Planar Broadband Circularly Polarized Antenna With Square Slot for UHF RFID Reader

Jui-Han Lu, *Senior Member, IEEE*, and Sang-Fei Wang

***Abstract*—Novel circular polarization (CP) design of planar broadband antenna with square slot for UHF RFID system is proposed and experimentally studied. By insetting the arc-shaped strip into the square slot, the proposed CP design can easily be achieved with the impedance bandwidth (RL $\geq$ 10 dB) of about 142 MHz (15.3% @ 931 MHz) and the 3 dB axial-ratio (AR) bandwidth of about 166 MHz (17.7 % @ 940 MHz) for UHF RFID applications. The measured peak gain and radiation efficiency are about 6.8 dBic and 98% across the operating band, respectively, with nearly bidirectional pattern in the XZ- and YZ-plane.**

***Index Terms*—Broadband, circular polarization, square slot.**

I. Introduction

RECENTLY, UHF (860–960 MHz) band radio-frequency identification (RFID) system becomes more attractive for many industrial services such as supply chain, tracking, inventory management and bioengineering applications because it can provide longer reading distance, fast reading speed and large information storage capability. The RFID reader antenna is one of the important components in RFID system and has been designed with CP operation. The detection range and accuracy are directly dependent on the performance of reader/tag antennas. Since the RFID tags are always arbitrarily oriented in practical usage and the tag antennas are normally linearly polarized, circularly polarized (CP) antennas become the most popular candidates to receive the RF signal that emanates from arbitrarily oriented tag antennas for improving the reliability of communications between readers and tags. Moreover, circularly polarized antennas can reduce the loss caused by the multi-path effects between the reader and the tag antenna. However, the UHF frequencies authorized for RFID applications are varied in different countries and regions. Hence, a universal reader antenna with desired performance across the entire UHF RFID band operated at 860–960 MHz (a fractional bandwidth of 11.1%) would be beneficial for the RFID system configuration and implementation to overcome the operating frequency shift and impedance variations due to the manufacturing process errors. Circular polarization can be obtained by exciting the two orthogonal linearly polarized modes with a 90° phase offset. Numerous CP reader antennas for UHF RFID system have been presented such as the aperture-coupled annular ring patch antenna with thick high-dielectric substrate [1], a sequentially fed stacked corner-truncated CP patch antenna [2], the stacked patch antenna composed of two corner-truncated patches with a horizontally meandered strip [3], a circularly polarized patch antenna excited by an open circular ring microstrip line through multiple slots [4], asymmetric-circular shaped slotted microstrip antenna [5]. Although, the above mentioned reader antennas are focused on the unidirectional radiation pattern, they have disadvantage of bulky volume [1], [3], [4] or complex structure [2]. The reader antenna with bidirectional radiation can be introduced in the entry-way scanning system to minimize the number of needed reader antennas with unidirectional radiation, which definitely reduces the implemented cost. Two RFID reader antennas have also been presented such as the square-ring antenna fed by a Wilkinson power divider [6] and the annular-ring slot antenna with a slotline feed [7]. The former design is with less antenna gain while the latter design is with narrower 3-dB AR bandwidth which can't meet the overall bandwidth specification of global RFID system. Under the condition of the same antenna size, using a printed slot antenna is a certain method, which is due to the fact that printed slot antennas usually have a wider impedance bandwidth than the microstrip patch antennas [8]–[10], can be the effective way to improve the operating bandwidth. Several slot antennas with CP operation have been presented such as the slot antenna with the truncated corner and a grounded inverted-L strip at the two opposite corners [11], with a T-shaped stub and a microstrip T-junction [12], with multi parallel slots [13], a pair of orthogonally positioned radiating slots with a three-stub hybrid coupler as the feeding network [14], a stair-shaped slot antenna with a longitudinal slot etching at the middle part [15] and a number of CP slot antennas fed by an L-shaped strip [16]–[23]. However, wide slot antennas with CP design for UHF RFID system are very scant in the open literature. Therefore, in this article, we present a novel CP design of planar broadband UHF RFID reader antenna with bi-directional reading pattern. This RFID reader antenna is composed of the square slot antenna with the insetting grounded arc-shaped strip and fed by the F-shaped microstrip line to obtain the broadband CP operation. Due to the grounded arc-shaped strip to disturb the surface electric field distribution on the square slot, two near-degenerated resonant modes (TE_{10} and TE_{01} modes) with 90 degrees phase difference can be closely excited to form a wider CP operating bandwidth for UHF band. The obtained impedance bandwidth across the operating band can reach about 142 MHz (15.3% centered at 931 MHz) and the 3 dB axial-ratio (AR) bandwidth of about 166 MHz (17.7% centered at 940 MHz). With bi-directional reading pattern, the maximum antenna peak

