Polarization Insensitive Compact Chipless RFID Tag

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Abstract **─** This research article proposes a highly dense, inexpensive, flexible and compact 29 x 29 mm^2 chipless radio frequency identification (RFID) tag. The tag has a 38-bit data capacity, which indicates that it has the ability to label 2^{38} number of different objects. The proposed RFID tag has a bar-shape slot/resonator based structure, which is energized by dual-polarized electromagnetic (EM) waves. Thus, portraying polarization insensitive nature of the tag. The radar cross-section (RCS) response of the proposed tag design is analyzed using different substrates, i.e., Rogers RT/duroid®/5880, Taconic (TLX-0), and Kapton®HN (DuPont™). A comparative analysis is done, which reveal the changes observed in the RCS curve, as a result of using different substrates and radiators. Moreover, the effect on the RCS response of the tag is also examined, by bending the tag at different bent radii. The compactness and flexible nature of the tag makes it the best choice for Internet of things (IoT) based smart monitoring applications.

Index Terms **─** Chipless tag, Radar Cross-Section (RCS), Radio Frequency Identification (RFID).

I. INTRODUCTION

The continuous evolution of Internet of things (IoT) is the outcome of its tremendous scope in the present technological era. The fundamental concept of IoT is to create a web of interconnected smart objects [1]. Thus, IoT guarantees to provide every object with a communication capability and radio frequency identification (RFID) is the key enabler that gives a taste of reality to this aspect [2]. Hence, with the ever growing communication technology, IoT has been the center of attention for researchers to provide real-time solutions for the welfare of humanity [3].

RFID is one of the leading facilitator of IoT, which has spell-bound the global market due to its affordability, increased efficiency, compact size, and numerous applications in logistic [4], supply chain management, vehicle identification [5], baggage tracking on airports, etc. Furthermore, in recent years in order to meet the growing IoT trends, sustained advancement is observed from chip-based to chipless RFID technology. Chip-based tags are not much preferred because of the embedded silicon IC, which ultimately leads to higher price tags that are not suitable for a number of low-cost applications [6]. The identification cost should not be greater than the worth of object/item to be tagged.

Chipless tags do not have an integrated chip (IC) and therefore can be printed easily on to the goods. Moreover, this has also reduced their cost as compared to the chip-based counterparts. Consequently, the research efforts are more concentrated towards the development of low-cost, passive chipless RFID tags.

Various researches have revealed different passive chipless tags having compact and polarization insensitive geometries. In [7], a cross loop resonator based tag with a polarization independent nature is presented. It has the ability to store 20-bit data within a footprint of 4 x 4 cm^2. Then in [8], a chipless tag; consisting of multiple circular ring patch resonators, insensitive to polarization, is disclosed. The tag is designed in a compact dimension of 3 x 3 cm^2 with a coding capacity of upto 19 data bits.

This research work proposes a novel, compact, polarization insensitive, passive chipless RFID tag, comprising of a bar-shape slot/resonator based structure. The proposed tag is capable of yielding 38-bit high data capacity within a compact size of 29 x 29 mm^2. The tag is analyzed for various substrates along with different materials as radiators. Initially, the tag is designed using Rogers RT/duroid®/5880 substrate with copper metal as radiator in a frequency range of 4.6–14.3 GHz. Another tag is inspected using Taconic (TLX-0) along with copper radiator, and its response is analyzed for a frequency range of 4.62–14.4 GHz. Furthermore, to achieve flexibility within a reasonable budget, the tag is also examined using Kapton®HN substrate along with aluminum and silver nano-ink (Cabot ink CCI-300) as a radiator. The

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RF range for Kapton®HN along with aluminum radiator is 5.4–17.97 GHz and 5.3–17.95 GHz for silver nano-ink.

