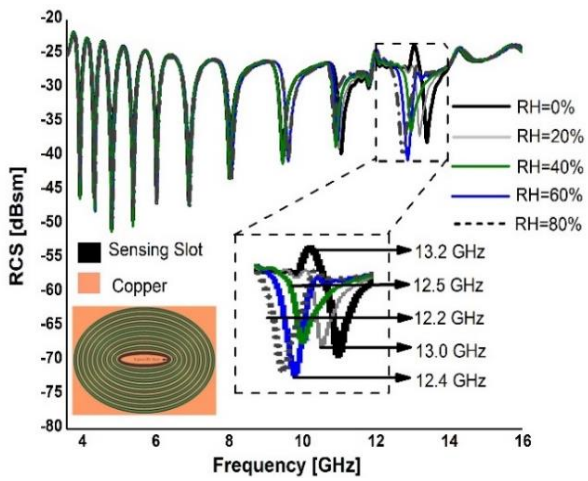

Fig. 8. RCS response for moisture sensing.

It is observed that when the % RH increments from 20% to 80%, the overall response of the tag shifts and the resonance frequency of sensing slot starts drifting from 13.2 GHz to 12.2 GHz. Thus, the integration of moisture sensing in proposed chipless RFID tag makes it novel as no external circuit is required for sensing purpose and it can be easily deployed for various smart sensing applications. The formulated tag provides the additional advantages of compactness, symmetry, flexible nature, low-cost, robustness, and moisture sensing.

The comparative analysis of the elliptically shaped tag with previously published research articles is demonstrated in Table 2.

Table 2 illustrates that proposed tag design has the ability to encode 10-bits over the miniaturized footprint of 3.648 cm^2. In contrast with other tag designs, the presented tag yields a high bit density of 2.74 bits/cm^2 with the additional feature of humidity sensing using flexible laminates.

VI. CONCLUSION

A novel, compact, robust and flexible 10-bit moisture sensing chipless RFID tag over the miniaturized dimensions of 22.8 mm × 16 mm is presented in this research article. The RCS response of the elliptically shaped tag design is optimized and investigated for three distinct substrates, i.e., rigid Rogers RT/duroid®/5870, flexible Rogers RT/duroid®/5880 and Taconic TLX-0. The proposed structure has the capacity to generate 2^{10}= 1024 exclusive IDs with the additional functionality of moisture sensing. Kapton®HN tape is used as moisture sensitive material on the shortest slot within a squeezed frequency band from 3.5 GHz to 15.5 GHz, and a shift in resonant frequency is observed by increasing the moisture level. Flexible nature of the realized chipless tag by using Rogers RT/duroid®/5880 substrate enhances its attractiveness for its deployment on bendable surfaces. Hence, the presented symmetrical geometric structure is a potential candidate for data encoding and various low-cost moisture sensitive applications.

Table 2: Comparison with already published work

Parameters	L-shape [10]	Rectangle [12]	Square [17]	E-shaped [19]	Ellipse Shape
Size [cm^2]	7.14	3.387	20.25	17.7	3.648
Tran. Bits	8	6	3	8	10
Bit density [Bits/cm^2]	1.120	1.771	0.14	0.45	2.74
Flexibility	✓	×	✓	×	✓
Sensing	✓	×	✓	×	✓

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