# A Planar Slotted RCS Based UWB RFID Tag on a PCB and a Flexible Substrate for Packaging Application

**A. K. M. Zakir Hossain, M. Z. Abidin Bin Abd Aziz, A. W. Y. Khang, and W. A. Indra**

**Abstract** The passive chipless ultra wide band RFID tags are at the forefront of the research to replace the existing barcode technology. The attributes of the RFID system out-run various problems associated with the barcode system such as line of sight, wear and tear, tampering and etc. The chipless RFID tag in ultra wide band contains no chip that inherently makes it cheaper compared to chipped tags. However, due to their dimensions, sometime in the packaging industry, it exceeds the size of the package and also it comes with inadequate bit density. In addition, the fabricated tag is mostly designed on printed circuit boards that takes away the raping ability on the surface of the product. The tags on flexible substrates can be a good solution for this problem. In this paper, the radar cross-section response of a new planar Dual L-Slotted ultra wide band RFID tag has been studied and investigated on a printed circuit board and a flexible substrate. The tag contains 16 bits within the compact size of 15.2 × 7.2 $mm^2$, having a bit density of 14.62 bit/$cm^2$. The tag has been realized on Taconic TLX-8 as the rigid printed circuit board and a flexible substrate, Kapton®HN. For both cases the code "1111111111111111" has been successfully extracted. Both are suitable for RFID applications whereby the tag realized on the flexible substrate has the potentiality to use in the packaging industry and also in sensing applications.

**Keywords** Passive chipless ultra wide band RFID · Barcode · Packaging industry · Flexible substrates · Radar cross-section

A. K. M. Zakir Hossain (✉) · A. W. Y. Khang · W. A. Indra
Centre for Telecommunication Research & Innovation (CeTRI), Fakulti Teknologi Kejuruteraan Elektrik & Elektronik (FTKEE), Universiti Teknikal Malaysia Melaka (UTeM), Hang Tuah Jaya, 76100 Durian Tunggal, Melaka, Malaysia
e-mail: zakir@utem.edu.my

M. Z. Abidin Bin Abd Aziz
Centre for Telecommunication Research & Innovation (CeTRI), Fakulti Kejuruteraan Elektronik & Kejuruteraan Komputer (FKEKK), Universiti Teknikal Malaysia Melaka (UTeM), Hang Tuah Jaya, 76100 Durian Tunggal, Melaka, Malaysia



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## 1 Introduction

The Radio Frequency IDentification (RFID) is a well-established technique to identify or track items/products. The RFID is a proven solution in many industries such as packaging, process, toll collection, library management, livestock and etc. [1]. The RFID provides a solid encryption and security to preserve the accurate identity and original information about the product/object to be identified. The revolution on RFID has begun back there in the World War II (WWII). Where, the first reported application of RFID was to identify the airplane that was friend or foe by the allied forces. Since then, the interests in RFID research and development have been in increasing trend day by day. One more good aspect about the RFID system is that, this does not need the line of sight (LOS) for the detection. It is less vulnerable to hacks and tempering, and also atmospheric stresses do not affect the system [2, 3]. In addition, dent, wear, tear has less effect on reading and identification whereas the conventional existing barcode system is still suffering these issues. Due to these reasons, in the last decade, many researchers have involved in developing the RFIDs that can replace the conventional barcode system [4].

The RFID system can be classified (in terms of power on board) into three categories: (i) Active, (ii) Semi active/passive and (iii) passive tags. Active tag is fully battery assisted and does not rely on the power from the reader. Similarly, the semi active/passive tags also have the battery on board but it's to power the internal circuitry (IC) only of the tag. The needed power for communication between the reader and the tag relies on the interrogation signal power from the reader. Due to this half active and half passive behavior, this type of tag sometimes called semi-active and also called as semi-passive tags. On the other hand, passive tags do not comprise any battery on board and rely merely on the radiated power from the RFID reader. Active and semi active/passive both types of tag has IC on board. However, the passive types either can have IC or can be chipless also. Since the chipless tags do not have the IC, its make them inherently cheap and put them as a potentially suitable candidate for the replacement of the barcode system [5, 6].

