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First-Order Minkowski Fractal Circularly Polarized Slot Loop Antenna with Simple Feeding Network for UHF RFID Reader

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Abstract—A circularly polarized (CP) antenna with simple feeding network for ultra-high-frequency (UHF) radio-frequency identification (RFID) reader application is presented in this letter. The proposed antenna consists of a slot loop etched on the ground and a simple feeding network using bended microstrip lines. And the two parts of the antenna are printed on either sides of a thin substrate, thus a low-profile antenna is obtained. The slot loop is meandered based on the first-order Minkowski fractal technique for antenna size reduction. To generate circularly polarized radiation, two branches of the feeding network are designed to be orthorhombic with 90° phase difference. The antenna is simulated and practically fabricated with a compact size of $80 \times 80 \times 1.6\,\text{mm}^3$. The 10-dB impedance bandwidth and 3-dB axial-ratio (AR) bandwidth are measured to be 50 MHz (0.896–0.946 GHz) and 12 MHz (0.916–0.928 GHz), respectively. The measured peak gain exhibits stable value of 3 dBi over the impedance bandwidth. Furthermore, a wide 3-dB beamwidth of 120° is achieved for the proposed antenna. Based on the above, this antenna is well suited for applications in UHF RFID handheld readers.

1. INTRODUCTION

In recent years, radio frequency identification (RFID) technology has attracted extensive attention and shown great potential in applications including logistics management system, access control system and electronic toll-collection system, etc. [1, 2]. RFID is a non-contact auto-identification technology used to identify either static or mobile objects by electromagnetic coupling in the space [3]. Compared with the contact recognition technology established on mechanical or optical connection, RFID has the advantages of faster transmission rate, longer readable range, better anti-interference ability, etc.

For RFID technology, circularly polarized (CP) reader antenna plays an important role in the system. It is known that most of the RFID tag antennas are linearly polarized (LP), while CP reader antenna can receive tag information regardless of the tag antenna's polarization, thus CP characteristics can reduce the mismatch of the polarization between the tag and reader antennas. Therefore, the high-performance RFID reader antennas with the characteristics of compactness, low profile and especially circularly polarized feature are ever increasingly demanded in the practical RFID applications [3]. The general frequency band of UHF RFID system for global applications is 840–960 MHz, while different countries have different frequency divisions in the UHF band, such as 840.5–844.5 MHz and 920.5–924.5 MHz bands in China, 866–869 MHz and 920–925 MHz in Singapore, and 902–928 MHz in America [2].

To realize CP characteristics, there are many methods proposed in previous studies. The edge truncated method is more useful and traditional which usually needs a substrate with high dielectric constant and high thickness [4, 5]. Due to their own structural characteristics, some feeding networks

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can realize 90° phase difference and equal amplitude between their two output ports directly, such as power divider and branch-line coupler [6, 7]. They can realize CP feature well, while these feeding networks are complicated. The aperture coupling antenna realizes circular polarization by coupling the two orthogonal slots through a feeding network with a phase difference of ±90° and radiates energy through the radiation patch located on the upper layer [8, 9]. This stacked structure is not suitable for compact antenna, especially for some handheld reader devices.

In this paper, a single layer slot loop patch antenna with a simple feeding network is presented for UHF RFID handheld reader applications. A slot loop which has the length of one wavelength is etched on the ground plane. Meanwhile, the first-order Minkowski fractal technique [10] is employed on the slot loop to achieve a compact antenna structure. Finally, the designed feeding network has produced two orthogonal working modes in the slot, and the two modes have a 90° phase difference. Therefore, the ideal circular polarization characteristics are obtained in the far field. The main contributions of this work are summarized as follows. Firstly, wide 3-dB AR beamwidth is obtained, and wider AR beamwidth can widen the range of recognition for RFID applications. Secondly, the volume of the antenna is reduced while keeping a similar performance. Meanwhile, the superiority of the simple structure and low-profile characteristics can contribute to the fabrication.

2. ANTENNA DESIGN

The geometry of the proposed antenna is illustrated in Fig. 1. It consists of two main parts, the radiation part and feeding network. The radiation part, shown in Fig. 1(a) with a slot loop, is printed on the top side of an FR4 substrate with thickness of 1.6 mm and a relative permittivity of 4.4. The feeding network, shown in Fig. 1(b), is located on the bottom of the substrate, and one port of the feeding network is connected to an SMA connector. The other two ports are underneath the slot loop structure.

