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MINIATURIZED L-SHAPED AND U-SHAPED RESONATOR BASED 8-BIT AND 12-BIT CHIPLESS RFID TAG

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ABSTRACT: Chipless Radio Frequency Identification (RFID) technology is a wireless technology that uses radio frequency signals (RF) to identify objects automatically. Chipless RFID tags promise a low-cost and printable solution for item tracking, authentication, and sensing in various applications, including supply chain management and the Internet of Things (IoT). In this work, two compact-sized prototypes of 8-bit chipless radio frequency identification (RFID) tags are modeled as L-shaped and U-shaped resonators. The proposed tags are printed on (14.5mm × 14.5mm) Rogers RT5880 substrate with a dielectric constant, $\varepsilon_r = 2.2$, and a thickness, $h = 1.575\ mm$. The simulated RCS responses for both the L-shaped and the U-shaped 8-bit chipless RFID tags are presented. A prototype of 12 back-to-back L-shaped resonators with different lengths corresponding to resonant frequencies between 5 and 8.5 GHz is proposed to increase the chipless RFID tag capacity. The proposed 12 back-to-back L-shaped resonators chipless RFID tag is printed on (15mm × 25mm) Rogers RT5880 substrate. The simulated RCS response for the compact 12-bit L-shaped resonator-based chipless RFID tag is calculated.

ABSTRAK: Teknologi Pengenalan Frekuensi Radio Tanpa Cip (Chipless RFID) merupakan teknologi tanpa wayar yang menggunakan isyarat frekuensi radio (RF) bagi mengenal pasti objek secara automatik. Tag RFID tanpa wayar menawarkan penyelesaian kos rendah yang berpotensi bagi menjejak item, pengesahan, dan pengesanan dalam pelbagai aplikasi termasuk pengurusan rantaian bekalan dan Internet Benda (IoT). Kajian ini membentangkan dua prototaip bersaiz kompak; iaitu tag RFID 8-bit tanpa wayar yang dimodelkan sebagai resonator berbentuk-L dan berbentuk-U. Tag yang dicadangkan ini dicetak pada substrat Rogers RT5880 (14.5 mm × 14.5 mm) dengan pemalar dielektrik, , dan ketebalan, h = 1.575 mm. Respons simulasi RCS bagi kedua-dua tag 8-bit berbentuk-L dan berbentuk-U dibentangkan dalam kajian ini. Bagi meningkatkan kapasiti tag RFID tanpa wayar, satu prototaip yang terdiri daripada 12 resonator berturutan berbentuk-L dengan panjang berbeza dan berfrekuensi resonan antara 5 hingga 8.5 GHz telah dicadangkan. Tag RFID tanpa wayar ini dicetak pada substrat Rogers RT5880 (15 mm × 25 mm). Respons simulasi RCS bagi tag kompak RFID 12-bit tanpa wayar turut dikira.

KEYWORDS: *Chipless RFID, L-shaped resonator, U-shaped resonator, compact size, Radar cross section (RCS), reading distance.*

1. INTRODUCTION

Radio frequency identification (RFID) is a wireless technology that automatically uses radio frequency signals (RF) to automatically identify objects. An RFID system comprises

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three main components: an RFID tag in which the data is encoded, an RFID reader used to encode the data extracted from the tags, and a host computer, Figure 1, [1]. RFID is commonly used in numerous applications such as security, asset tracking, automatic product identification, and library tracking books. RFID is gradually replacing the traditional barcode. However, the challenge in appropriately using RFID technology instead of conventional barcodes is the cost of the tag [2]. The tag cost depends on the cost of its IC. Thus, efforts have been concentrated on developing chipless RFID tags for low-cost communication systems [3], compact size, and high capacity. In [1], chipless RFID tags are classified into three categories: spectrum-signature-based, amplitude-phase-backscatter-modulation-based, and time domain reflectometry-based chipless RFID tags. Data is encoded into the spectrum using resonant structures in the spectrum-signature-based RFID tags. These tags have several advantages, including being fully printable, having a greater capacity rate, and being inexpensive.