II. WORKING MECHANISM

The passive chipless RFID tag/transponders do not need a battery to power them up [9]. They communicate using the principle of backscattering [10]. The proposed RFID tag has a dual-polarized slot/resonator based structure which means that the tag consists of horizontal and vertical slots. Consequently, the reader circuitry comprises of horizontally and vertically polarized transmitting and receiving antennas. The horizontally polarized transmitting antenna powers up the horizontal slots and the vertically polarized transmitting antenna excites the vertical slots of the RFID tag. Ultimately, the horizontal and vertical receiver antennas, present on the reader side, gather the modulated backscattered signals from the slots arranged in two different orientations. Besides, the dual-polarized structure of the tag depict its polarization insensitive nature. Owing to the fact, and unlike [11], the length of the horizontal slots is kept different from the length of vertical slots in the proposed tag structure, consequently they resonate at different frequencies which prevents mutual interference between the slots. Thus, the proposed tag always yields 38-bits, irrespective of the angle, to which it may be rotated. Ultimately, it can be used as 38-bit polarization insensitive tag. Moreover, the sharpness and the clarity of the resonant dips is not effected by rotating the tag. The RCS response of a single slot/resonator of the tag i.e., *S27* and *S28* on H and V-probe, at different angles of rotation is shown in Fig. 1.

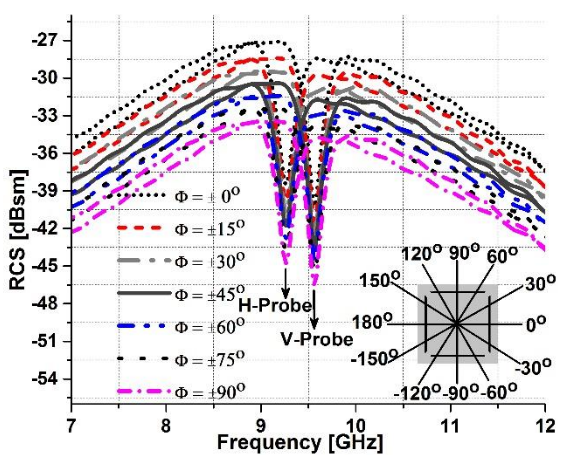

Fig. 1. Polarization insensitivity depicted by the tag.

The E-field circular wave equation is stated as:

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

where $\boldsymbol{E}$ represents the electric field, ω shows the angular frequency, *(x,y,z)* represents the position vector and k constitutes the wave number.

III. PROPOSED CHIPLESS TAG DESIGN

Researchers have explored different aspects of the chipless technology. Efforts have been made to cater high data capacity requirement. The novelty of the proposed tag lies in its flexible nature, along with the ability to yield 38-data bits in a compact size while remaining insensitive to polarization. The tag is designed using CST STUDIO SUITE®. Furthermore, the flexible Kapton ®HN substrate based tag is printed with the help of DMP2800 inkjet printer which consists of a single refillable piezo-based print cartridge having 16 nozzles in a single row. The nozzles have a spacing of 254 µm and can eject drops within a range of 1pl to 10pl subjected to the type of cartridge used. The proposed tag is printed using 10pl cartridge (DM-11610) filled with silver nano-ink, i.e., (Cabot CCI-300). Moreover, the sintering process is carried out at 150 ºC for 2 hours. The printing accuracy is determined by observing the tag under ULTRA-55 Field Emission Scanning Electron Microscope from Carl Zeiss NTS. The 29 x 29 mm^2 chipless tag is capable of encoding 38-bit data which indicates that it can tag 2^{38} number of items/objects. In this research article, the tag design consists of horizontal and vertical bar-shaped slot/resonators of varying lengths, which are arranged in a square shape fashion. The resonating structures are meant for storing the encrypted information. When the EM waves strike these resonators then, each slot, i.e., (gap between the metallic parts), corresponds to one dip, which ultimately represents one bit or a logic state ‘1’. Subsequently, a logic state ‘0’ is used to represent a slot that has been shorted. The proposed tag design is shown in Fig. 2.