To generate the CP performance, a simple feeding network using bended microstrip lines is utilized. The equivalent model of the feeding network is shown in Fig. 1(d), and it needs to satisfy three basic

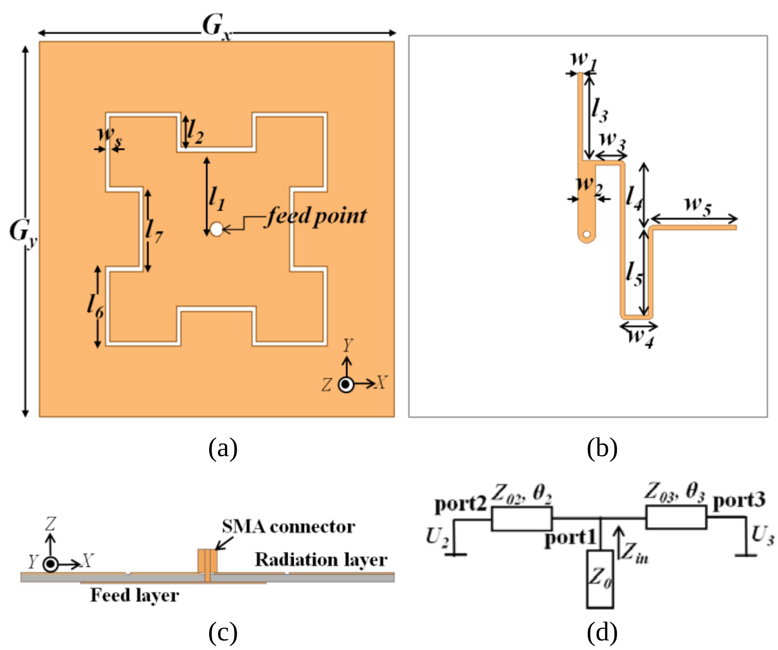


Figure 1. Structure of the proposed antenna: (a) radiation layer, (b) feeding network, (c) side view, (d) the equivalent model of the feeding network. ($G_x = G_y = 80$ mm, $l_1 = 16.5$ mm, $l_2 = 8.5$ mm, $l_3 = 15$ mm, $l_4 = 11$ mm, $l_5 = 16$ mm, $l_6 = 17$ mm, $l_7 = 18$ mm, $w_s = 1$ mm, $w_1 = 0.75$ mm, $w_2 = 3$ mm, $w_3 = 5$ mm, $w_4 = 5.5$ mm, $w_5 = 15$ mm).

demands [11]. Firstly, port1 has no reflection, i.e., $Z_0 = Z_{in}$, where $Z_{in} = (Z_{02} \cdot Z_{03})/(Z_{02} + Z_{03})$. Secondly, the output voltages of port2 and port3 need to be equal. Finally, the output powers of the two ports are equal, so $Z_{02} = Z_{03} = 2 \cdot Z_0$. Based on the comprehensive analysis, the input port is connected to the microstrip line with characteristic impedance of 50-Ohm for good impedance matching, and then the microstrip line is divided into two shunt parts with the characteristic impedance of 100-Ohm in this design. The two shunt parts feed in the center of horizontal and vertical slots respectively, to generate two orthogonal modes for the antenna. The difference of the electric length between two shunt parts is equal to quarter wavelength, i.e., $|\theta_2 - \theta_3| = \lambda_g/4$, which can exert 90° phase difference between the two coupling ports, so that the circularly polarized characteristics can be realized.

As for the radiation part, a rectangular slot loop with one wavelength is etched on the ground plane. And the first-order Minkowski fractal technique is utilized in the slot loop to achieve the compactness of the antenna. Compared to the aperture coupling antennas published in the past, the slot loop structure proposed in this antenna can not only couple energy from the feeding network but also radiate energy to the far field. Thus a single layer and low-profile antenna can be achieved. The final detail dimensions of the antenna are attached in the caption of Fig. 1.