Two techniques are used to design chipless RFID tags in the frequency domain: planar circuits [4] and LC resonators [5-8]. For instance, in [4], an array of identical 18 mm planar dipoles printed on TLY-5 substrate, supplied by Taconics with a thickness of 0.53 mm, a dielectric constant of 2.2, and (tan delta = 0.001), was capacitively tuned to operate between 5 and 6 GHz. Microstrip TL resonator structures were later introduced to increase bit capacity and obtain a compact size. A 6-bit 30 mm x 35 mm meandered microstrip TL tag operating from 3 to 5 GHz was presented in [5] as a chipless RFID tag printed on Taconic substrate with a dielectric constant of 2.75, a thickness of 1 mm, and ($tan\delta$ = 0.0003). Two prototypes of open-circuited stubs were used: straight-line and meandered-line stubs. The idea behind the meandered stubs is to reduce the size of the chipless RFID tag. Spurline resonators were an alternative in [6], enabling the design of 8-bit chipless tags within a compact 60 mm × 30 mm size. The tag was fabricated on a CMET/LK4.3 substrate with a dielectric constant of 4.3 and ($tan\delta$ = 0.0018) and operates from 2.38 to 4.04 GHz. Similarly, [7] presented open-stub microstrip resonators achieving 8-bit encoding over a broad frequency range of 1.9 to 4.5 GHz. The proposed tag was fabricated on a 50 mm x 30 mm substrate with a thickness of 1.6 mm, a dielectric constant 4.4, and ($tan\delta$ = 0.0018).

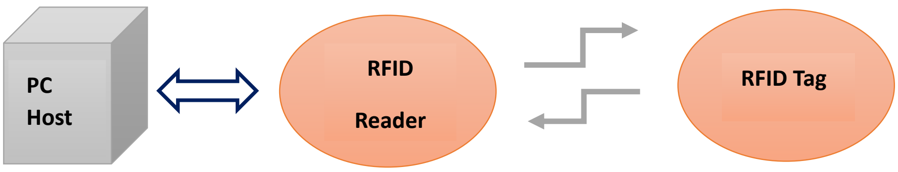


Figure 1. RFID block diagram.

An 8-bit L-shaped resonator on a 20 mm × 20 mm Rogers substrate was proposed in [8], operating between 3 and 6 GHz. In [9], an 8-bit tag with discontinuities was created using embedded passive components. The tags were modified for different IDs by connecting the specified discontinuities to the transmission line (TL). In the design, eight planar capacitors were used as discontinuities. The TL length was 400 mm. Multiple resonators were used simultaneously to achieve a compact chipless RFID tag and high capacity. The resonators are equivalent to parallel and series LC circuits for different bit combinations. Further size reductions and improved frequency control were explored through bending arm resonators in [10], where two 8-bit tag prototypes used single and dual-sided configurations, operating between 4.9 GHz and 5.7 GHz. Complementary split ring resonators (CSRRs) were used in [11] to design an 8-bit 25 mm × 50 mm tag operating over a wider frequency band (3.4–7.4 GHz) on a flexible polyethylene terephthalate substrate with a dielectric constant of 3.0 and (tand ($tan\delta$ = 0.002). To achieve high-capacity encoding, a 20-bit tag using a cross-loop resonator to support polarization independent of the incident wave was presented in [12], operating across a wide frequency band from 3.1 to 10.1 GHz. The proposed tag was printed on a 40 mm × 40 mm RT Duroid 5880 substrate with a dielectric comprised of 2.2 ($tan\delta$ = 0.0008), and a thickness of 1 mm. In [13], a 16-bit moisture-sensing tag printed on a 13.2 mm × 19.6 mm paper substrate with (thickness 1.25 mm, dielectric constant 3.2, and ($tan\delta$ = 0.04) was designed to operate over 0.5–14 GHz. The tag was loaded with different lengths and widths of slots for tuning.

Furthermore, different shape resonators: rectangular-shaped [14], triangular-shaped [15], T-shaped [16], and C-shaped [17] were proposed. The structures in [14-16] were designed based on a finite metallic frequency selective surface (FSS) with a size of (30 mm × 30 mm), (27.5 mm × 30 mm), and (15 mm × 15 mm), respectively. In [17], a C-shaped resonator-based chipless RFID tag was proposed. Five C-shaped resonators are designed on a FR-4 substrate of size (20 mm × 40 mm). The suggested tag operates over a frequency band (2.5 and 7.5 GHz). A spiral-resonator-based chipless RFID tag was suggested in [18]. The proposed tag is printed on 108 mm × 64 mm Taconic TF-290 laminate and encodes 23 bits. The operating spectrum of the design is between 5 GHz and 10.7 GHz. In [19], a chipless RFID tag consists of (6) spiral resonators placed next to a microstrip line. The design is printed on a Taconic TLX-0 substrate and operates over a 2- and 2.5 GHz frequency band.

