Progress In Electromagnetics Research C, Vol. 149, 105-109, 2024

PIER C

(Received 2 September 2024, Accepted 22 October 2024, Scheduled 29 October 2024)

A Low Profile 20-Bit Frequency-Coded L-Shape Multi-Slot Resonator for Chipless RFID Applications

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ABSTRACT: This research work investigates the performance of a novel low profile 20-bit frequency coded L-shape slot loaded resonator for chipless RFID applications. The proposed chipless RFID comprises a CPW-fed UWB radiator and an L-shaped multi-slot resonator to achieve 20-bit data capacity. CPW technique is implemented to enhance antenna bandwidth and radiation characteristics. The designed UWB radiator covers the entire band from 3 to 12 GHz with better return loss. Also, the peak gain is measured as 6 dBi in the respective frequency spectrum. The proposed L-shaped frequency-coded multi-slot resonator is developed with a compact size of $23.6 \times 14.1 \times 1.6\,\mathrm{mm}^3$. Moreover, the frequency coding technique allows for a wide range of frequency combinations for data representation, as well as contributes to reducing the RFID tag size. The research holds significance in propelling RFID technology forward and ushering in a new era of small, efficient, and flexible data encoding solutions.

1. INTRODUCTION

Radio Frequency Identification (RFID) technology has evolved and reindustrialised enormous sectors by establishing efficient and automated data identification and tracking. Traditional RFID systems rely on electronic chips embedded within tags for data storage and transmission [1, 2]. However, the integration of such chips poses limitations in size, cost, and flexibility. Chipless RFID technology emerges as a promising alternative, offering advantages in terms of reduced complexity, cost-effectiveness, and enhanced flexibility in data encoding [3, 4]. Considering this era, microstrip radiators have gained primary attention in RFID applications due to their ability to achieve high gain and directivity while maintaining a compact form factor [5, 6]. The integration of resonant structures in RFID tags enhances the performance, particularly read range, data capacity, and reliability. Among various resonator designs, L-shaped open stub resonators have garnered attention for their simplicity, compactness, and effectiveness in RFID tag applications. Several authors proposed a few techniques based on the RFID applications. Vijay et al. [7] designed a chipless RFID for internet of things (IoT) applications to support 5G using spectral signature. The tag uses an open stub L structured resonator based on a hybrid data encoding technique with 12 bits of data capacity. Ref. [8] focuses on chipless RFID with 3-bit holding capacity to alter conventional barcodes for short-distance applications where one tag antenna has been multiplexed for both uplink and downlink purposes. Goudos et al. [9] presented a planar spiral-shaped antenna for a passive tag at ultra-high frequency band. The antenna size and gain have been minimized and optimized respectively based on the Artificial Bee Colony (ABC) algorithm. In addition, the work reported by Huang and Su [10] demonstrates a compact design of dual-polarized tag. The design highlights loop resonators of square shape arranged orthogonally for dual polarizations and holds up to 18 bits. Oliveira and Silva [11] proposed a design of Ultra High Frequency (UHF) RFID that features a meander line antenna. Coplanar Waveguide (CPW) elements are loaded to the antenna, and to achieve stable gain an optimization algorithm is applied. Most of the referred works have used complex algorithms to improve the RFID tag's holding capacity. The proposed work uses a simple CPW technique to enhance the antenna performance in terms of gain and reduce its size. On the other hand, an L-shaped multi-slot resonator is designed to improve the capacity of the RFID chipless tag.