The tag contains thirty-eight slot resonators, out of which nineteen are horizontally polarized, and nineteen are vertically polarized. The slots are represented as *S1-S38*. The horizontal slot resonators are odd numbered and are labeled as *S1, S3* onwards. Horizontally polarized plane wave energizes them. Whereas, the vertical slot/resonators are even numbered and are labeled as *S2, S4* onwards. They are excited by the vertically polarized plane waves. The metallic parts of the tag are referred as *M1-M38* each having width of 0.2 mm. The slot *S1* and *S2* have 8.3 mm and 8.2 mm width, respectively. Besides, all the slots from *S5-S38* have a constant width of 0.3 mm, whereas, slot *S3* and *S4* are optimized to 0.5 mm width. Since, keeping their width equal to 0.3 mm, affects their corresponding resonant dips, and makes them hardly detectable on RCS curve; due to mutual interference. Thus, the widths of all the slots are optimized in such a way, so that sharp and clear resonant dips are achieved on the RCS plot. Furthermore, the tag is kept at a far-field distance from the reader to measure its radar cross section (RCS) response. The far-field distance of the tag can be calculated from (2):

$$R = 2D^2 / \lambda, \quad (2)$$

where D symbolizes the largest dimension of the tag and λ indicates the wavelength. In the proposed research, the largest dimension of the tag is 29 mm or 0.029 m (for use in calculation), whereas λ is calculated using (3):

$$\lambda = c / f, \quad (3)$$

where c is the speed of light, i.e., 3 x 10^8 m/s and f is the central frequency, i.e. 9.45 GHz for this tag. After substituting value of λ in (2) the far field distance comes out to be 52.9 mm. Moreover, the resonant frequency of every individual dip corresponding to each slot can be found by (4) [12]:

$$f_r = \frac{c}{2L}\sqrt{\frac{2}{\varepsilon_r + 1}}, \quad (4)$$

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

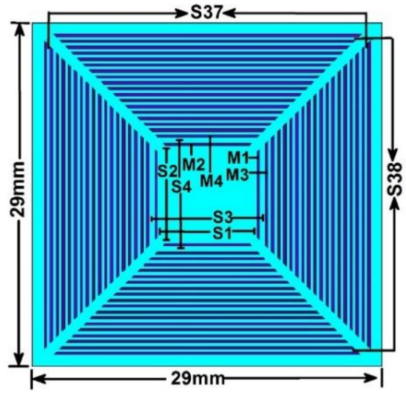

Fig. 2. Proposed tag design.

IV. RESULTS AND DISCUSSION

In this section the RCS plots of the proposed tag structure, analyzed using three different substrates, i.e., Rogers RT/duroid®/5880, Taconic TLX-0 and Kapton®HN, along with three different radiators that include copper, aluminum and silver nano-ink, are demonstrated. It is observed, that the tag design analyzed for different radiators and substrates; (having varying electrical properties), demonstrate a shift in RCS curve on the frequency axis. This is quite evident from the results of simulations discussed in this section. The characteristic comparison of the tag design examined using different substrates is given in Table 1.

A. Tag response using Roger RT/duroid®/5880

The proposed tag analyzed using Rogers RT/duroid®/5880 substrate along with copper metal used as radiator is referred as 'Tag-A'. Each slot of the tag represents a bit or a logic state-1, which can be seen as a separate resonance dip on the RCS plot, hence the tag yields 38-data bits represented as Tag-A ID. The substrate has a permittivity of 2.2 whereas copper radiator has thickness of 0.035 mm. RF band from 4.6–14.3 GHz is utilized to transmit data. Furthermore, due to low water absorbing property of rigid Rogers RT/duroid®/5880, the tag is ideal for use in high moisture environments. The computed RCS curve of 'Tag-A' along with its 38-bit tag ID is shown in Fig. 3.