Chipless RFID systems often face challenges balancing miniaturization with increased bit capacity and performance over wide frequency bands. This work introduces a compact and high-capacity chipless RFID tag to achieve high capacity within a reduced size by employing back-to-back L-shaped resonators, significantly improving conventional chipless RFID designs. Two compact 8-bit chipless RFID tag prototypes based on L-shaped and U-shaped resonators are designed and analyzed to address this issue. A novel 12-bit chipless RFID tag comprising back-to-back L-shaped resonators with varying lengths, corresponding to resonant frequencies between 5 and 8.5 GHz, is proposed to increase tag capacity further.

2. CHIPLESS RFID TAG DESIGN

In this work, different prototypes of resonator-based chipless RFID tags are presented. To design an 8-bit resonator-based chipless RFID tag, the number of resonators is relative to the number of encoding bits. The resonator is designed in this work as an open-circuited length of transmission line with L-section and U-section resonator types. Such a resonator behaves as a parallel RLC resonant circuit when the length is half a wavelength ($\frac{\lambda}{2}$), or multiples of half-wavelength ($\frac{\lambda}{2}$).The input impedance of an open-circuited line of length l is, [20]:

$$Z_{in} = Z_o \frac{1+j\tan\beta l \tanh\alpha l}{\tanh\alpha l + j\tan\beta l} \quad (1)$$

where, Z_{in} is the input impedance of the line, Z_o is the characteristic impedance of the line, β is the propagation constant, α is the attenuation constant, and $l = \lambda/2$ at $\omega = \omega_o$. The lumped element values in the equivalent parallel RLC circuit are calculated as, [20]:

$$R = \frac{Z_o}{\alpha l} \quad (2)$$

$$C = \frac{\pi}{2\omega_o Z_o} \quad (3)$$

$$L = \frac{1}{\omega_o^2 C} \quad (4)$$

where the resonant frequency, $\omega_o = \frac{1}{\sqrt{LC}}$. The proposed chipless RFID tag is printed on (14.5mm × 14.5mm) Rogers RT5880 substrate with a dielectric constant, $\varepsilon_r = 2.2$, and a thickness, $h = 1.575\ mm$. The effective dielectric constant, ε_{eff} , of the transmission line is calculated as, [20]:

$$\varepsilon_{eff} = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2}\frac{1}{\sqrt{1+12h/W}} \tag{5}$$

where, $h = 1.575\ mm$ is the thickness of the Rogers RT5880 substrate and W = 0.25 mm is the width of the resonator. The resonant frequency, f_o, is related to the resonator length, l, as:

$$f_o = \frac{c}{2l\sqrt{\varepsilon_{eff}}} \tag{6}$$

where, c is the free space velocity, l is the resonator length, and ε_{eff} is the effective permittivity. For Rogers RT5880 substrate and a transmission line of width W = 0.25 mm, the effective dielectric constant, ε_{eff} is calculated to be 1.67. The resonator length vs the corresponding resonant frequency, f_o is plotted in Matlab based on Eq.6, Figure 2. Table 1 summarizes the resonator lengths versus the corresponding resonant frequencies.

