Directly Printable Frequency Signatured Chipless RFID Tag for IoT Applications

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Abstract. *This paper proposes a low-cost, compact, flexible passive chipless RFID tag that has been designed and analyzed. The tag is a bowtie-shaped resonator based structure with 36 slots; where each patch is loaded with 18 slots. The tag is set in a way that each slot in a patch corresponds to a metal gap in the other patch. Hence there is no mutual interference, and high data capacity of 36 bits is achieved in such compact size. Each slot corresponds to a resonance frequency in the RCS curve, and each resonance corresponds to a bit. The tag has been realized for Taconic TLX-0, PET, and Kapton®HN (DuPont™) substrates with copper, aluminum, and silver nanoparticle-based ink (Cabot CCI-300) as conducting materials. The tag exhibits flexibility and well optimized while remaining in a compact size. The proposed tag yields 36 bits in a tag dimension of* 24.5×25.5 *mm*^{2}*. These 36 bits can tag* 2^{36} *number of objects/items. The ultimate high capacity, compact size, flexible passive chipless RFID tag can be arrayed in various industrial and IoT-based applications.*

Keywords

Chipless, Radio Frequency Identification (RFID), Radar Cross-Section (RCS), backscattering

1. Introduction

Internet of things (IoT) is a combination of number of smart objects, connected via wired/wireless networks to the internet [1–5]. RFID and wireless sensor networks (WSN) are major entities of IoT system. Latest developments in RFID have enabled IoT [6]. RFID is an emerging contactless data capturing technology which is widely used for tracking purposes, theft control, health monitoring, food monitoring, luggage tracking, clothing, electronic cards and pollution control, etc., [7]. An estimated 75 billion products equipped with RFID tags will be sold yearly till the year 2019 [8]. RFID has to upswing for the latest requirement of IoT development and emergence to meet the demands of modern era [9]. Limitations of RFID technology are cost, reliability and recycling aspects [10]. The main hindrance in RF identification deployment depends on its cost per tag [11]. The emerging aspect of RFID technology and such limitations have motivated the researchers to move towards chipless tags that outperform compared to conventional chip-based tags hence tremendously reducing the cost compared to chip-based tags [10], [12]. Chipless RFID involves information coding in the form of electromagnetic signature (EMS) [13]. Chipless RFID does not need any communication protocol for identification process [13]. The most promising benefit of chipless RFID tag is that they can be printed directly on the products [8]. The reliability and versatility of chipless RFID tags can be depicted from the fact that they can replace ten trillion barcodes yearly [8].

Chipless RFID has been an interesting field for researchers because of some challenging features like enhancing the coding capacity, miniaturization, within a suitable frequency band and an enhanced read range [12]. A number of papers have appeared addressing various such aspects [12], [14–16]. One of the major aspects is to enhance data density while maintaining a suitable tag size in a reasonable frequency band [12]. Various researchers have addressed such aspect [12], [17–28]. In [29], a 3.8 bits/cm^2 compact polarization independent, discrete slot ring resonator based chipless RFID tag has been proposed. It gives back-scattered frequency signature in a compact size with enhanced coding capacity. Another spurline resonator based chipless RFID tag in a size of 40×27 mm^2 yielding 8-bit data capacity has been proposed [30]. In [27], a low-profile data encoding chipless RFID tag is designed. In this design, the data is encoded as complex natural resonances (CNRs) on the structure within an area of 24×24 mm^2 yielding 24-bit data. Similarly, a compact, flexible 24-bit dual polarized chipless RFID tag in a size of 20.6×19.9 mm^2 is designed [7]. It discusses flexibility in very compact size.

In this paper, a novel 36-bit chipless RFID tag is presented. The novelty of the tag relies on its flexibility, compact size and high data capacity of 36 bits, which has not been done so far in such a compact size. Also, the tag is

Parameters	Tag-1	Tag-2	Tag-3	Tag-4	Tag-5
Substrate	Taconic TLX-0	PET	PET	Kapton®HN	Kapton®HN
Permittivity	2.45	2.9	2.9	3.5	3.5
Radiator	Copper	Aluminum	Silver nano ink	Aluminum	Silver nano ink
Thickness [mm]	0.035	0.007	0.015	0.007	0.015
Trans. bits	36	36	36	36	36
No. of tagged objects	68,719,476,736	68,719,476,736	68,719,476,736	68,719,476,736	68,719,476,736
Freq. band [GHz]	5–15.5	5.3–18.2	4–18.2	5–17	4–17
Size [mm^2]	27 × 26	24.5 × 25.5	24.5 × 25.5	24.5 × 25.5	24.5 × 25.5
Flexibility	x	✓	✓	✓	✓

Tab. 1. Characteristic comparison table.

equipped with flexibility which is the recent requirement of RFID industry applications especially green electronics. PET and Kapton®HN are considered in the tag as flexible substrates, whereas, silver nanoparticle-based ink is used for cheap printability of the design. The conductivity of nanoparticle-based ink is 9×10^6 S/m.