2. ANTENNA DESIGN

The proposed CPW-fed I-slotted ultra-wideband (UWB) radiator is crafted on a rigid FR-4 substrate, with a thickness and a relative dielectric constant of 1.5 mm and 3.38 respectively as shown in Fig. 1. The design includes a radiator formed by combining rectangular and semi-circular patches with a CPW ground plane. The radiating patch is fed through a CPW line with the impedance of 50 ohm. Initially, the antenna width and length are determined using Equations (1) and (2). Therefore, the overall length and width of the proposed CPW I slotted antenna is $27.7 \times 29.9\,\mathrm{mm}^2$. Furthermore, to achieve wide impedance characteristics the I-shaped slot is incorporated in the middle of the radiating patch which modifies the surface current distribution in the radiating patch as depicted in Fig. 1(c). The designed antenna achieves the resonant fre-

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(a) (b) (c)

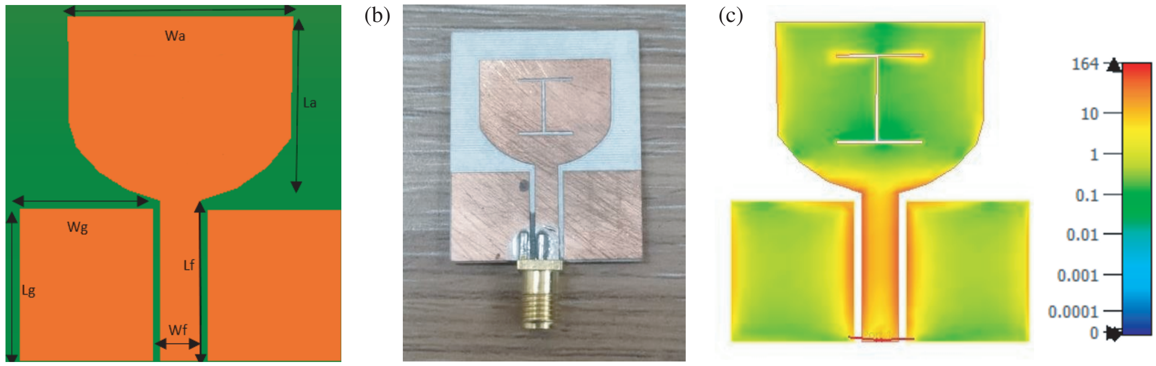

FIGURE 1. Antenna layout, (a) CPW I-slotted UWB antenna, (b) fabricated CPW I-slotted UWB antenna, (c) surface current $La = 22$, $Wa = 16$, $= 13.5$, $Wf = 2.3$, $Lg = 13$, $Wg = 10.6$, $Ls = 11$, $Ws = 17.6$ (All dimensions are in mm).

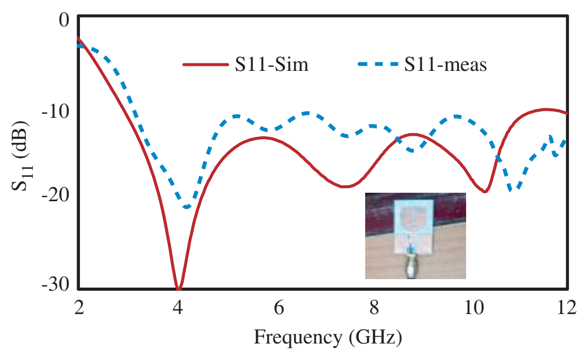

FIGURE 2. S_{11} characteristics of proposed CPW I-shaped slotted antenna.

quency bandwidth from 3 to 12 GHz which covers the ultra-wideband frequency range. The reflection characteristics of the proposed CPW-fed I slotted antenna is illustrated in Fig. 2 which includes both simulated and measured graphs.

$$W = \frac{c}{2f_0\sqrt{\frac{\varepsilon_r+1}{2}}} \tag{1}$$

$$L = \frac{c}{2f_0\sqrt{\varepsilon_{eff}}} - 0.824h\left\{\frac{(\varepsilon_{eff}+0.3)(\frac{W}{h}+0.264)}{(\varepsilon_{eff}+0.238)(\frac{W}{h}+0.8)}\right\} \tag{2}$$

3. PROPOSED 20-BIT MULTI-SLOT RESONATOR DESIGN AND EVOLUTION

Resonators play a crucial role in chipless RFID tags by encoding frequency information into the reflected signal, allowing for data storage and retrieval without the need for integrated circuits or chips. In the first iteration shown in Fig. 3(a), a single stub in an inverted "L" shape is introduced, which is attached to the transmission line, and 1 bit of data capacity at 2.5 GHz is achieved as portrayed in Fig. 3(a). In the second iteration shown in Fig. 3(b), the number of stubs is increased to three, resulting in 7 bits of data capacity, where the first 3 bits are present in the frequency range of 2–3 GHz, and the remaining 4 bits are in the range of 7–12 GHz.