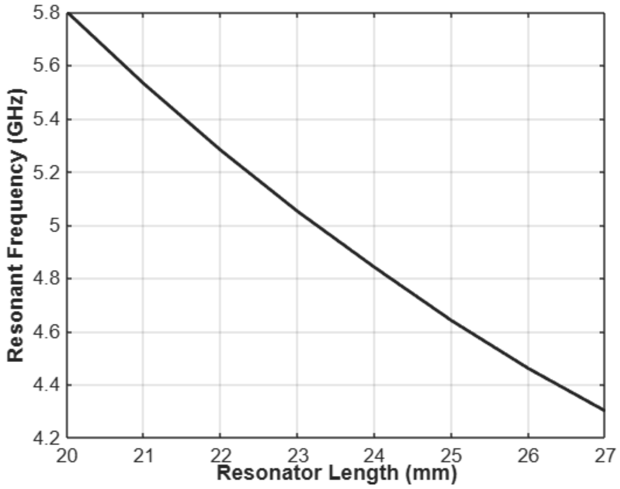


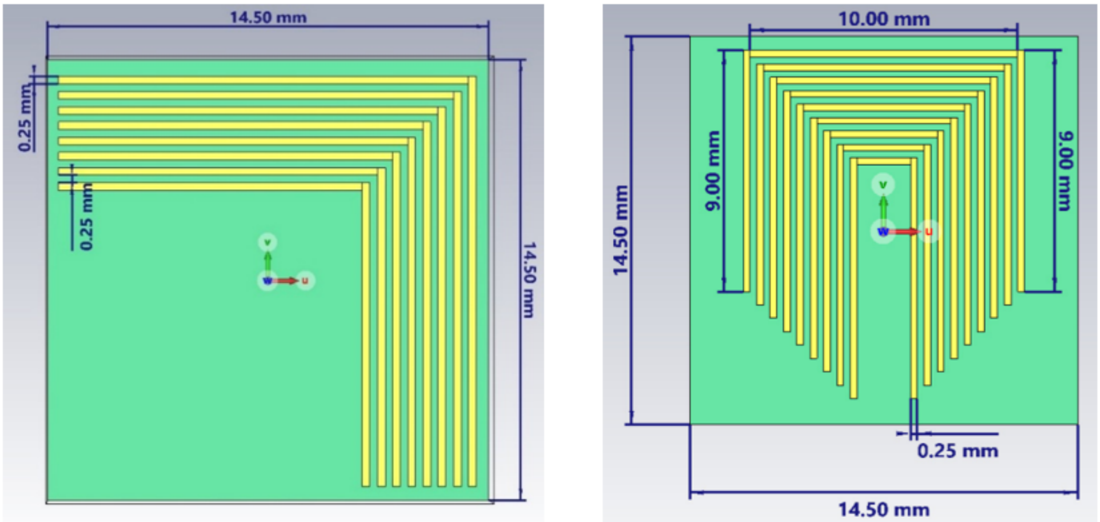
Figure 2. Resonator lengths vs corresponding resonant frequencies.

Table 1. Resonator lengths versus corresponding resonant frequencies for the 8-bit L-shaped resonator-based chipless RFID tag.

Resonator length (mm)	Resonant frequency (GHz)
27	4.30
26	4.46
25	4.64
24	4.84
23	5.05
22	5.28
21	5.53
20	5.80

The resonant frequency is inversely proportional to the resonator length. The lengths of the resonators are calculated such that the resonant frequencies extend between 4 and 6 GHz. Eight resonators are designed to correspond to an 8-bit chipless RFID tag. This work presents two compact-sized prototypes of 8-bit chipless RFID tags based on L-shaped and U-shaped resonators. The 8-bit L-shaped and U-shaped resonators are designed and simulated in CST.

Figure 3a and b show the L-shaped and U-shaped 8-bit resonators, respectively. The proposed tags are printed on (14.5mm × 14.5mm) Rogers RT5880 substrate with a dielectric constant, $\varepsilon_r = 2.2$, and a thickness, $h = 1.575\ mm$.



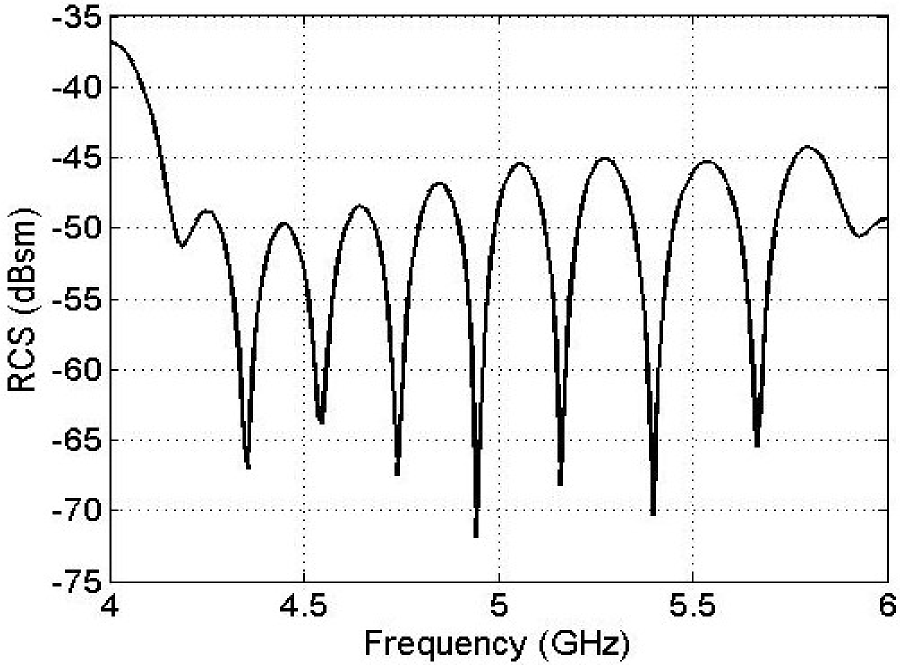
(a) (b)

Figure 3. (a) An eight-bit resonator-based chipless RFID tag. (a) L-shaped and (b) U-shaped resonator.