The tag is a resonator based structure that is excited by a linear polarized incident plane wave in a tag dimension of 24.5 × 25.5 mm^2. Firstly, copper is used as a radiator for the Taconic TLX-0 substrate to achieve desired RCS response. Then, aluminum and silver nanoparticle-based ink are deployed as a radiator for PET and Kapton®HN substrates to achieve printability along with flexibility in a reduced tag design. The entire tag yields a data capacity of 36-bit, hence 2^{36} number of objects can be tagged. The frequency ranges for Taconic TLX-0 along with copper as the radiator is 5–15.5 GHz, for PET along with aluminum is 5.3–18.2 GHz and 4–18.2 GHz with silver nanoparticle-based ink. The frequency range for Kapton®HN along with aluminum as the radiator is 5–17 GHz and 4–17 GHz for silver nanoparticle-based ink as a radiator.

2. Theory and Fundamental Principle

RFID involves electromagnetic waves to identify a tagged object [13] remotely. The tag is a resonator structure, where each slot corresponds to one dip and each dip corresponds to one bit. Hence 36 slots yield 36 bits data density. 36-bit tag is designed using CST STUDIO SUITE®. The tag is excited by using linearly incident plane wave. The E-field plane wave equation is given as

$$\mathbf{E}(x,y,z,t) = E_0 \exp\left[\mathrm{j}\left(wt - kz\right)\right]\hat{\mathbf{x}} + E_0 \exp\left[\mathrm{j}\left(wt - kz + \frac{\pi}{2}\right)\right]\hat{\mathbf{y}} \quad (1)$$

where **E** is an electric field, w is the angular frequency, t is time, k is wave vector, (x,y,z) is the position vector.

Chipless RFID tags are classified as retransmission based tags and backscattering based tags [31]. The main working principle of chipless RFID tags is backscattering. Identification is based on unique frequency signature generation in a desired frequency range that is measured as radar cross-section (RCS) of the tag [12], [32]. The radar cross-section (RCS) versus frequency shows the electromagnetic behavior of tags. The RCS is analyzed at far-field distance given by Fraunhoffer distance formula

$$R = \frac{2D^2}{\lambda} \quad (2)$$

where D is the radiator's largest dimension and λ is the wavelength of radio wave [33].

To measure RCS response of chipless RFID tag, we need two antennas: one for transmitting and the other for receiving. Reader antenna sends an electromagnetic wave (EW) also known as '*interrogator signal'* towards the tag [34]. The tag then encodes the data information in that signal and sends the '*backscattered signal'* containing encoded information towards the reader [35]. The back-

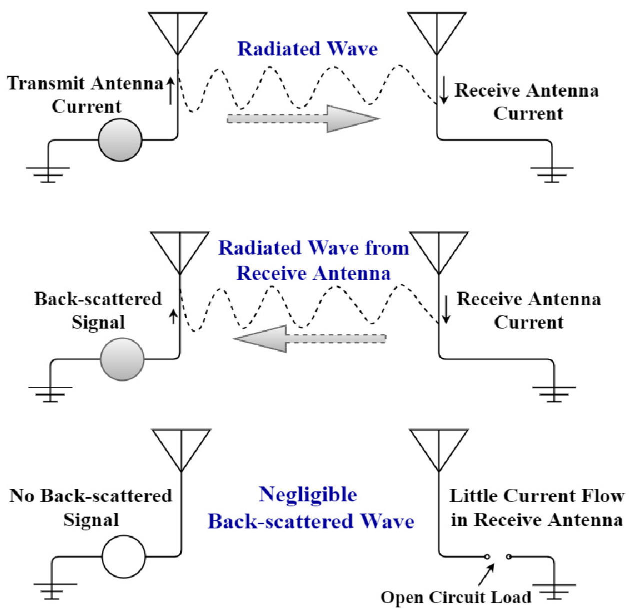

Fig. 1. Simplified physics of backscattering phenomena.