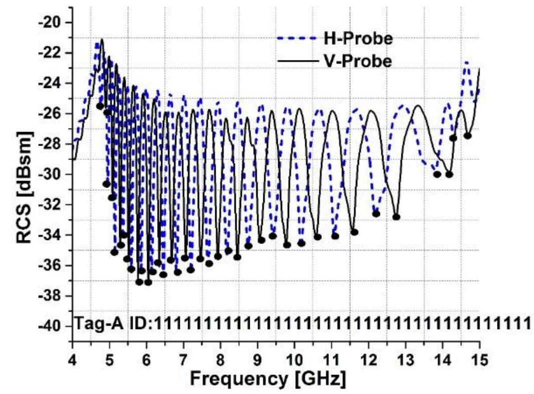

Fig. 3. Computed RCS response of 'Tag-A'.

Moreover, the proposed tag design analyzed using Taconic TLX-0 substrate along with copper radiator is referred as 'Tag-B'. The RCS plot of 'Tag-B' is similar to the response of the 'Tag-A' with a very nominal shift in the frequency band, i.e., from 4.62–14.4 GHz.

B. Tag response using Kapton®HN

Keeping in view the flexibility and excellent ability of the Kapton®HN to maintain its electrical properties over a wide range of temperature, the tag is analyzed for Kapton®HN substrate along with two different radiators, i.e., aluminum and silver nano-ink.

'Tag-C' is analyzed using Kapton®HN substrate exhibiting a permittivity value of 3.5, accompanied by aluminum radiator having a thickness of 0.007 mm. It utilizes the frequency band from 5.4–17.97 GHz. Computed RCS response for 'Tag-C' is shown in Fig. 4.

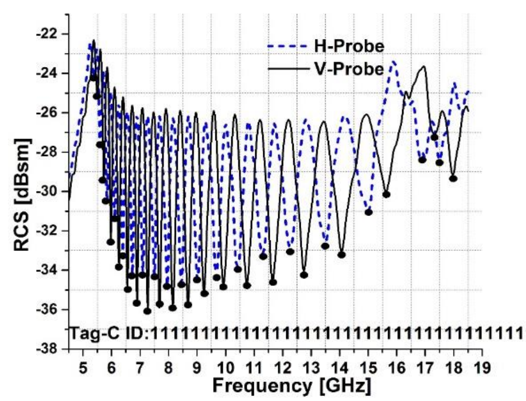

Fig. 4. Computed RCS response of 'Tag-C'.

Table 1: Characteristic comparison table

Parameters	Tag-A	Tag-B	Tag-C	Tag-D
Substrate	Rogers RT/duroid®/5880	Taconic TLX-0	Kapton®HN	Kapton®HN
Substrate Thickness [mm]	0.787	0.5	0.125	0.125
Permittivity	2.2	2.45	3.5	3.5
Radiator	Copper	Copper	Aluminum	Silver nano-ink
Radiator Thickness [mm]	0.035	0.035	0.007	0.015
Freq. band [GHz]	4.6–14.3	4.62–14.4	5.4–17.97	5.3–17.95
Flexibility	x	x	✓	✓

‘Tag-D’ is analyzed using Kapton®HN substrate, along with silver nano-ink radiator having a thickness of 0.015 mm. The silver nano-ink radiator has a good electrical conductivity, i.e., 9 x 10^6 S/m, and is potentially resistant to oxidation. Besides, due to its porous nature it can be deployed easily on the substrates thus leading to its full printability. The RCS plot of the ‘Tag-D’ covers the frequency band from 5.3–17.95 GHz. Moreover, both ‘Tag-C’ and ‘Tag-D’, are capable of producing 38-bits which is unveiled by their respective tag ID’s. The computed RCS response of ‘Tag-D’ is shown in Fig. 5.