The passive chipless tags are mostly consists of resonators which can be read in the spectral/frequency domain (FD) or in the time domain (TD) [3]. The modulation in FD or TD follows the on off keying (OOK). Where, the presence and absence of the resonators determines the numbers of bits and the combinations for the encryption. If there are "N" numbers of resonators can be accommodated on the tag, the number of combinations can be $2^{N}$. Due to this obvious reason, to increase the number of bits on board of the tag, the number of resonators has to be increased and consequently it makes the tag dimensions larger proportionally. In FD, the RFID chipless tags have been validated either through S-parameter ($S_{21}/S_{11}$) measurement [7] or the radar cross-section (RCS) of the tag which are basically designed in ultra wide band (UWB) region. The chipless tags may or may not consist of antennas. Among the chipless tags, those which do not employs the antenna(s) for communication with reader, are smaller in size due to the exclusion of the antenna on board and consequently puts them at the forefront of the research to replace the barcode. These

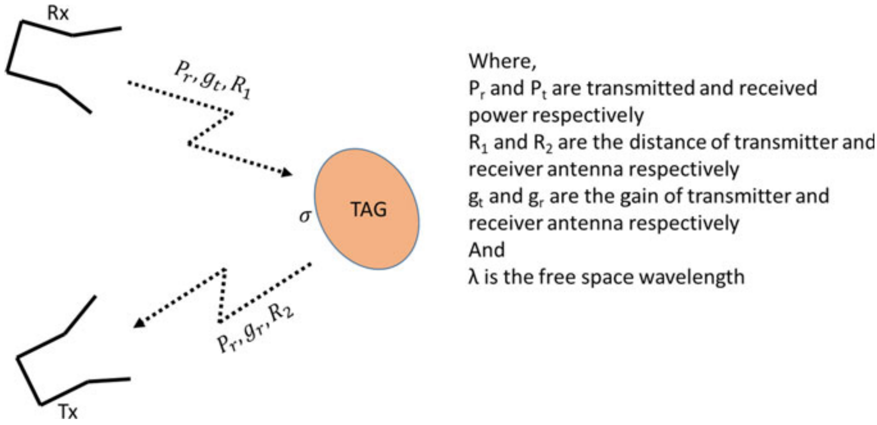


**Fig. 1** Bi-static radar configuration for RCS based chipless tags

types of tags can be and usually are validated through the RCS response from the tag. Furthermore, researchers have also validated the tag through RCS response but the bit extraction has been done by different novel methods [8]. Figure 1 shows the conventional diagram for a chipless RFID system with Eq. (1) to estimate the bi-static radar based RCS (σ) [9].

In [8], so far, the highest bit density has been exhibited by the tag called slot loaded rectangular patch (SLRP). The authors have achieved bit density of 16.6 bit/cm$^2$ with dual polarized 16 bits (8-bits vertical and 8-bits horizontal) on board while the tag is partially validated with the RCS and detected by a four antenna (two cross polar at Tx and two cross polar at Rx) method. However, this combination of antennas makes this method difficult to practically implicate and makes a complex nature of detection. Also, the stated bit density decreased to half (8.3 bit/cm$^2$) if only one polarized bits are extracted. Furthermore, although the tag is claimed to be fully printable, the authors have not

$$\sigma = \frac{(4\pi)^3 P_r}{P_t g_t g_r}\left[\frac{R_1 R_2}{\lambda^2}\right] \tag{1}$$