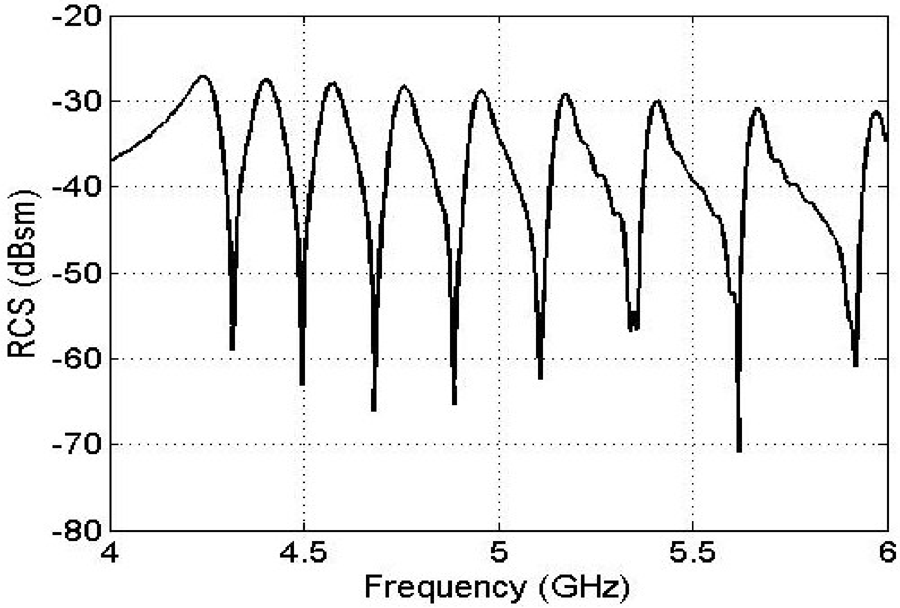
The basic concept for the chipless RFID system is the same as a monostatic radar system. Where the reader radiates a power P_{rad} with a gain G, the power density incident on the tag is, [20]:

$$P_{inc} = \frac{P_{rad}G}{4\pi R^2} \tag{7}$$

where R is the distance to the tag. The tag will scatter the incident power; the ratio of the scattered power P_{scat} to the incident power P_{inc} is described as the radar cross section (RCS). It depends on the incident and reflection angles, in addition to the polarization of the incident wave. The simulated RCS responses for both the L-shaped and the U-shaped 8-bit chipless RFID tags are shown in Figure 4a and b, respectively. The resonant frequencies calculated in Table 1 using Eq.6 are slightly different from the simulated resonant frequencies obtained in Figure 4. This difference in the resonant frequencies between the calculated and simulated ones is owing to the mutual coupling effect of nearby resonators. Based on Eq.6, the resonators are considered as isolated resonators. While in CST simulation, the mutual coupling effect is considered between adjacent resonators. Due to taking into consideration the mutual coupling effect, the simulated resonant frequencies are shifted compared to the isolated resonances. The L-shaped and U-shaped resonators are chosen in this design due to their ability to create compact current paths and support multiple resonant frequencies by adjusting resonator lengths without increasing the substrate dimensions. To increase the chipless RFID tag capacity, a prototype of 12 back-to-back L-shaped resonators with different lengths corresponding to different resonant frequencies between 5 and 8.5 GHz is proposed, Figure 5. The L-shaped resonators are arranged in a back-to-back manner that supports a compact size chipless RFID tag and decreases the mutual coupling effect between the successive elements.



(a)



(b)

Figure 4. Simulated RCS for the eight-bit resonator-based chipless RFID tag. (a) L-shaped resonator and (b) U-shaped resonator.

The proposed 12 back-to-back L-shaped resonators chipless RFID tag is printed on (15mm × 25mm) Rogers RT5880 substrate with a dielectric constant, $\varepsilon_r = 2.2$, and a thickness, $h = 1.575\ mm$. The low dielectric loss tangent (0.0009) and stable dielectric constant (2.2) over a wide frequency range make Rogers RT5880 substrate highly preferred for high-frequency RFID applications. The resonator lengths versus corresponding resonant frequencies are calculated based on Eq.6 and summarized in Table 2. The simulated RCS response for the compact size 12-bit L-shaped resonator-based chipless RFID tag is shown in Figure 6.