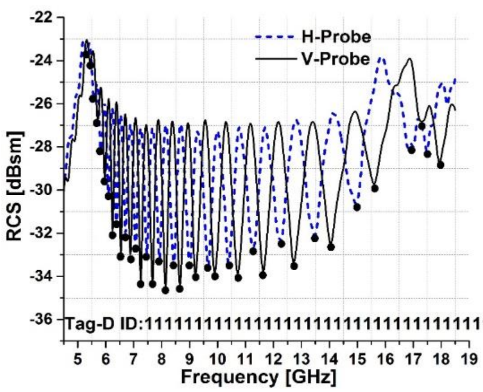

Fig. 5. Computed RCS response of ‘Tag-D’.

A comparison is done between the RCS curves of proposed tag structure, analyzed using different substrates. It is observed that as the permittivity of the substrates decrease, i.e., from 3.5 to 2.2, the resonant dips, drift towards the lower frequencies. Thus, illustrating a left shift in overall RCS response of the tag. This is quite evident from the frequency bands of various tags, as given in Table 1.

Furthermore, a comparative analysis is done between the RCS response of ‘Tag-C’ and ‘Tag-D’; that are analyzed using Kapton®HN substrate along with two different radiators. It is observed that by changing the radiator, while keeping same substrate, there is a slight variation in resonances of the tag. Consequently, a minor frequency shift in RCS curves of the two tags is noticed. This can be visualized from the behaviour of their least significant bits (LSB) that corresponds to the shortest slot. The comparison curve along with the prototype of the proposed tag is shown in Fig. 6.

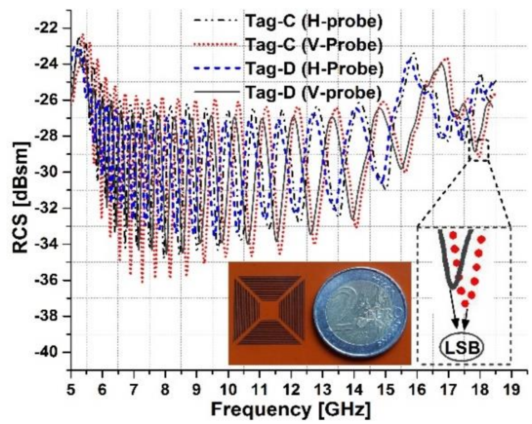

Fig. 6. RCS comparison curve of ‘Tag-C’ and ‘Tag-D’.

Ultimately, to analyze the robustness of the tag, its reliability factor is determined. For this purpose, five to six prototypes of every tag are fabricated and tested experimentally. The tag depicts a tolerance of 0.25% in the desired RF band, whereas 0.3% tolerance is notified along RCS axis. Thus, it is inferred that the proposed tag constitutes a reliable behaviour. The reliable performance of proposed tag on H-probe and V-probe is illustrated in Figs. 7 (a) & (b), respectively.

When incident plane waves excite the tag structure, then each individual slot gives a single resonant dip on a distinct frequency. Each slot corresponds to a logic state ‘1’. These slots are shorted in order to shift the logic state from ‘1’ to ‘0’. A shorted slot does not gives a dip at a specific resonant frequency, thus corresponds to ‘0’ logic state. Hence, by shortening; different tag IDs can be assigned to each tag, which ultimately, prevents the collision of data in the network. Since in the proposed tag, each slot produces a resonant dip at a different frequency; thus, shorting any slot will have a minor effect on the frequency response of the neighboring slots [13]. A comparison of tag carrying all 1’s; denoted by 11111111111111111111111111111111111111 tag ID, with the tag comprising of shorted *S10*, *S17* and *S24* slots; represented by the unique tag ID:

1111111110111111011111101111111111111 is illustrated in Fig. 8.