revealed any experimental results of the designed tag to support the claim and the tag has not been realized on any flexible substrates. As a result, the tag cannot be considered as in printable RFID family. Many other researchers have also proposed a numbers of tags with different shapes that can be validated through RCS response [10–13] and fully converted them into printable tags on flexible substrates. However, still now, through FD technique, the number of bits and bit density is not adequate as to counter the passive IC tags which has 96–124 EPC bits even though the area of the RIFD tag has been shorten significantly through chipless approach. Following the same trend, in this paper, a new Dual L-slotted (DLS) rectangular shaped (LSRS) chipless RFID tag in UWB has been design that potentially can accommodate high data bit density. The designed tag has been investigated with a rigid substrate (PCB laminate), Taconic TLX-8 and a flexible substrate, Kapton®HN. The simulation has been performed in CST microwave studio (CST MWS) 2019 to design, optimize and validate the design.

## 2 Tag Design

Figure 2 illustrates the design geometry of the 16-bit chipless tag. The tag comprises 16 different DLSs to make it as a 16-bit structure. One group of 8 L-slotted resonators ($L_1$ to $L_{15}$) are positioned at the right side of the tag and at the left side, 8 more inverted L-slotted resonators ($L_2$ to $L_{16}$) are placed. Since, the tag comprises two different L-slotted groups, it's called a DLS 16-bit structure. The width of the parallel lines (W) and the gap (g) between them is 0.2 mm respectively. The resonant frequency of each DLS resonator can be estimation by following Eq. 2 [8].

$$f_r = \frac{C_0}{2(L_X)}\sqrt{\frac{2}{\varepsilon_r + 1}} \tag{2}$$

where, $L_X$ is the length of the slot of each resonator and $X = 1, 2, \ldots, 16$. $C_0$ is the speed of light at free space and $\varepsilon_r$ is the dielectric constant of the substrate material. The 8-resonator group at the right side of the tag represents the odd number frequencies in the spectrum. Each resonator in their corresponding groups has a difference in length ($\Delta L$) of 0.4 mm from there adjacent slots. The first odd resonator $L_1$ has a length of 14.8 mm. The following resonator ($L_3$) in the same group has a length of $L_3 = L_1 -$

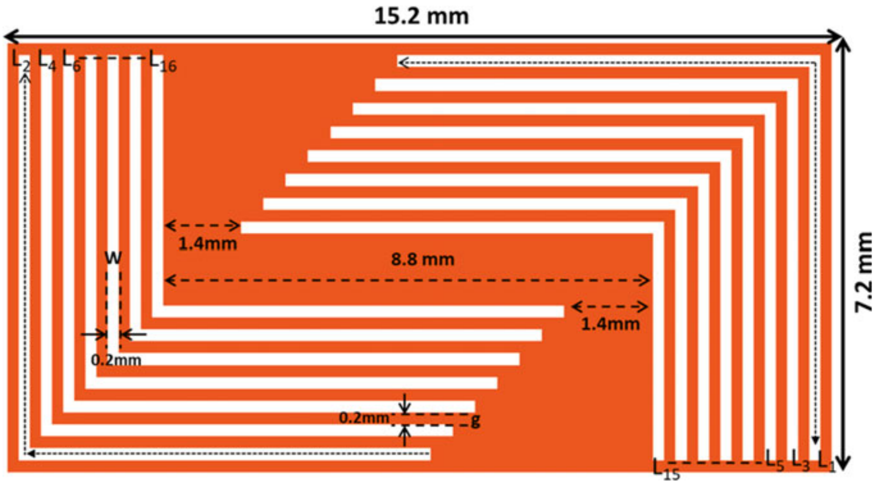


**Fig. 2** Double L-Slotted (DLS) chipless tag geometry

$\Delta L = 14.4$ mm and so on as the $L_{15} = 12$ mm. Similarly, the other 8-resonator group at the left side of the tag that represents the even number frequencies in the spectrum, also has the same difference of 0.4 mm such as $L_2 = 14.6$ mm and $L_4 = L_2 - \Delta L = 14.2$ mm and so on. This combination of lengths gives a constant difference between all the resonators ($L_1$ to $L_{16}$) of 0.2 mm. Consequently, due to this difference in the slot resonators length, all the resonators represent unique resonant frequencies i.e. $L_1$ represents the first (lowest) resonant frequency $f_1$, $L_2$ represents the $f_2$ and so on as the 16th resonator ($L_{16}$) represents the highest resonant frequency $f_{16}$ in the spectrum. The tag dimension is $15.2 \times 7.2$ mm$^2$ and with 16 resonators (bits) on board, the bit density becomes 14.62 bit/cm$^2$ which is the highest so far reported among the chipless tags on printable/flexible substrates.