Parameters		Tag-1		Tag-2		Tag-3		Tag-4		Tag-5	
Substrate		Taconic TLX-0		PET		PET		Kapton®HN		Kapton®HN	
Radiator		Copper [mm]		Aluminum [mm]		Silver nano-particle-based ink [mm]		Aluminum [mm]		Silver nano-particle-based ink [mm]	
Slot width	Metal width										
*S*1	*M*1	0.3	0.2	0.4	0.5	0.5	0.4	0.6	0.3	0.6	0.3
*S*2	*M*2	0.3	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
*S*3	*M*3	0.3	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
*S*4-*S*32	*M*4-*M*32	0.3	0.2	0.3	0.2	0.3	0.2	0.3	0.2	0.3	0.2
*S*33	*M*33	0.3	0.3	0.3	0.6	0.3	0.6	0.3	0.6	0.3	0.6
*S*34	*M*34	0.3	0.3	0.3	0.5	0.3	0.5	0.3	0.5	0.3	0.5
*S*35	*M*35	0.6	1	0.6	0.7	0.6	0.7	0.6	0.7	0.6	0.7
*S*36	*M*36	0.4	0.9	0.4	0.7	0.4	0.7	0.4	0.7	0.4	0.7

Tab. 2. Proposed tags dimensions.

scattered signal contains unique frequency signature for identification. So, there is no need for any integrated circuit to encode the data. Figure 1 shows the backscattering phenomenon.

The power received from a transmitting antenna by a receiving antenna is given by Friis transmission equation [36]

$$\frac{P_{\mathrm{RX}}}{P_{\mathrm{TX}}} = \left(\frac{\lambda}{4\pi r}\right)^2 G_{\mathrm{TX}} G_{\mathrm{RX}} \tag{3}$$

where r is the distance between transmitter and receiver, G_{TX} and G_{RX} are the gain of the transmitter and receiver, P_{TX} is power transmitted and P_{RX} is power received.

All the tagged items/objects should lie in the read range/working space of system for proper RFID operation [37]. The maximum theoretical read range of chipless RFID system can be calculated from (4) [23], [38]

$$R^{\max} = \sqrt[4]{P_{\mathrm{TX}} G_{\mathrm{TX}} G_{\mathrm{RX}} \frac{\lambda^2}{(4\pi)^3 P_{\mathrm{RX}}} \sigma_{\min}} \tag{4}$$

where P_{TX} is transmitting power, G_{TX} is transmitting antenna gain, G_{RX} is receiving antenna gain, λ is the wavelength, P_{RX} is the sensitivity of the receiver and $\sigma_{\min}$ is the most minimum RCS level possible to be detected by the reader.

3. Proposed Tag Design

The proposed tag is loaded with 36 slots, each of varying length in a tag dimension of 24.5×25.5 mm^2. Each slot is numbered according to its length. Each slot of different length corresponds to a dip that resonates at a particular frequency. So there are 36 dips corresponding to 36 bits yielding 2^{36} number of possible tag ID combinations. The tag is designed in a way that each slot in upper patch corresponds to metal in the lower patch and vice versa. Therefore, the slots are at alternate positions with metal gaps for adjacent patches. Hence, each slot will be of different length, resonating at a different frequency. Ultimately, there will be no mutual coupling and high dense data in a compact size is achieved while fully utilizing the frequency band. The proposed tag design is shown in Fig. 2.

There are five tags that have been designed using Taconic TLX-0, PET, and Kapton®HN substrates along with copper, aluminum and silver nanoparticle-based ink as radiators. We can analyze that along with changing substrate and radiator; there is variation in tag electrical properties. The tag has been designed and optimized for different substrates, so there is a slight variation in dimensions while optimizing the tag for flexible substrates. The detailed characteristic comparison of all the tags is shown in Tab. 1. It can be observed from Tab. 1 that the tag has been initially designed for the Taconic TLX-0 substrate. Then the tag has further been optimized for PET substrate to achieve flexibility. To meet the modern application requirements there is a trade-off between the bandwidth and