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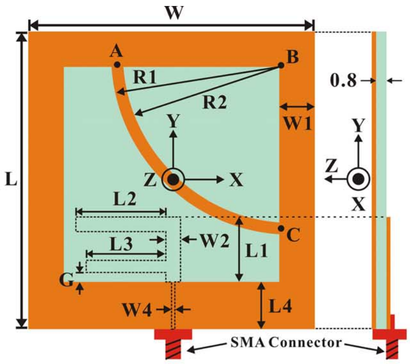
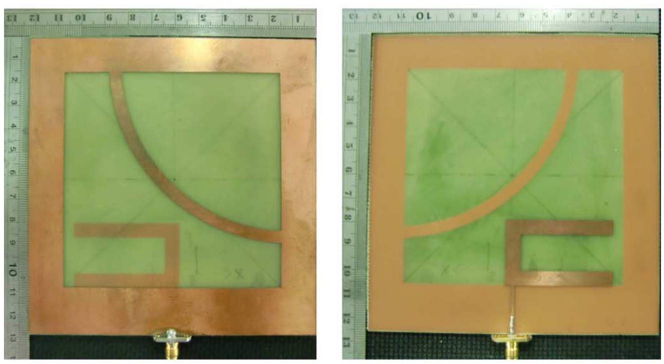


(a)



Top view

Bottom view

(b)

Fig. 1. Geometry and photograph of the proposed planar broadband circularly polarized antenna with square slot for UHF RFID Reader. (a) Geometry, (b) Photo.

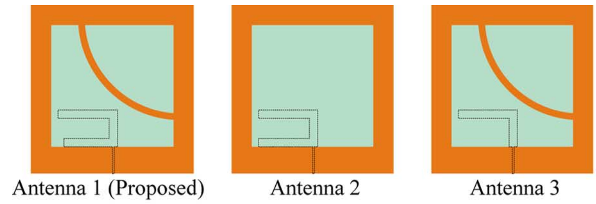
TABLE I
THE OPTIMAL DIMENSIONS OF THE PROPOSED BROADBAND CIRCULARLY POLARIZED ANTENNA WITH SQUARE SLOT

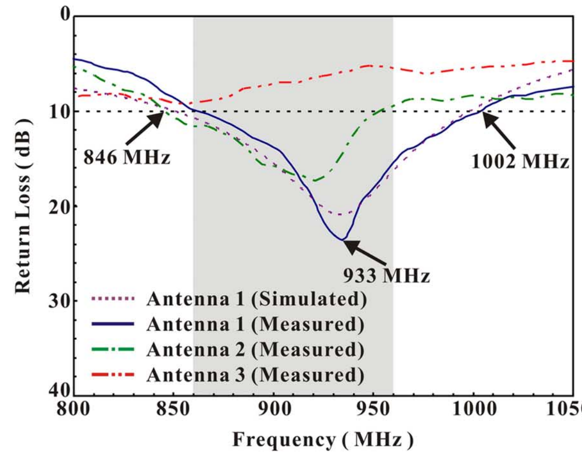
Parameter	Value (mm)	Parameter	Value (mm)
L	126	W	121
L1	27.5	W1	15
L2	38	W2	6.2
L3	38	W4	1.48
L4	20	R1	71
G	0	R2	66

gain and radiation efficiency across the operating band are about 6.8 dBic and 98%, respectively, which is more than that of the presented square-ring antenna [6]. Noted that a square metallic reflector can be arranged below the slot antenna to provide a unidirectional broadside patterns and reduce the backlobe radiation; its physical position is about one-quarter wavelength below the slots [15]. Details of the proposed UHF RFID reader antenna design is described and its experimental results from the obtained CP performance as operating at 900 MHz band are presented and discussed as well. A parametric study for the major parameters of the proposed CP antenna is also conducted.

II. Antenna Configuration and Design Consideration

The geometry and photograph of the proposed broadband circularly polarized antenna with square slot is shown in Fig. 1. The circularly polarized antenna with the total antenna size of 126×121 mm^2 is printed on an FR4 substrate





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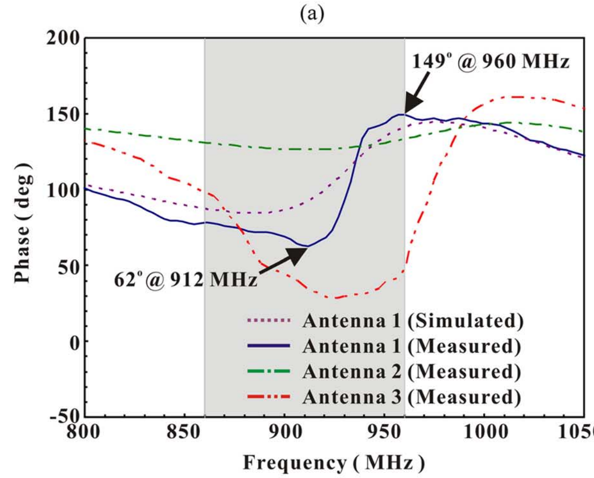