While exposed in plane wave in the spectral domain, the variation from the constant amplitude and/or phase of the RCS response from the tag, the resonance can be detected. If one or more resonator is absence (by shorting or removing), the spectral amplitude will not have any variation for those corresponding resonant frequency points related to the resonators. This is called the OOK method for detection of chipless RFID [9]. Whether it's with S-parameter or with RCS response, this is how the detection done conventionally. In the following section the concept has been validated.

## 3 Tag Validation by Simulation

To prove the concept, the tag has been simulated in CST MWS 2019. The designed RCS based chipless tag has been exposed to a circular polarized plane wave in the simulator. Figure 3a shows the simulation setup to find RCS response of the tag in CST MWS. To validate the tag structure integrity, at first, the surface current accumulation has been investigated through simulation for first two resonators ($L_1$ and $L_2$) only and the response can be seen in Fig. 3b. It is observed that while the surface current accumulates on one resonator ($L_1$) indicating the resonance whereby at the same time, the other resonator ($L_2$) has a lower surface current indicating no resonance and vice versa.

For the RCS simulation, the tag needs to be placed at the far-field region from the excitation/reader and has to have a minimum distance ($R_m$) away from the excitation signal (or reader antennas). Too close to the reader will make the tag fall inside the nearfield region and RCS response will not appear in the spectrum. To make sure the tag falls in the far-field region, the Rm has been calculated with (3) as follows [14],

$$R_m = \frac{2D^2}{\lambda} \tag{3}$$

where, D is the largest dimension of the object (chipless tag), in this case, 15.2 mm. And the wavelength, $\lambda$ for a selected center frequency of 6.5 GHz in UWB is 46.15 mm. From Eq. (3), the calculated minimum distance Rm = 11.01 mm. Here,