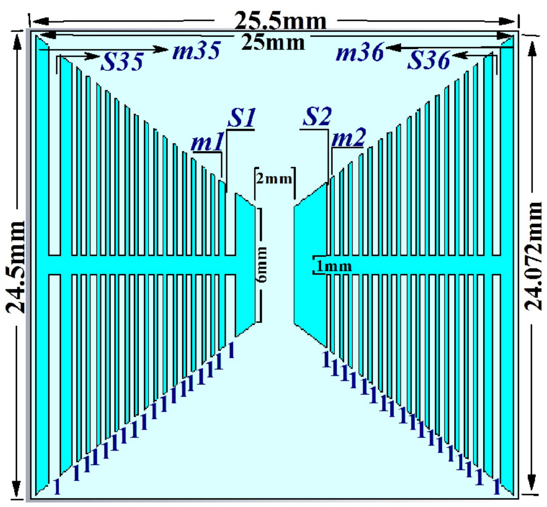

Fig. 2. The layout of designed tag.

tag size/flexibility. Moreover, for efficient band utilization while using flexible substrate, the tag design is optimized for Kapton®HN.

4. Results and Discussion

The proposed tag design encodes 36 bits data. The tag has been designed for different substrates of varying electrical properties using different conducting materials. The detailed analysis of tag dimensions for all the designed tags is shown in Tab. 2.

4.1 Taconic TLX-0 Substrate

The tag designed using Taconic TLX-0 substrate and copper radiator is referred as 'Tag-1'. The RCS vs. frequency response for Tag-1 is shown in Fig. 3. The electrical permittivity of Taconic TLX-0 is 2.45, deployed using copper as a radiator with a thickness of 0.035 mm. 36-bit tag response has been analyzed in the frequency range between 5 GHz and15.5 GHz.

4.2 PET Substrate

Tags referred as 'Tag-2,' and 'Tag-3' are designed using PET substrate along with aluminum and silver nano-particle-based ink as conducting materials, respectively. The electrical permittivity of PET is 2.9. The tag designed using PET as substrate and aluminum as radiator is referred as 'Tag-2'. The RCS vs. frequency response for Tag-2 is shown in Fig. 4. Aluminum used as radiator has thickness of 0.007 mm. The tag yields 36 bits in the frequency range of 5.3–18.2 GHz.

The tag represented as 'Tag-3' is designed using PET substrate along with silver nanoparticle-based ink as conducting material. The RCS response for Tag-3 is shown in Fig. 5. The thickness of the silver nanoparticle-based ink is 0.015 mm. The RCS curve for Tag-3 lies in the frequency range of 4–18.2 GHz.

4.3 Kapton®HN Substrate

The tags referred as 'Tag-4,' and 'Tag-5' are designed on Kapton®HN substrate using aluminum and silver nanoparticle-based ink as radiators.

The electrical permittivity of Kapton®HN is 3.5. Kapton®HN is deployed for its easy availability and low-cost along with flexibility. By changing the radiator, there is variation in resonances of the tag. 'Tag-4' has been designed using aluminum radiator on Kapton®HN substrate. The RCS vs. frequency response for Tag-4 is shown in Fig. 6. Aluminum in Tag-4 has thickness of 0.007 mm and yields 36-bit data in the frequency range between 5 GHz and 17 GHz.

The tag designed using silver nano ink radiator on Kapton®HN substrate is referred as 'Tag-5'. The RCS response for Tag-5 along with fabricated design is shown in Fig. 7.

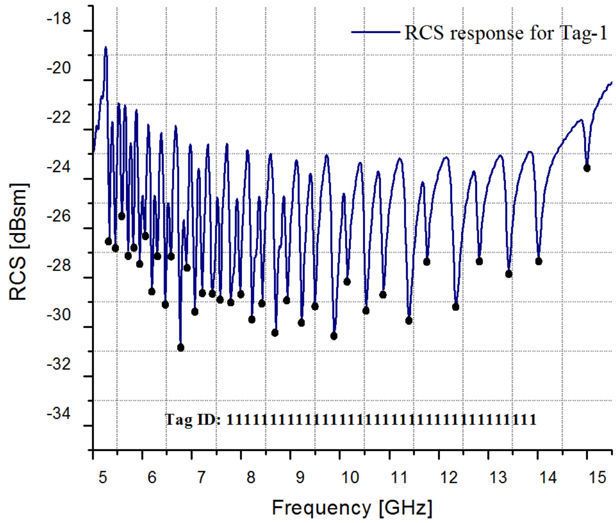

Fig. 3. RCS response for Tag-1.