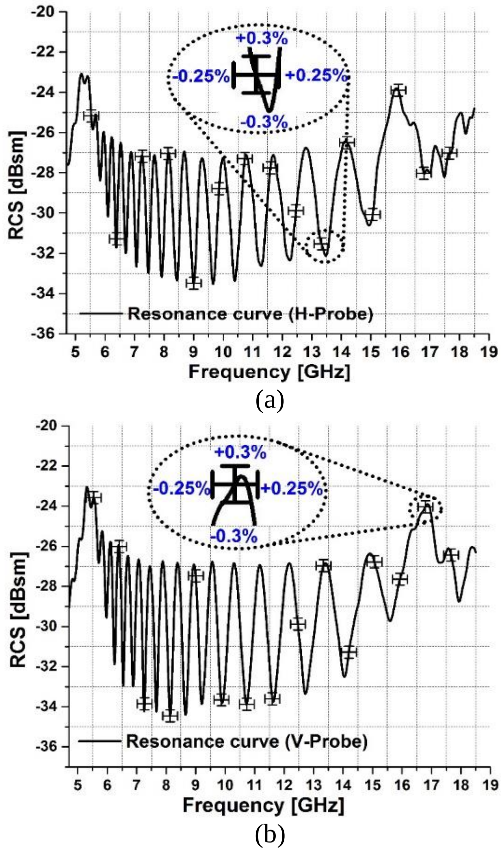

Fig. 7. (a) Reliability curve of ‘Tag-D’ (H-Probe), and (b) reliability curve of ‘Tag-D’ (V-Probe).

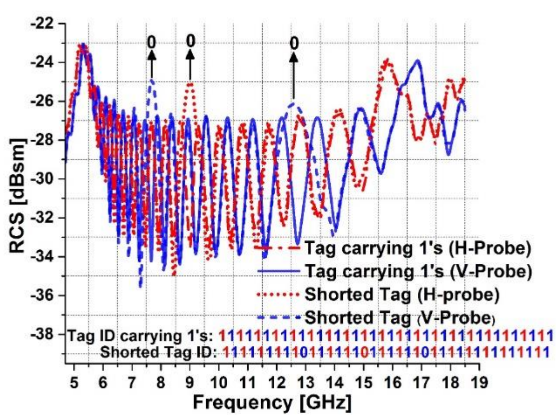

Fig. 8. Comparison of reference and shorted tag.

V. BENDING EFFECT ON TAG

The RCS response of the proposed tag is also examined by bending it at different bent radii, i.e., 18 mm, 60 mm, 80 mm, 90 mm. While performing the experiments the tag is attached to cylindrical polystyrene molds; which are designed with different curvature radii; corresponding to the various bending radii at which the RCS response of the tag is to be analyzed. The molds are designed using polystyrene material because it has a relative permittivity approximately equal to unity, which does not effects the RCS response of the tag. It is observed that with the decrease in the bending radius of the tag, its RCS response is effected yielding less prominent but still detectable resonant dips as in [10]. Hence, the data stored in the tag can be retrieved successfully at different bending radii. The RCS response of the tag on H and V-Probe at various bent radii represented by r, along with the proposed tag bent at a radius of 18 mm are illustrated in Figs. 9 (a) & (b), respectively.

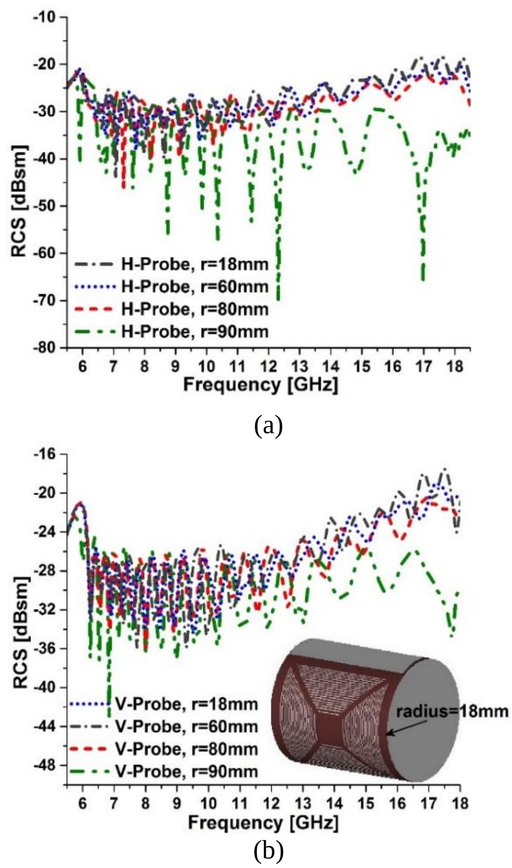

Fig. 9. (a) Bending effect on tag (H-Probe), and (b) bending effect on tag (V-Probe).