When the number of stubs is increased to 12 in Fig. 3(c), the number of bits achieved is 14, where the first 9 bits occupy the frequency range of 2.5–6.5 GHz, and the remaining 5 bits occupy the range of 8–12 GHz. While 12 stubs are placed above the transmission line and 12 stubs below the transmission line in Fig. 3(d), 18 bits of data are achieved, where 12 bits could be accommodated in the frequency band of 2.44–4.04 GHz and the remaining 6 bits in the frequency band of 4.28–12 GHz. Finally, in Fig. 3(e), by adding 13 stubs above and below the transmission line, 20 bits of data are achieved, with the maximum number of bits in the range of 2.4–7.9 GHz, and the comparison graph is depicted in Fig. 4(b). Moreover, the resonance behaviour of the multi L-stub resonator is designed based on odd and even mode technique. The first odd-mode operating frequency can be determined as,

$$f = \frac{c}{4L_1\sqrt{\varepsilon_{eff}}} \tag{3}$$

$$f_{e1} = \frac{c}{4(L_1+L_3)\sqrt{\varepsilon_{eff}}} \tag{4}$$

$$f_{e2} = \frac{c}{4(L_1+L_2)\sqrt{\varepsilon_{eff}}} \tag{5}$$

The developed RFID tag setup is demonstrated in Fig. 3(f) having the transmitting antenna and RFID tag at transmitter side and the receiving antenna and RFID tag at the receiver side in order to transmit and decode the signal with 20 bit data capacity respectively. The proposed UWB antenna and resonator performance is measured and analyzed using Vector Network Analyzer (VNA) which is depicted in Fig. 5.

3.1. Results and Discussion

The simulated E and H plane co- and cross-polarization characteristics are illustrated in Fig. 6. The simulated & measured results exhibit that the antenna possesses very low cross-polarization level. The cross-polarization value of -15 dB is achieved at the operating frequency range. The antenna achieves an approximately isotropic radiation pattern in the H-plane (YZ $\Phi = 90°$) and an omnidirectional radiation pattern in the E-plane (XZ plane, $\Phi = 0°$) which is evident from the 2D radiation graph.