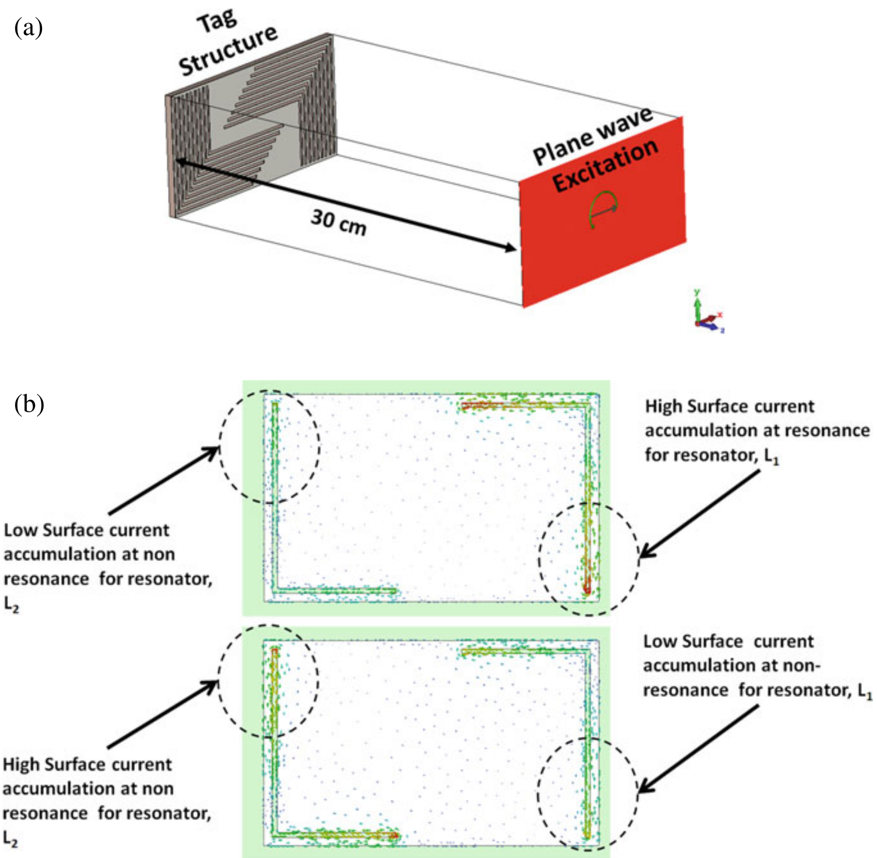


**Fig. 3** Simulation setup and surface current accumulation for the chipless tag. **a** Simulation setup in CST MWS. **b** Surface current accumulation for resonant and non-resonant slots

to make sure the far-field region, the distance of the probe (RCS) has been chosen as 300 mm (30 cm) away from the tag to measure the RCS response. Figure 4a shows the simulated RCS response of the tag modeled on Taconic TLX-8 substrate. The tag structure has been designed for the band 5–9 GHz in UWB range. The reason for that is, the dimensions basically follows Eq. 2. Any inclusion of lower frequency bands (as low as 3 GHz) will ask for longer length slots. Consequently, the whole tag size will be larger and the bit density will suffer. On the other hand, it has been seen that frequency higher than 8.5 GHz gives resonance response too small to retrieve as a bit. However, the investigation has not been shown as it has been considered irrelevant for the scope.

Accordingly, the response is taken from 5–9 GHz span and can be seen that the variations in the amplitude only between 6 and 8.5 GHz. The portion that has variation in amplitude has been expanded and investigated further. It is seen that from 6 to 8.5 GHz there is a presence of 16 distinguished dips in the RCS versus