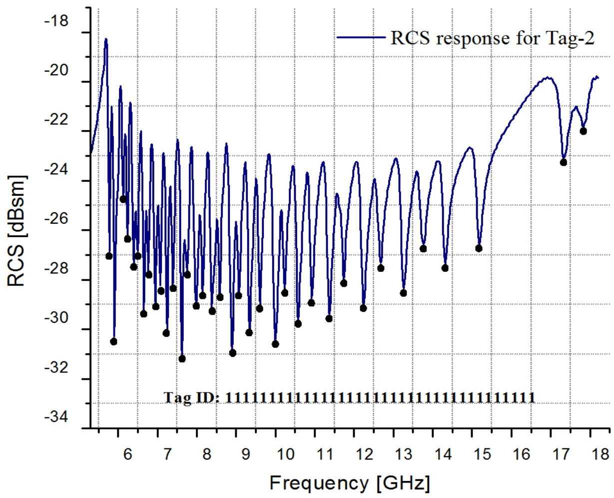

Fig. 4. RCS response for Tag-2.

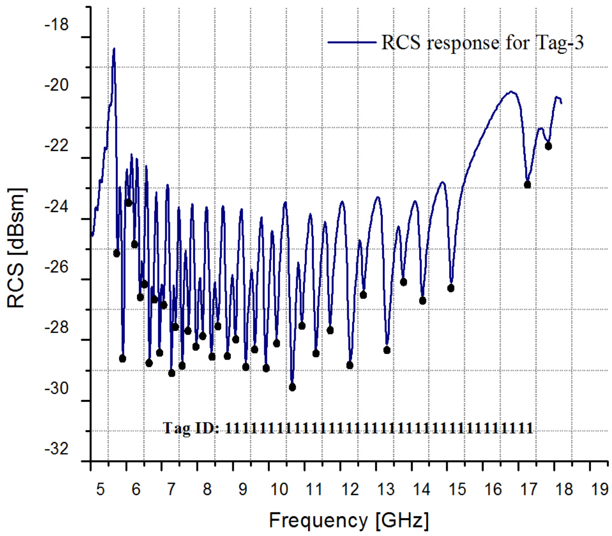

Fig. 5. RCS response for Tag-3.

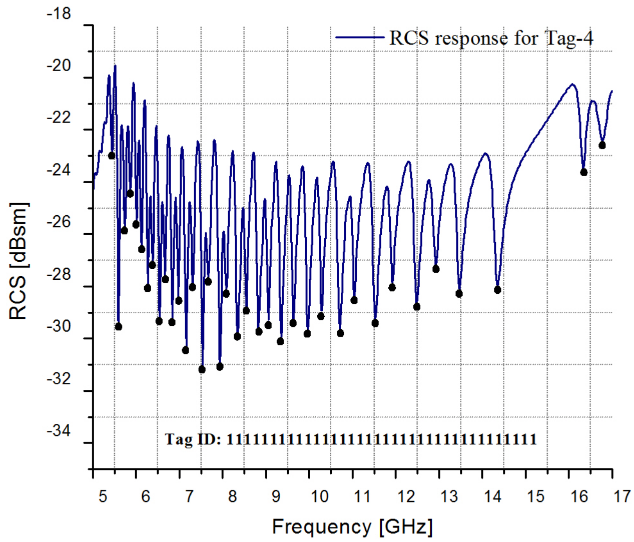

Fig. 6. RCS response for Tag-4.

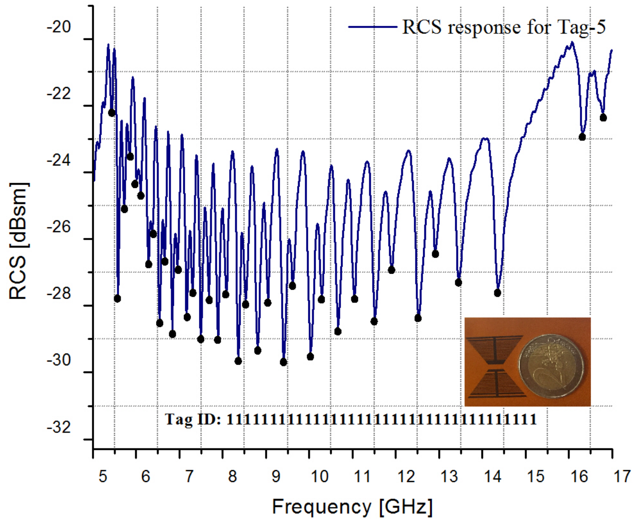

Fig. 7. RCS response for Tag-5.