VI. COMPUTED AND MEASURED RESULTS

The computed and measured results of the proposed tag design, on H-probe and V-probe are depicted in Figs. 10 (a) & (b), respectively. The measured and computed results of the tag demonstrate an acceptable agreement. A slight shift in the resonances is observed, as detected by the reader circuitry. The testing of the tag is done in standard environment using a bistatic radar system [13].

The experimental setup used for testing of the tag consists of a Vector Network Analyzer (VNA) R&S®ZVL13 and two horn antennas, one is transmitter and the other is receiver. Transmitter antenna directs interrogator signal on the transponder, set at a far-field distance. The receiver antenna then collects the backscattered signal encoded with unique identification code using VNA.

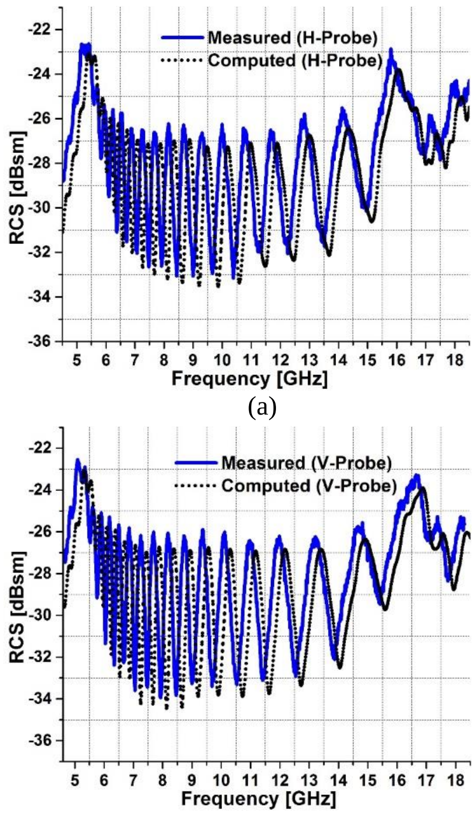

Fig. 10. (a) Measured RCS response (H-Probe), and (b) measured RCS response (V-Probe).

Table 2 shows a comparative study of the previous research works and the proposed tag design.

Table 2: Comparison with previous research work

Parameters	I-Slot [11]	Circular [14]	Square [15]	Proposed Research
Size [cm^2]	7.29	2.36	9	8.41
Tans. bits	32	9	5	38
Bit density [$Bits/cm^2$]	4.38	3.80	0.55	4.51
Flexibility	x	x	x	✓

From Table 2, it is evident that the proposed tag has the capability to encode 38-bit data in a miniaturized footprint of 8.41 cm^2. Thus, yielding a high bit density comparatively. Moreover, the flexible characteristic of the tag allows it to be deployed on irregular surface.

VII. CONCLUSION

A compact 29 x 29 mm^2 chipless RFID tag, having a high data capacity of 38-bits is revealed in this research work. The proposed tag structure yield very stable resonant dips, when analyzed for multiple substrates. The tag analyzed using Kapton®HN substrate is found to be of utmost significance; because of its flexible nature, easy printability and stability toward thermal changes. The tag analyzed using Rogers RT/duroid®/5880 substrate exhibits electrical stability towards high humidity levels. Consequently, providing an optimal solution for moisture rich atmospheres. Thus, the proposed tag can be used in different environmental conditions; becoming the ideal choice for IoT based industrial applications.

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