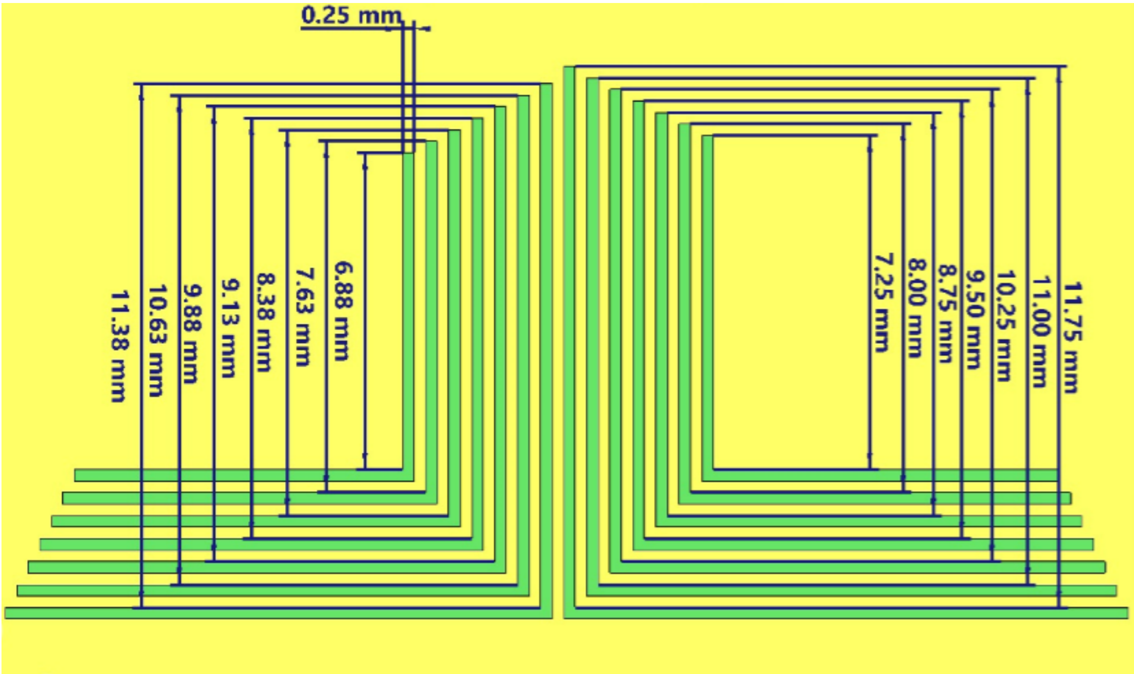


Figure 5. A compact size 12-bit L-shaped resonator-based chipless RFID tag.

The resonant frequencies calculated in Table 2 using Eq. 6 are slightly different from the simulated resonant frequencies obtained in Figure 6. This difference in the resonant frequencies between the calculated and simulated ones is due to the mutual coupling effect of nearby resonators. Based on Eq. 6, the resonators are considered as isolated resonators. While in CST simulation, the mutual coupling effect is considered between adjacent resonators. Table 3 summarizes the specifications for the three prototype chipless RFID tag designs. The suggested chipless RFID tag specifications in this study are compared to tags in the literature (Table 4). The proposed chipless RFID tag in this work offers a more compact size than those presented in references [8, 11, 14, 15, 17-19], while achieving a higher encoding bit capacity than implementations presented in references [8, 11, 14-17, 19].

Table 2. Resonator lengths versus corresponding resonant frequencies for the 12-bit L-shaped resonator-based chipless RFID tag.

Resonator length (mm)	Resonant frequency (GHz)
22.00	5.28
21.26	5.46
20.50	5.66
19.76	5.87
19.00	6.11
18.26	6.36
17.50	6.63
16.76	6.93
16.00	7.25
15.26	7.61
14.50	8.01
13.76	8.44