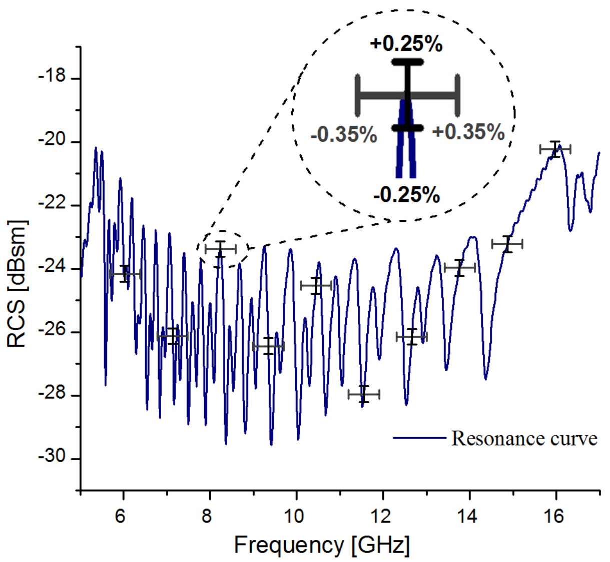

Fig. 8. Reliability curve of Tag.

The tag RCS response for 36 bits using silver nano ink radiator of 0.015 mm thickness lies in the frequency range of 4–17 GHz. We analyze that by the change of conducting material, there is variation in resonances of the tags.

To analyze the reliability parameters, five prototypes of each substrate are manufactured and tested. The corresponding reliable performance is shown in Fig. 8. It has been observed that the tag shows 0.25 % tolerance in RCS values and exhibits 0.35 % tolerance in the frequency band of interest.

By changing the substrate, there is variation in electrical properties which consequently results in frequency shift in RCS curve. With decreasing permittivity, there is a right shift in resonances which can be analyzed from '*LSB*' (Least significant bit) of comparison graph shown in Fig. 9. A comparative analysis of previous research works and the proposed research work is shown below in Tab. 3.

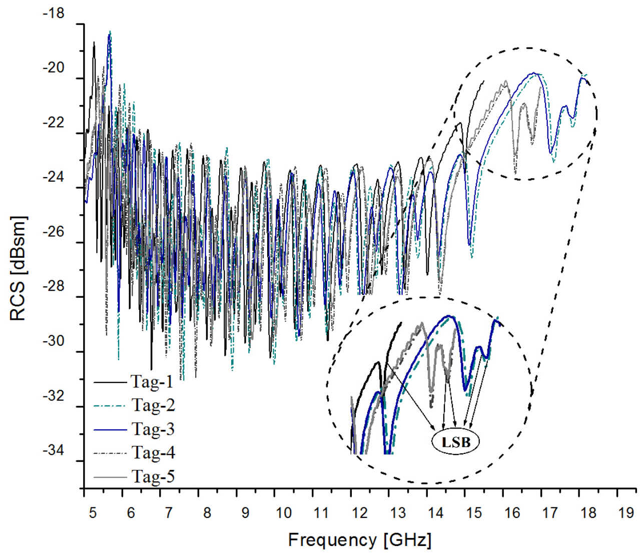

Fig. 9. Comparison graph of all presented tags.

Parameters	**Paper 1** [36]	**Paper 2** [7]	**Proposed paper**
Trans. Bits	12	24	36
No. of tagged items	4096	16777216	68,719,476,736
Size [mm^2]	35 × 33	20.6 × 19.9	24.5 × 25.5
Flexibility	x	✓	✓

Tab. 3. Comparison table.

To analyze different coded combinations, various tag ID's have been generated, simulated and tested. A comparative analysis of presented full tag with two different tag ID's along with their prototypes is shown in Fig. 10. Tag-A corresponds to all 1's with a tag ID

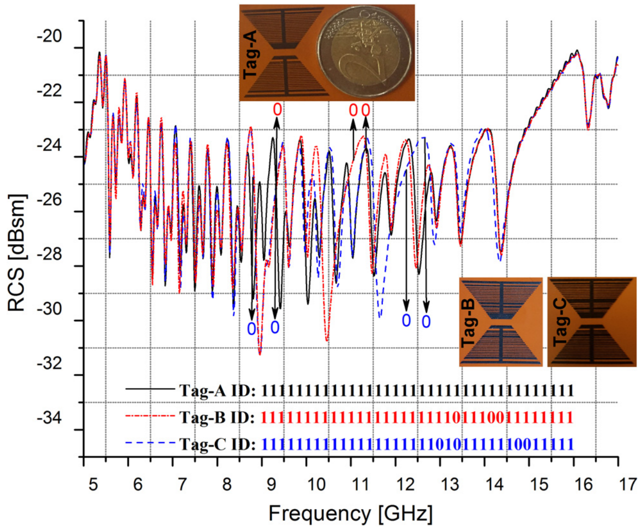

Fig. 10. Comparison of different ID combinations.