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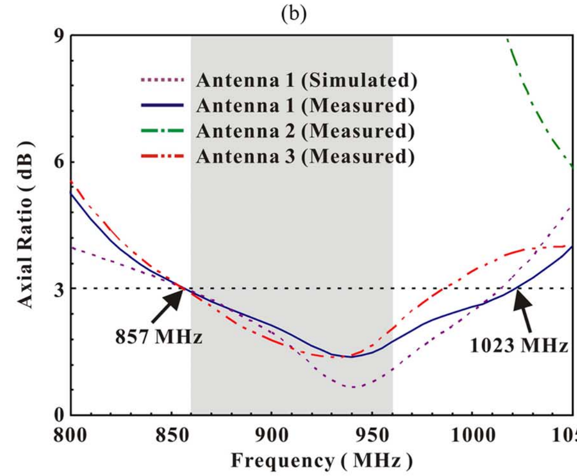


(c)

Fig. 2. Simulated and measured results against frequency for the proposed planar broadband circularly polarized antenna with the grounded arc-shaped strip or not. (a) Return Loss. (b) Phase diagram. (c) Axial Ratio.

($\varepsilon_r = 4.4$, thickness $= 0.8$ mm, loss tangent $= 0.0245$). The optimal dimensions of this proposed broadband circularly

TABLE II
SIMULATED AND MEASURED RETURN LOSS AND AXIAL RATIO AGAINST FREQUENCY FOR THE PLANAR BROADBAND CIRCULARLY POLARIZED ANTENNA WITH THE GROUNDED ARC-SHAPED STRIP OR NOT

	$f_L \sim f_H$ (MHz) (RL $\geqq$ 10 dB)	Center Frequency (MHz)	B.W. (MHz / %)	$f_L \sim f_H$ (MHz) (AR $\leqq$ 3 dB)	Center Frequency (MHz)	B.W. (MHz / %)
Antenna 1 (Simulated)	850 ~ 998	924	148 / 16.1	857 ~ 1016	937 MHz	159 / 17.0
Antenna 1 (Measured)	860 ~ 1002	931	142 / 15.3	857 ~ 1023	940 MHz	166 / 17.7
Antenna 2	846 ~ 951	899	105 / 11.7	----	----	----
Antenna 3	----	----	----	857 ~ 988	923 MHz	131 / 14.2

polarized antenna with square slot are listed in Table I. This radiating square slot is set to be the dimension of 91 × 91 mm^2 as to degenerate TE_{10} and TE_{01} components of CP. We obtain the operating frequency 915 MHz calculated by (1) and they are roughly the same as the frequency with the lowest axial ratio centered at 940 MHz in Fig. 2.

$$f_c = \frac{c}{2\pi\sqrt{\varepsilon_{\text{eff}}}} \times \sqrt{\left(\frac{m\pi}{a}\right)^2 + \left(\frac{n\pi}{b}\right)^2} \quad (1)$$

In (1), c is 3×10^8 m/s and ε_{eff} is the effective permittivity of the FR4 substrate. Note that (1) is approximate formulas to predict the operating frequencies of two CP modes for this designed slot antenna and they would have obvious errors when the width (W1) of the ring ground plane is too narrow. An F-shaped strip is etched on the bottom-layer of the substrate and fed through a matching 50 Ω microstrip feed line which has a width (W4) of 1.48 mm and length (L4) of 20 mm. The vertical strip (L1) that succeeds the microstrip feed line is of 27.5 mm long. The first horizontal strip has a length (L2) of 38 mm and a 4.3 mm gap is made at the strip end and the ring ground plane as to provide capacitive effects. In addition, the second horizontal strip is placed above the ring ground plane with the gap (G) and has the length (L3) of 38 mm as the tuning stub to adjust the input impedance of this proposed CP antenna, which is different from the design using high characteristic impedance of the feeding microstrip line [17]–[23]. The resonant length $(\mathrm{L1}+\mathrm{L2})$ of the bent strip is 65.5 mm in corresponding to approximately 0.21 wavelength of the resonant mode at 940 MHz. The vertical and horizontal portions of the F-shaped strip have the same width (W2) of 6.2 mm. The vertical portion of the F-shaped strip is parallel to y-axis (side 1) contributing to TE_{10} mode while the other side (parallel to x-axis, side 2) contributing to TE_{01} mode. The current phase on side 2 lags behind that of side 1, which causes 90 degrees out of phases between Ex and Ey at the aperture.