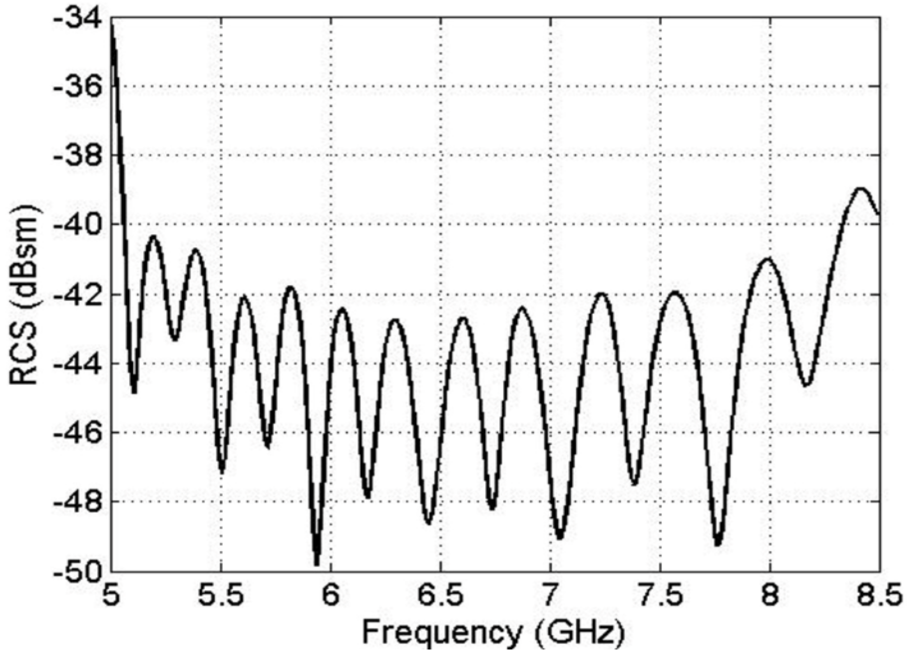


Figure 6. Simulated RCS for the compact size 12-bit L-shaped resonator-based chipless RFID tag.

Table 3. A summary of the specifications for the three prototype chipless RFID tag designs.

Chipless RFID Tag	Prototype 1	Prototype 2	Prototype 3
Structure	L-shaped resonator	U-shaped resonator	Back-to-back L-shaped resonator
Dimensions	14.5mm × 14.5mm	14.5mm × 14.5mm	15mm × 25mm
Capacity	8-bit	8-bit	12-bit
Substrate	Rogers RT5880	Rogers RT5880	Rogers RT5880
Bandwidth	4.0 to 6.0 GHz	4.0 to 6.0 GHz	5.0 to 8.5 GHz

Table 4. Comparison with other chipless RFID tags.

Benchmark	Capacity (bit)	Bandwidth (GHz)	Substrate	Dimensions (mm^2)
[8]	8	3.0 – 6.0	Rogers RT5880	20 mm × 20 mm
[11]	8	3.4 – 7.4	Polyethylene terephthalate	25 mm × 50 mm
[14]	5	2.0 – 8.0	FR-4	30 mm × 30 mm
[15]	10	4.0 – 11.0	FR-4	27.5 mm × 30 mm
[16]	10	5.0 – 15.0	FR-4	15 mm × 15 mm
[17]	5	2.5 – 7.5	FR-4	20 mm × 40 mm
[18]	23	5.0 – 10.7	Taconic TF-290 laminate	108 mm × 64 mm
[19]	6	2.0 – 2.5	Taconic TLX-0	66 mm × 60 mm
This work	12	5.0 – 8.5	Rogers RT5880	15 mm × 25 mm

3. CONCLUSION

Miniaturized L-shaped and U-shaped resonator-based 8-bit Chipless RFID tags are presented. The proposed tags are printed on (14.5mm × 14.5mm) Rogers RT5880 substrate with a 4 to 6 GHz frequency band. To increase the chipless RFID tag capacity, a prototype of 12 back-to-back L-shaped resonators with different lengths corresponding to different resonant frequencies between 5 and 8.5 GHz is proposed. The proposed 12 back-to-back L-shaped resonators chipless RFID tag is printed on (15mm × 25mm) Rogers RT5880 substrate with a frequency band from 5 GHz to 8.5 GHz. The simulated RCS responses for the compact size L-shaped and U-shaped resonator-based chipless RFID tags are calculated. The resonant frequencies for isolated resonators are calculated and compared with those of the mutually coupled resonators. Due to current limitations in fabrication, the manufacturing and experimental validation of the proposed tag are considered part of our future work to verify the simulation results. Additionally, future efforts will focus on using flexible substrates for applications on wearable or curved surfaces.

REFERENCES

[1] S. Preradovic and N. C. Karmakar, (2010), Chipless RFID: Bar Code of the Future. IEEE Microwave Magazine, 11(7), 87–97. DOI:10.1109/MMM.2010.93857.

[2] H. F. Huang and L. Su, (2017), A Compact Dual-Polarized Chipless RFID Tag by Using Nested Concentric Square Loops. IEEE Antennas and Wireless Propagation Letters, 16, 1036–1039. DOI:10.1109/lawp.2016.2618928.

[3] S. Preradovic, N.C. Karmakar, (2012), Low cost chipless RFID systems, in Multiresonator-Based Chipless RFID, Springer, New York, pp. 9–24. DOI:10.1007/978-1-4614-2095-8.

[4] I. Jalaly, I.D. Robertson, (2005), Capacitively-tuned split microstrip resonators for RFID barcodes. In IEEE European Microwave Conference, vol. 2. DOI:10.1109/EUMC.2005.1610138

[5] M. E. Jalil, M.K.A. Rahim, N.A. Samsuri, R. Dewan, (2014), Chipless RFID tag based on meandered line resonator. In IEEE Asia Pacific Conference on Applied Electromagnetics (APACE), Malaysia, pp. 203–206. DOI: 10.1109/APACE.2014.7043780.