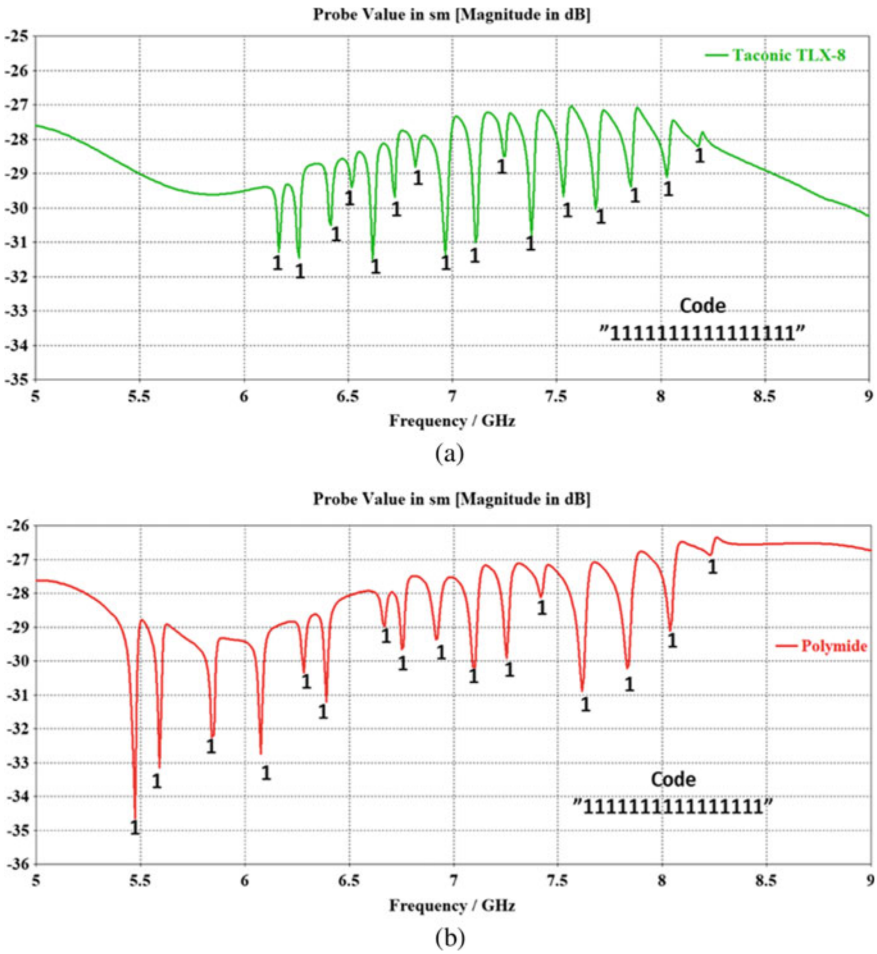


**Fig. 4** RCS response on **a** Taconic TLX-8 and **b** Kapton®HN substrate

Frequency response as it is anticipated. The longest resonator $L_1$ which corresponds to the frequency $f_1$ has a resonance dip approximately at 6.17 GHz and the smallest resonator $L_{16}$ that corresponds $f_{16}$, resonance dip at 8.2 GHz. The rest of the 14 resonators resonance in between with nominally same frequency distance apart.

The logic for one dip presence is "1" and absence is "0". Since all the 16 resonators (and their corresponding dips) are present in the spectrum, the coding bit stream can be coded as "1111111111111111". In Fig. 4b, the RCS response of the tag realized on the Kapton®HN film that has a dielectric constant of 3.5, the thickness of 125 μm and tangent loss of 0.0027. The response also shows exactly 16 bits same as the Taconic TLX-8 as in Fig. 4a, however, the resonance points are shifted as expected due to the change in dielectric constant as it follows the Eq. 2. Similarly, from Fig. 4b,

**Table 1** Comparison between existing works

| References | Number of bits | Tag area ($mm^2$) | Bit density ($bits/cm^2$) | Flexibility |
|---|---|---|---|---|
| [11] | 24 | 70 × 42 | 0.81 | Yes |
| [12] | 24 | 45.2 × 43.5 | 1.22 | Yes |
| [13] | 24 | 24 × 24 | 4.17 | Yes |
| [10] | 24 | 20.6 × 19.9 | 5.86 | Yes |
| [8] | 16 | 16 × 6 | 16.6 | No |
| This work | 16 | 13.3 × 9.4 | 14.62 | Yes |

it is seen that the code "1111111111111111" has been extracted. Table 1 shows the comparison between the existing and this proposed work.

From Table 1 it can be seen that the highest bit density is proposed in [8]. However, as mentioned earlier in this paper, this is not printable/flexible on nature. Among the other works in Table 1, the highest existing proposed chipless tag with a bit density of 5.86 $bits/cm^2$ in [10] whereas the proposed work in this paper achieved 14.62 $bits/cm^2$ which is the highest so far reported and also total number of $2^{16} = 65{,}536$ identities can be generated with this tag.

## 4 Conclusion

A 16-bit high bit density passive chipless tag has been designed and validated through simulation and experimentation. Good response has been found between while modeling the tag both on Taconic TLX-8 and Kapton®HN. All 16 bits has been successfully retrieved from both Taconic TLX-8 and Kapton®HN based tags. The code of all bit presence ('1111111111111111') has been also extracted from the RCS versus Frequency responses. So far here, one PCB and one flexible substrate has been investigated. The proposed work has achieved the highest bit density of 14.62 $bits/cm^2$ compared to other existing works so far in terms of the printable/flexible RFID techniques. With the potentiality to be implemented in the packaging industry, more investigations will be done on this design on few more different flexible substrates for item tracking RFIDs and also for environmental parameter sensors.

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