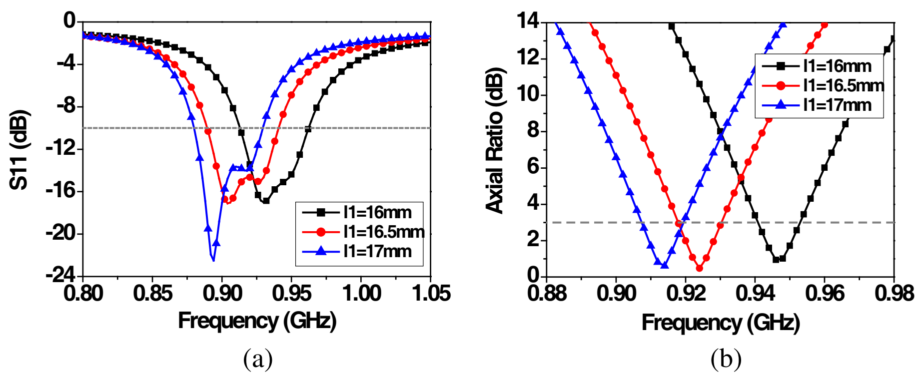


Figure 2. Simulation results of various dimensions of l_1: (a) S-parameter, (b) axial ratio.

To better understand the working mechanism of our proposed CP antenna, we analyze a set of parameters to verify the dimensions' influence on the antenna performance. The length of slot loop, l_1, and the length, l_3, of the shorter branch of the feeding line are studied. As shown in Fig. 2(a), the resonance frequency declines with the increase of the slot length. The CP characteristics present the same trends with S-parameters as shown in Fig. 2(b). Thus parameter l_1 can be used to adjust the operating frequency with good CP feature. Besides, the other parameters of the slot, like l_2 and l_6, have the same influence on S-parameters and AR as l_1, according to the inverse ratio rule of the electric length and resonant frequency. The S-parameters deteriorate when the length of the shorter branch of the feeding line l_3 increases as shown in Fig. 3(a). When l_3 equals 13 mm, S_{11} becomes better while the bandwidth is reduced. Additionally, the length differences of two feed branches will decrease when l_3 is increased while other feed line parameters keep fixed. Thus, the phase difference and amplitude ratio of the two orthogonal electric field components will also be changed as indicated in Figs. 3(b) and (c). When the phase difference is not near 90° and the amplitude ratio of the two orthogonal electric field not near 1 around the design frequency, the CP performance becomes bad, as shown in Fig. 3(d).

To explain the mechanisms of circular polarization clearly, the electric field distributions at 0.921 GHz with phases of 0°, 90°, 180° and 270° are illustrated in Fig. 4. When the phase degree equals 0°, the main electric field line points to $+Y$-axis. When the phase degree increases to 90°, the direction turns to $+X$-axis. The opposite electric field distributions of 0° and 90° are obtained, when phase equals 180° and 270°, respectively. As aforementioned, it is possible to conclude that the rotational direction of the electric field is clockwise along with input phase changing. Therefore, the antenna presents the characteristic of left-hand circular polarization (LHCP) in the $+Z$-axis direction. Furthermore, the antenna obtains a considerable 3-dB AR beamwidth of nearly 120° as shown in Fig. 5, which is much larger than the circularly polarized square-ring antenna proposed in [6].