[6] M. Sumi, R. Dinesh, C.M. Nijas, S. Mridula, P. Mohanan, (2014), Frequency coded chipless RFID tag using spurline resonators. Radio engineering, vol. 23, no. 1, 203–208.

[7] C. M. Nijas, R. Dinesh, U. Deepak, A. Rasheed, S. Mridula, K. Vasudevan, P. Mohanan, (2012), Chipless RFID Tag Using Multiple Microstrip Open Stub Resonators. IEEE Transactions on Antennas and Propagation, vol. 60, no. 9, pp.4429-4432. DOI:10.1109/TAP.2012.2207081.

[8] M. S. Hashimi, V. Sharma, (2020), Design, analysis, and realisation of chipless RFID tag for orientation independent configurations. The Journal of Engineering, vol. 2020 no. 5, pp. 189-196. Doi: 10.1049/joe.2019.0920.

[9] L. Zheng, R. Saul, L. Zhang, B. Shao, L. R. Zheng, (2008), Design and implementation of a fully reconfigurable chipless RFID tag using Inkjet printing technology. 2008 IEEE International Symposium on Circuits and Systems (ISCAS), May 2008, USA. DOI: 110.1109/ISCAS.2008.4541720.

[10] S. Jia; L. Xiuping; Z. Hua, (2017), Multiresonator-based chipless RFID system for low-cost application. 2017 Progress in Electromagnetics Research Symposium - Fall (PIERS - FALL), Nov. 2017, Singapore. DOI: 10.1109/PIERS-FALL.2017.8293197.

[11] M. E. Jalil, M. K. A. Rahim, N. A. Samsuri, R. Dewan, (2016), Flexible printed chipless RFID tag using metamaterial–split ring resonator. Applied Physics A Materials Science and Processing, (2016) 122:348. DOI 10.1007/s00339-016-9865-5.

[12] V. R. Sajitha, C. M. Nijas, T. K. Roshna, Kesavath Vasudevan, P. Mohanan, (2016), Compact cross loop resonator based chipless RFID tag with polarization insensitivity. Microwave and Optical Technology Letters, vol. 58, no. 4, pp. 944–947. Doi.org/10.1002/mop.29706.

[13] N. Javed, A. Habib, A. Akram, Y. Amin, and H. Tenhunen, (2016), 16-bit frequency signatured directly printable tag for organic electronics. IEICE Electronics Express, vol. 13, no. 11. DOI:10.1587/elex.13.20160406.

[14] F. Costa, S. Genovesi, A. Monorchio, (2013), A chipless RFID based on multiresonant high impedance surfaces. IEEE Transactions on Microwave Theory and Techniques, vol. 61, no. 1, pp.146-153. DOI: 10.1109/ TMTT.2012.2227777.

[15] S. Rauf, M. A. Riaz, H. Shahid, M. S. Iqbal, Y. Amin, H. Tenhunen, (2017), Triangular loop resonator based compact chipless RFID tag. IEICE Electronic Express, vol. 14, no. 4. DOI: 10.1587/elex.14. 20161262.

[16] M. A. Riaz, H. Shahid, S. Z. Aslam, Y. Amin, A. Akram, H. Tenhunen, (2017), Novel T-shaped resonator based chipless RFID tag. IEICE Electronic Express, vol. 14, no.18. DOI: 10.1587/elex.14.20170728.

[17] A. Vena, E. Perret, S. Tedjini, (2011), Chipless RFID Tag Using Hybrid Coding Technique. IEEE Transactions on Microwave Theory and Techniques, vol. 59, no. 12, pp. 3356 - 3364. DOI: 10.1109/TMTT.2011.2171001.

[18] S. Preradovic, S. Roy, and N. C. Karmakar, (2009), Fully printable multi-bit chipless RFID transponder on flexible laminate. In Proc. Asia-Pacific Micro. Conf., Singapore, pp. 2371–2374. DOI: 10.1109/APMC.2009.5385460.

[19] S. Preradovic, I. Balbin, N. C. Karmakar, and G. F. Swiegers, (2009), Multiresonator-based chipless RFID system for low-cost item tracking. IEEE Trans. Microw. Theory Tech., vol. 57, no. 5, pp. 1411–1419. DOI: 10.1109/RFID.2008.4519383.

[20] Pozar, D.M. (2005). Microwave engineering (2nd ed.). USA: John Wiley and Sons Inc.