The grounded arc-shaped strip is with the width of 5 mm and the radius of R1 with respect to the center set at point B. In this study, by introducing the grounded arc-shaped strip (point A → point C) inset into the square slot, the surface electric fields distributed on the square slot for are disturbed to excite two near-degenerated resonant modes (TE_{10} and TE_{01} modes) with 90 degrees phase difference to form a wider CP operating bandwidth for UHF band. The physical length difference between the grounded arc-shaped strip and section ABC (point A → point B → point C) is about 86.24 mm, which equals to 0.26 wavelength - close to one-quarter wavelength. By using the reflection formula, shown as following, the measured input impedance and resultant phase of the TE_{01} mode operating at 912 MHz can be determined:

$$Z_{\text{in}} = R_{\text{in}} + jX_{\text{in}} = 55.23 + j14.7\ (\Omega) \quad (2)$$

$$\Gamma = \frac{Z_{\text{in}} - Z_0}{Z_{\text{in}} + Z_0} = \frac{5.23 + j14.7}{105.23 + j14.7} = 0.147\angle 62.5^\circ \quad (3)$$

The phase angle is about 62.5 degrees. Likewise, the input impedance and phase angle of the TE_{10} mode operating at 960 MHz are:

$$\mathrm{Z}_{\text{in}} = R_{\text{in}} + jX_{\text{in}} = 36.71 + j6.54\ (\Omega) \quad (4)$$

$$\Gamma = \frac{Z_{\text{in}} - Z_0}{Z_{\text{in}} + Z_0} = \frac{-13.29 + j6.54}{86.71 + j6.54} = 0.17\angle 149.5^\circ \quad (5)$$

The phase angle is about 149.5 degrees. Consequently, the relative phase difference between two orthogonal modes (TE_{10} and TE_{01} modes) is about 87°; it proves that this design satisfies the phase requirement for the generation of CP radiation. Due to the fact that TE_{10} mode leading 90 degrees in phase compared to TE_{01} mode, the antenna configuration shown in Fig. 1 will radiate a left-hand CP (LHCP) wave. To demonstrate the above deduction and guarantee the correctness of simulated results, the electromagnetic simulator HFSS based on the finite element method [24] has been applied for the proposed slot antenna design for UHF reader.

III. RESULTS AND DISCUSSION

The proposed CP antenna is designed to operate at the centre frequency of about 940 MHz in the UHF band for RFID readers. The return loss is measured using an Agilent N5230A vector network analyzer. Fig. 2 shows the related simulated and experimental results of the return loss, phase diagram and axial ratio (in the boresight direction) for the proposed CP antenna of Fig. 1 fed by F-shaped or L-shaped microstrip line. The related results are listed in Table II as comparison. From the related results, the measured operating bandwidth (RL $\geqq$ 10 dB) can reach about 142 MHz (860–1002 MHz) or 15.3% centered at 931 MHz, which covers the entire UHF RFID band, and agrees well with the HFSS simulated results. Fig. 2(b) shows the simulated and measured phase diagram for the proposed CP antenna. It can be seen that these two orthogonal modes (912 MHz and 960 MHz) are excited, in 90° phase difference, resulting in good CP radiation. In Fig. 2(c), this broadband CP antenna also provides a 3-dB AR over the UHF band of 857–1023 MHz or 17.7% centered at 940 MHz. Meanwhile, it is found that the 3 dB AR