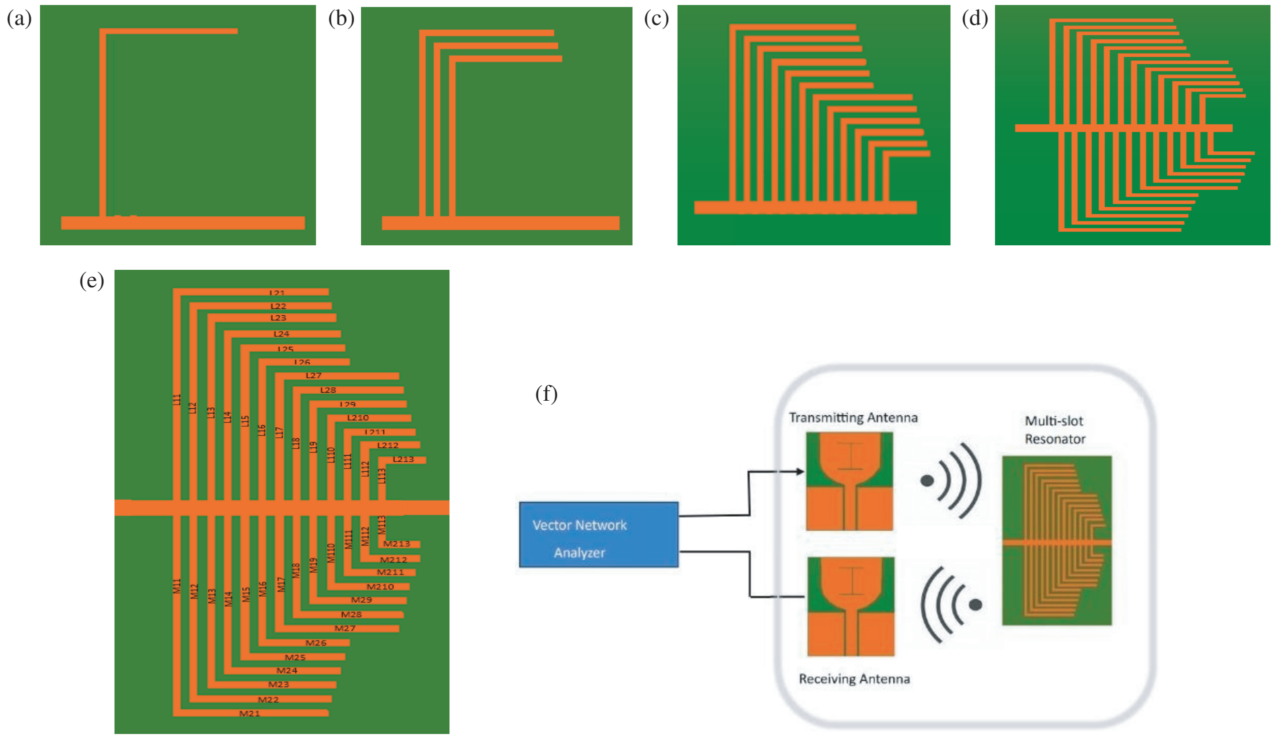

FIGURE 3. Different stages of proposed resonator. (a) First iteration. (b) Second iteration. (c) Third iteration. (d) Fourth iteration 4. (e) Fifth iteration. (f) RFID tag setup.

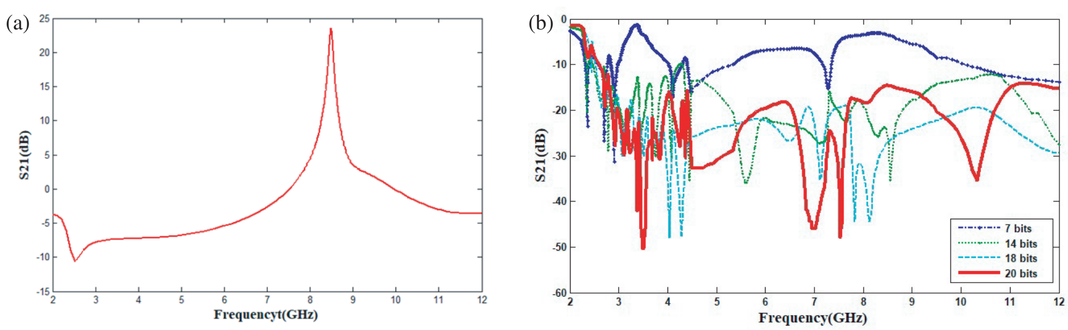

FIGURE 4. Evolution of multi stub resonator at different iterations, (a) 1 bit resonator, (b) different stages of the resonator from 7 to 20 bits.

4. SALIENT FEATURES OF THE PROPOSED WORK

(i) The proposed 20-bit RFID tag has 20-bit unique identifiers which allows a greater number of unique combinations.

(ii) Also, the developed RFID antenna has smaller bit size than higher bit tags. Hence, the processing and transmission of data are faster between the RFID reader and tag, further improving the speed of operations in real-time systems.

(iii) The proposed 20-bit RFID antenna and resonator occupy smaller size as $27.7 \times 29.9\,\text{mm}^2$ and $23.6 \times 14.1\,\text{mm}^2$ which reduces the overall size of the RFID system.

(iv) The designed RFID tag is suggested to use for applications such as inventory management, library system, and asset tracking in industries, since the antenna supports 20-bits RFID tag.

(v) The proposed antenna is cost effective and reduces the system complexity.