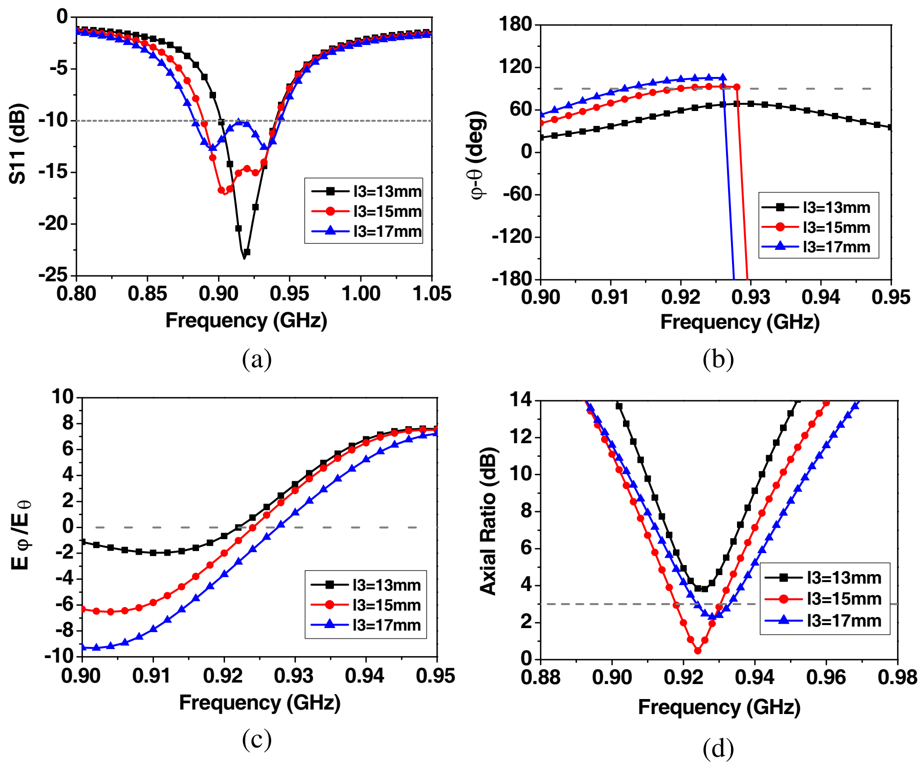


Figure 3. Simulation results of various dimensions of l_3: (a) S-parameter, (b) phase difference, (c) amplitude ratio, (d) axial ratio.

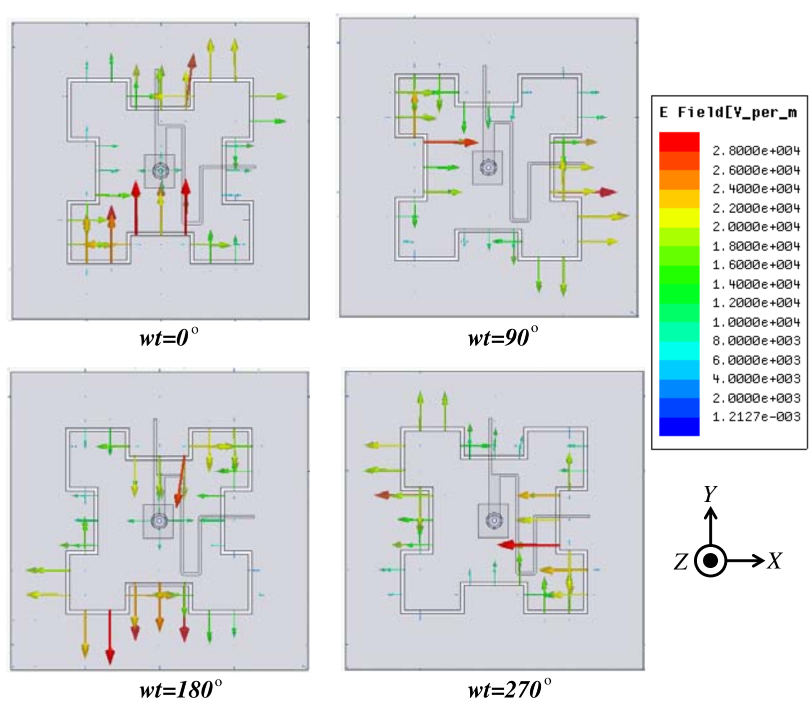


Figure 4. Electric field distribution at 0.921 GHz in the radiation patch of the proposed antenna.

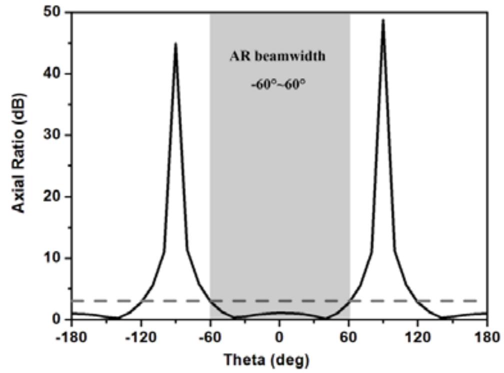


Figure 5. 3-dB AR beamwidth at the frequency of 0.921 GHz of the compact and low-profile antenna.