111111111111111111111111111111111111. For Tag-B, *S*9, *S*10 and *S*14 slots are shorted leading towards a coded combination of ID having ‘0’ bits: 111111111111111111111101110011111111. Again, another data word having ‘0’ bits representing tag ID: 111111111111111111110101111110011111 is presented as Tag-C by shorting *S*6, *S*7, *S*14, and *S*16. It has been analyzed that the occurrence of 0-bit has a slight effect on the amplitude and resonance frequency of neighboring peaks.

5. Measured Results

After testing, the results are measured and analyzed. The measured and computed results are shown in Fig. 11. RCS evaluation for each bit at a particular resonance can be calculated theoretically by using (5) [39]

$$f = \frac{c}{2L}\sqrt{\frac{2}{\varepsilon_r + 1}} \tag{5}$$

where ε_r is the relative permittivity of substrate, L is the slot length and c is the speed of light.

The experimental setup of chipless RFID for RCS evaluation includes two horn antennas; one transmitting and the other receiving as shown in Fig. 12. The tag deployed on the item is set at a far-field distance from the antennas. The transmitting antenna bombards an interrogator signal on the tag and receiver antenna then reads its response for identification using Vector Network Analyzer (VNA) R&S®ZVL13. The tag is printed using a table-top printer available from Dimatix “DMP2800” inkjet printer.

6. Conclusion

The research has proposed a novel, 36-bit passive chipless RFID resonator based tag. The tag has been designed, printed and tested. The tag consists of slots of different widths and lengths etched on the radiating patch. The proposed tag is of 24.5 × 25.5 mm^2 dimensions, designed on Taconic TLX-0, PET, and Kapton®HN substrates with copper, aluminum, and silver nanoparticle-based ink as radiators. The novelty of the tag relies on its compact size, high-density data and flexibility; deployed all together for green electronics, economic, environment-friendly and IoT-based applications.

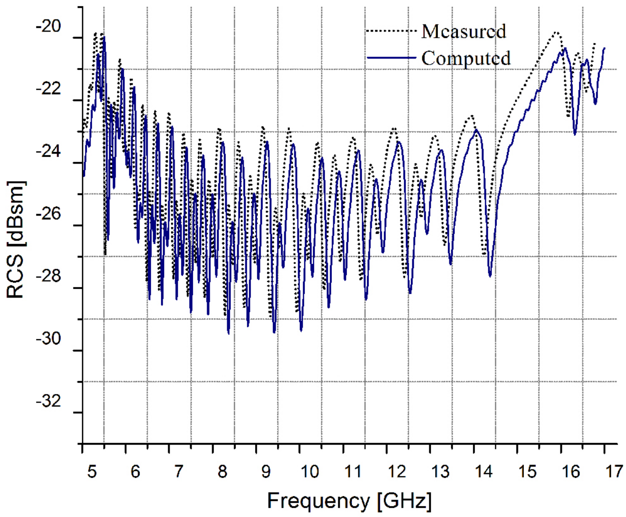

Fig. 11. Measured and computed RCS response.

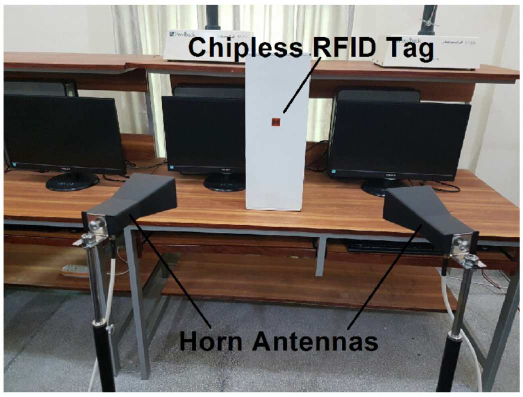

Fig. 12. Experimental set-up.

Acknowledgments

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