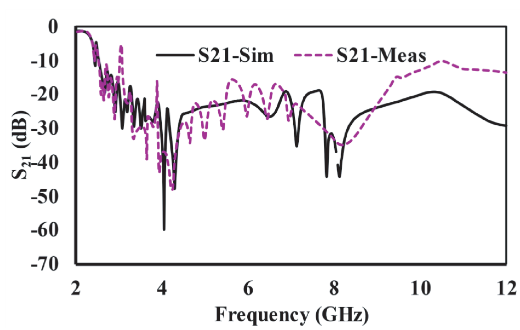

FIGURE 5. Measured and simulated image with Measurement setup.

TABLE 1. Performance comparison with other related research works.

R. No	Resonator type	Overall size (mm^2)	Frequency Range (GHz)	No. of bits
[12]	Microstrip stub resonator	30×25	1.9–4.5	8
[13]	CPW multi-resonator	154×55	3–6	8
[14]	Triple mode resonator	57×43	1.9–3.75	3
Prop. work	**L-shaped multi-slot resonator**	**21.3×12.8**	**2.6–10.6**	**20**

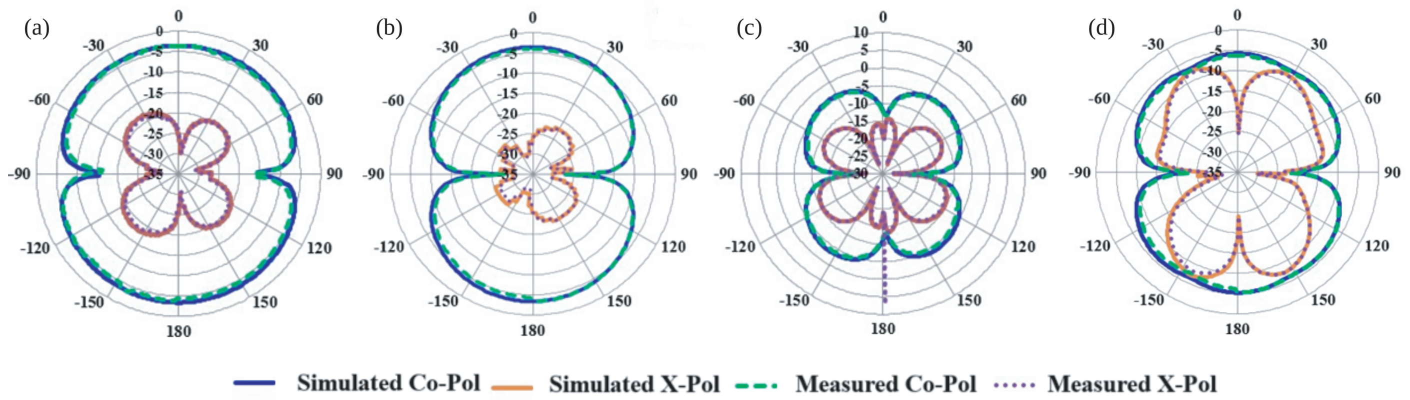

FIGURE 6. Far-field radiation characteristics of the I-slotted antenna, (a) 2 GHz, (b) 4 GHz, (c) 8 GHz, (d) 10 GHz.

The performance of the proposed work is analysed by comparing it with the related references mentioned in Table 1. Table 1 shows that the proposed resonator is smaller in size and covers broader range of bandwidth.

5. CONCLUSIONS

The conventional chip-based RFID tags, while are widely used, face limitations in complexity, size, and power consumption. Addressing these concerns, a 20-bit frequency-coded chipless RFID tag has been developed, replacing the integrated chip with an antenna and resonator. The proposed design features an ultra-wideband CPW-fed I-slotted microstrip patch radiator with a peak gain of 6 dBi and dimensions of $27.7 \times 34 \times 1.6\,mm^3$, coupled with an L-shaped slot-loaded resonator for frequency encoding with dimensions of $23.6 \times 14.1 \times 1.6\,mm^3$. Through fabrication and comparison of measured and simulated responses, the system demonstrates efficiency for UWB and RFID applications, promising a new era of compact, efficient, and adaptable data encoding solutions.

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