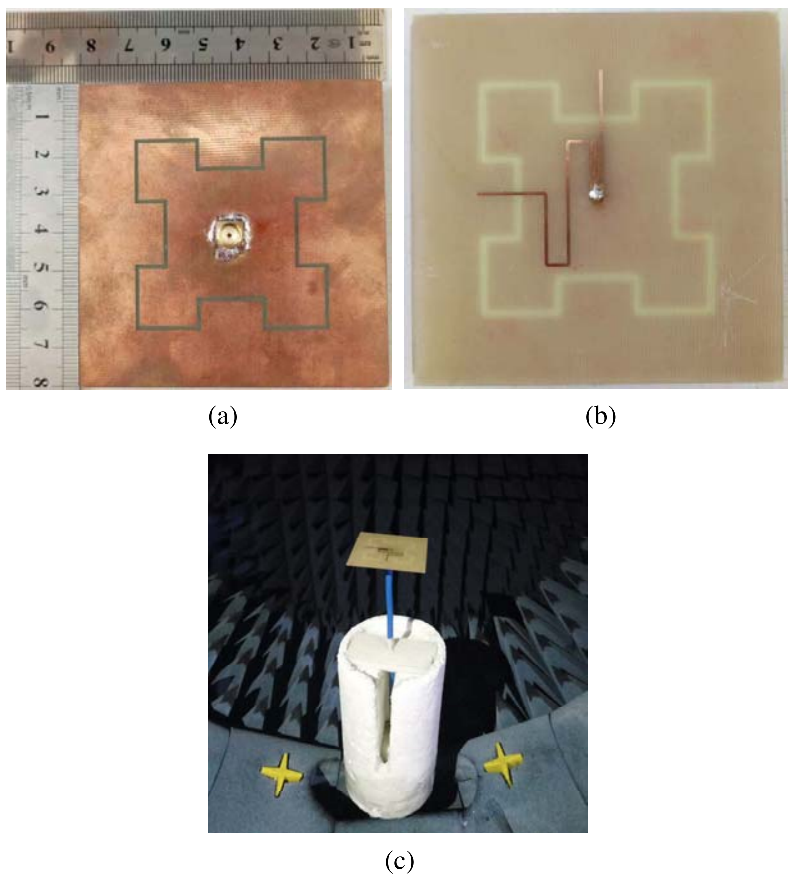


Figure 6. Photographs of the fabricated prototype: (a) top view, (b) bottom view, (c) far-field measurement setup.

3. RESULTS AND DISCUSSION

To verify the proposed antenna's performance, a prototype of the antenna is fabricated and measured. Fig. 6 shows the fabricated antenna and the far-field measurement setup. The simulated and measured return losses of the proposed antenna are exhibited in Fig. 7, and good agreement is observed. The measured results exhibit a 10-dB bandwidth of 50 MHz (0.896–0.946 GHz, 5.4%) with the central frequency of 0.921 GHz, and the simulated results also exhibit a 10-dB bandwidth of 50 MHz (0.89–

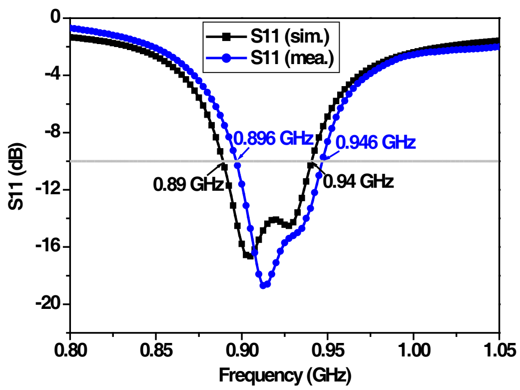


Figure 7. Simulated and measured return losses (S_{11}) of the compact and low-profile antenna.

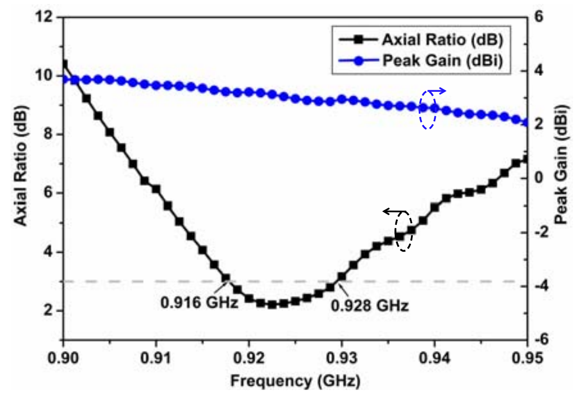


Figure 8. Measured axial ratio and peak gain of the proposed antenna.