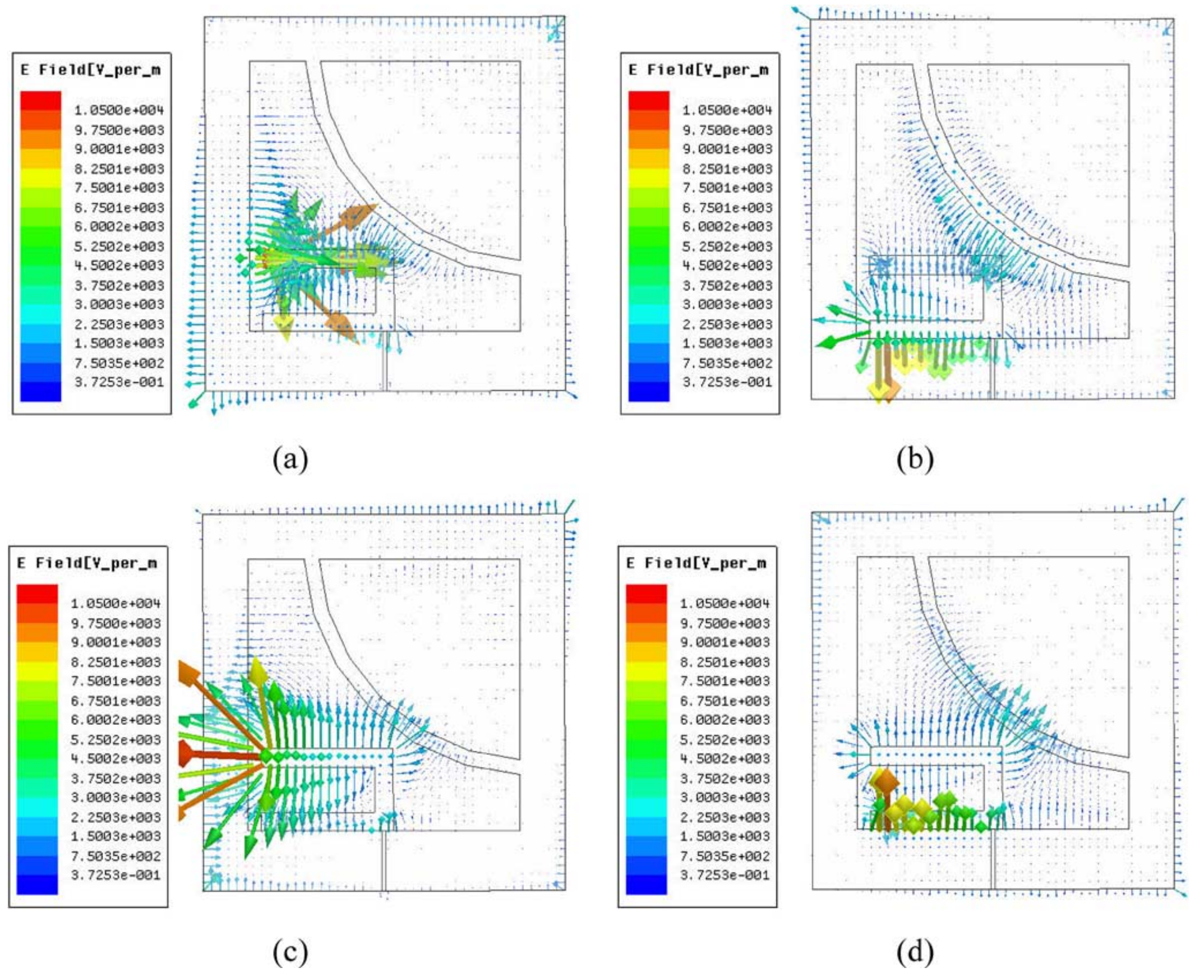


Fig. 3. Simulated electrical field distributions for the proposed LHCP antenna operating at 940 MHz with four phase angles: (a) 0°, (b) 90°, (c) 180°, (d) 270°.

bandwidth of the square slot antenna fed by L-shaped microstrip line (Antenna 3) can cover the entire UHF RFID bandwidth of 860–960 MHz, however, with poor impedance matching.

Due to the insetting arc-shaped strip to disturb the surface electric field distribution on this proposed square slot antenna, a LHCP performance with a wider operating bandwidth for UHF band can be obtained. To fully comprehend the excitation of the operating frequency at 940 MHz, the electric field distributions on the square slot antenna are shown in Fig. 3 including the interpretation of CP radiation. We observe that the electric field distributions are located on the surface of the slot for four phase angles of 0°, 90°, 180° and 270°, respectively. Every instantaneous phase displayed at every 90 intervals demonstrates a very strong left-handed circularly polarized (LHCP) wave; that is, the electric field flows from the y-axis into the x-axis, becoming as a left-handed circular polarization. Notice that the right-handed circularly polarized (RHCP) radiation can be obtained by simultaneously inverting the directions of both the grounded arc-shaped strip and the F-shaped feed line with respect to the y-axis.

IV. Parametric Studies and Optimization

In order to achieve the desired axial ratio and impedance match, we need to slightly modify corresponding parameters in cooperating with the antennas modification from which the CP radiation is generated. Return loss and AR performance are mainly affected by the dimensions of the grounded arc-shaped strip, F-shaped feeding line and the ring ground plane to ensure a phase lag for the proposed CP antenna.

A. Effects of the Grounded Arc-Shaped Strip

In this study, by properly adjusting the outer radius (R1) of the grounded arc-shaped strip as 71 mm, two near-degenerated resonant modes (TE_{10} and TE_{01} modes) with 90 degrees phase difference are excited to form a wider CP operating bandwidth for UHF band. The related simulated axial ratio across the operating UHF band is shown in Fig. 4 for the proposed broadband CP antenna with various outer radii of the arc-shaped strip. It is found that, as the outer radius (R1) decreases to make the operating frequency increasing, the 3 dB AR bandwidth can't totally cover the specification of UHF band. While rotating the arc about its axis by 180 degree as Antenna 4, the effect of outer radius of the arc-shaped strip has also been investigated and shown in Fig. 5. As the relative length difference between the grounded arc-shaped strip and the ring ground plane does not equal to one-quarter wavelength, the CP radiation can't be achieved.

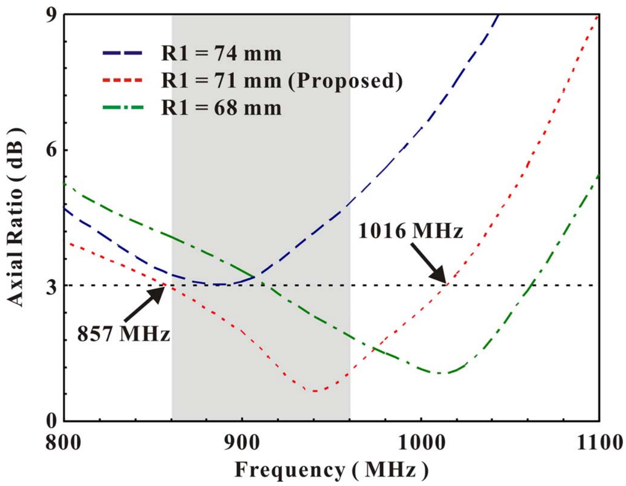


Fig. 4. Simulated axial ratio versus frequency for the proposed broadband CP antenna with various outer radii of the grounded arc-shaped strip.

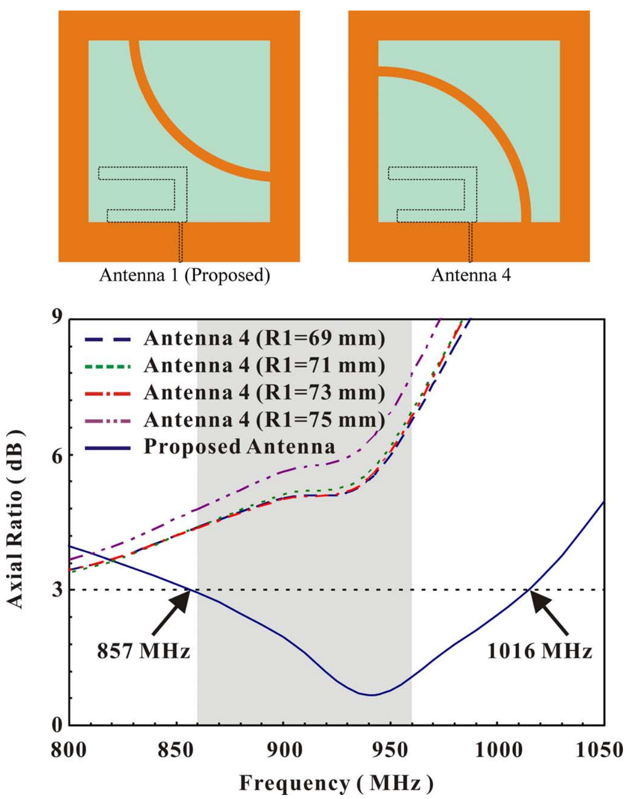
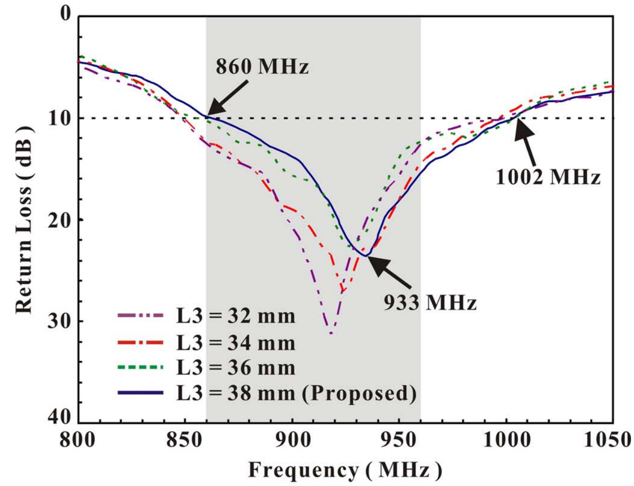


Fig. 5. Simulated axial ratio versus frequency for the proposed broadband CP antenna with various outer radii of the arc-shaped strip.