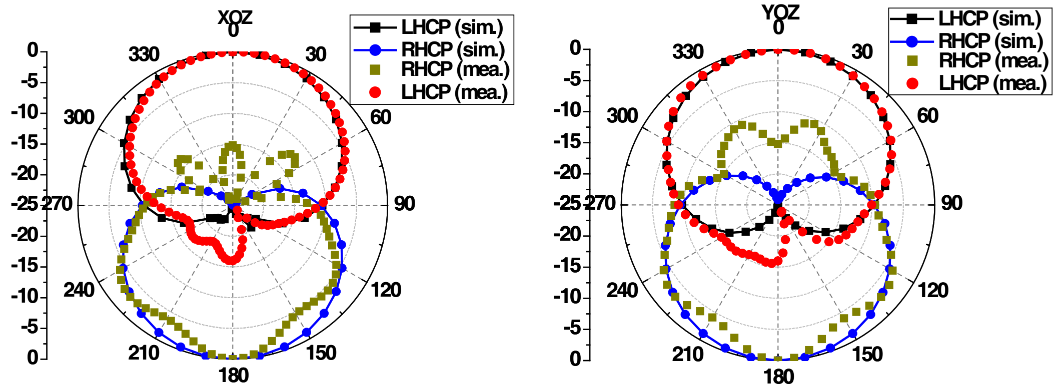
0.94 GHz) with the central frequency of 0.915 GHz. The slight frequency shift is probably from the fabricated tolerance. The peak gain and axial ratio of the proposed antenna are measured in an authorized anechoic chamber, and the measured results are illustrated in Fig. 8. The antenna exhibits a stable gain of 3 dBi within the impedance bandwidth. Although the gain is not high enough, it can be used for the UHF RFID reader system sufficiently. The 3-dB AR bandwidth ranges from 0.916 GHz to 0.928 GHz in the measured results. Regardless of the fact that the axial ratio bandwidth is narrower than the impedance bandwidth, it is enough for UHF RFID reader antenna used in 0.920–0.925 GHz band.

The simulated and measured CP radiation patterns of the proposed antenna at both XOZ- and YOZ-planes for the center frequency of 0.921 GHz are shown in Figs. 9(a) and (b) respectively. The measured results show good agreement with the simulated ones. The slight difference may be due to the fabrication errors and oxidation of metal. In the $+Z$-axis direction, the proposed antenna is mainly expressed as left-hand circularly polarized, which coincides with the above analysis. The measured 3-dB beamwidths at the center frequency of 921 MHz are 96° and 104° on the XOZ- and YOZ-planes, respectively.

Table 1 presents the comparison between the proposed antenna and several published relevant CP antennas in terms of size, bandwidth, maximal gain and 3-dB AR beamwidth. Due to a simple feeding network and a bended slot loop, the proposed antenna obtains the most compact size and one of the lowest profiles in the comparison, but the gain is not the best. Although the working bandwidth of the proposed antenna is not the widest, it has the widest 3-dB AR beamwidth.

Table 1. Comparison of circularly polarized UHF RFID reader antenna.

Ant.	Impedance bandwidth (MHz)	3-dB AR bandwidth (MHz)	Maximal gain (dBi)	3-dB AR beamwidth (deg.)	Size $l \times w \times h$ (mm^3)
Ref. [3]	899–916	904–909	3.5	100	$90 \times 90 \times 4.57$
Ref. [7]	880–1100	901–930	7.3	75	$150 \times 150 \times 33$
Ref. [8]	725–1129	875–955	2.5	70	$95 \times 95 \times 1.6$
Ref. [12]	748–1076	805–970	3.1	-	$95 \times 100 \times 13.6$
Proposed	896–946	916–928	3.2	120	$80 \times 80 \times 1.6$



(a) (b)

Figure 9. Measured and simulated radiation patterns in (a) XOZ-plane and (b) YOZ-plane at the center frequency of 0.921 GHz.

4. CONCLUSION

A low-profile and circularly polarized antenna with a simple feeding network for a UHF RFID handheld reader system is presented in this letter. A simple feeding network using bended microstrip lines have been adopted to generate CP radiation. The size of the proposed antenna is significantly reduced by utilising the first-order Minkowski fractal technique on the slot loop. As a result, the low-profile antenna obtains a compact size of $80 \times 80 \times 1.6\,\text{mm}^3$, which is suitable for RFID handheld readers. The antenna obtains a 10-dB impedance bandwidth of 50 MHz (0.896–0.946 GHz), 3 dB axial ratio bandwidth of 12 MHz (0.916–0.928 GHz) and stable gain of 3 dBi. Additionally, the antenna has a wide 3-dB AR beamwidth of 120°, which is desirable for wide-coverage RFID applications.

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