B. Effects of the F-Shaped Feeding Line

First, effects of the stub length (L3) and the gap (G) of the F-shaped feed line on the antenna performances are shown in Fig. 6. Small effects on the impedance matching with various lengths (L3) are observed to have more manufacture tolerance for this broadband CP antenna. Likewise, in Fig. 6(b), it is found that when the gap (G) increases from 0 mm to 3 mm, the 3-dB AR bandwidth becomes slightly narrower. Hence, by properly selecting the stub length (L3) and the gap (G) (38 and 0 mm,



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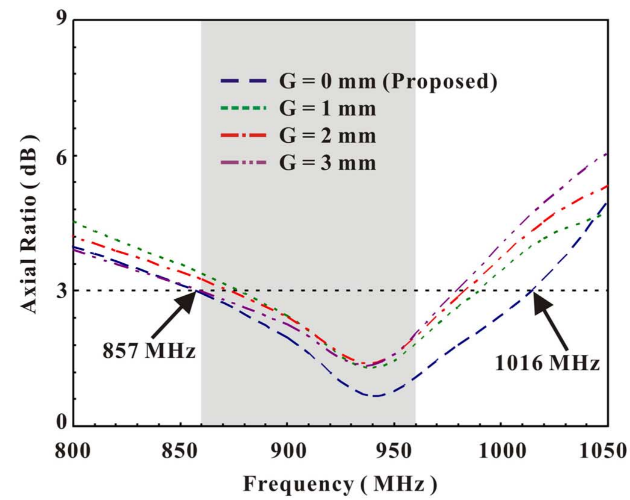


(b)

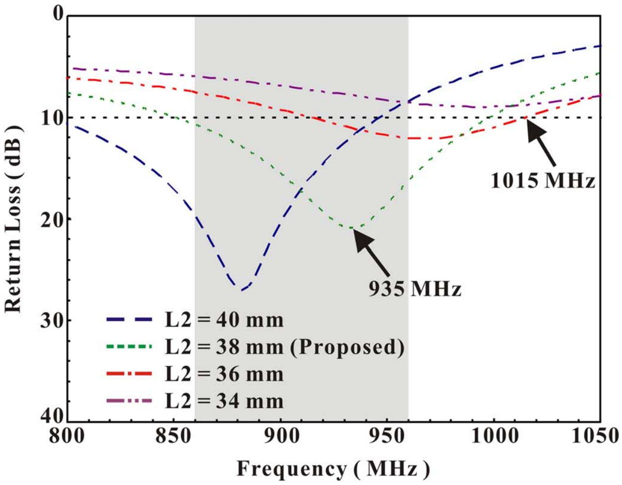
Fig. 6. (a) measured return loss vs the stub length of L3 and (b) simulated axial ratio vs the gap of G for the proposed broadband CP antenna.

respectively, in this study), the operating band can be easily adjusted to cover the desired frequency range of 860–960 MHz for UHF band.

Then, Fig. 7 shows the related simulated axial ratio and return loss for the proposed broadband CP antenna with various horizontal lengths (L2) of the F-shaped feed line across the operating UHF band. We find that, as the length (L2) decreases to make the operating frequency significantly increasing with worse impedance matching, the 3-dB AR bandwidth becomes narrower and can't meet the specification of UHF band. Additionally, the effects of the vertical strip's length, L1, of the F-shaped feed line on the antenna performances are shown in Fig. 8. As the length (L1) decreases to make the operating frequency increasing, on the other hand, small effects on the operating bandwidth of the axial ratio are seen to bear more manufacture tolerance for this broadband CP antenna.

C. Effects of Widths of the Ring Ground Plane

Finally, we come to study the effect of the ring ground plane. Referring to Fig. 9(a), the resonance frequency and impedance



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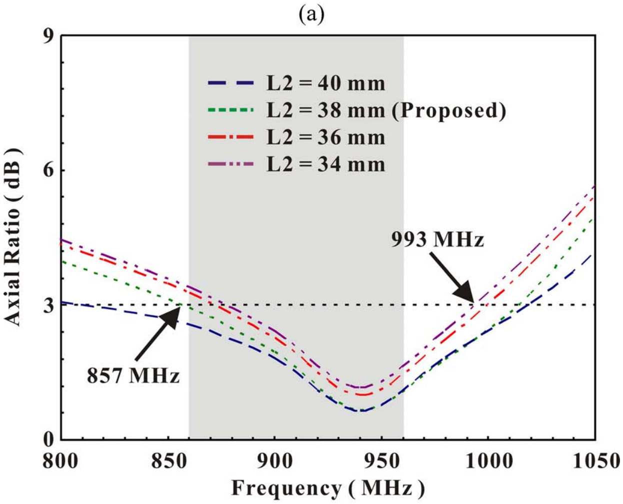
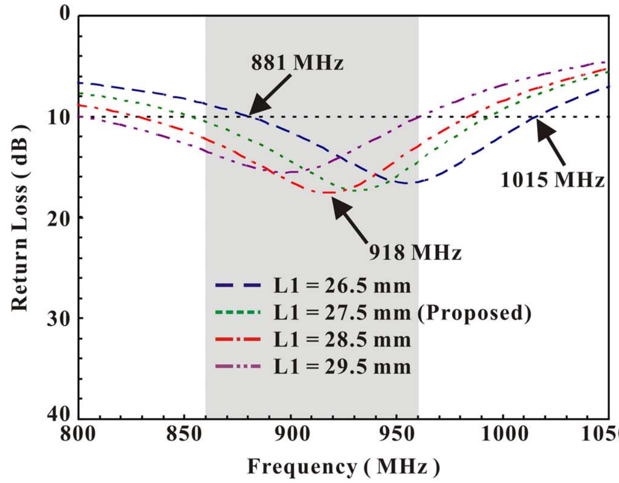


(b)

Fig. 7. Simulated results against frequency for the proposed planar broadband CP antenna with various horizontal lengths (L2) of the F-shaped feed line. (a) Return Loss. (b) Axial Ratio.



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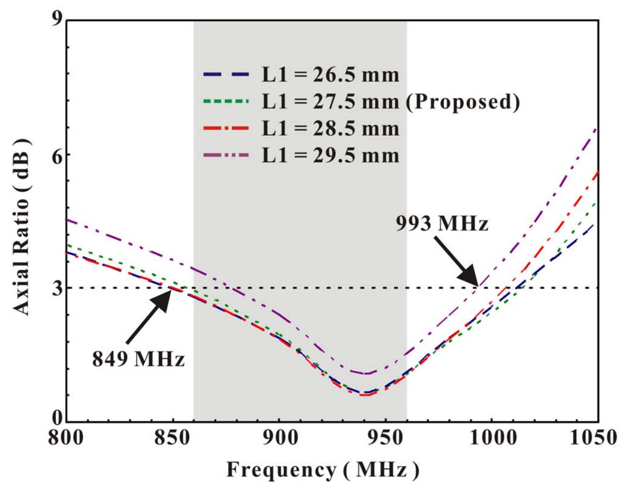

(b)

Fig. 8. Simulated results against frequency for the proposed planar broadband CP antenna with various vertical lengths (L1) of the F-shaped feed line. (a) Return Loss. (b) Axial Ratio.

levels of the excited mode are slightly affected by the width (W1) of the ring ground plane. However, it can be seen from Fig. 9(b) that care should be taken of the ARs as the ground-plane size has relatively larger effects on them. With the width (W1) of the ring ground plane increasing, the 3-dB AR bandwidth becomes narrower. By properly selecting the width to be 15 mm (in this study), the operating band can be easily adjusted to cover the desired frequency range of 860–960 MHz for UHF band.

For a complete study of the far-field performance of the proposed broadband CP antenna inside an anechoic chamber, an Agilent N5230A vector network analyzer and a computer workstation running 3D NSI 800F far-field measurement software is introduced by following the generally applied methodology for the measurement of antenna gain, directivity and efficiency from IEEE Standard Test Procedures for Antennas: ANSI/IEEE-STD149-1979 [25]. A broadband double-ridged horn antenna (DRHA) is introduced for the operating frequency of 1–18 GHz as the transmitted antenna. Note that the axial ratio mentioned throughout this paper is measured at broadside by using a linearly-polarized spinning source, and its value is determined by the amount of variation while the source is continuously rotating on the plane [26]. The CP radiation pattern measured at 940 MHz is plotted in Fig. 10, and good symmetry of bidirectional radiation has been observed. Results show the coherent agreement between the measured and simulated results. Since a CP slot antenna radiates a bidirectional wave, the radiation patterns on both sides of the proposed CP antenna are almost the same, in which a contrary circular polarization is produced; the front-side radiates LHCP while the back-side radiates RHCP. By verification, this antenna structure has successfully achieved a cross polarization discrimination of 20 dB on a wide azimuth range, which is more than the related slot antennas fed by the L-shaped probe [16]–[23].

Plus, the radiation patterns also show that the 3-dB AR beamwidths are about 83 degrees, with symmetry in both the XZ and YZ planes. The related measured result against the operating frequency is shown in Fig. 11. It is found that the variation of the 3-dB AR beamwidth is less than 3 degrees across the overall UHF operating band. Then, based on the backscattering method, the dynamic measurement with the proposed CP antenna is carried out in anechoic chamber by

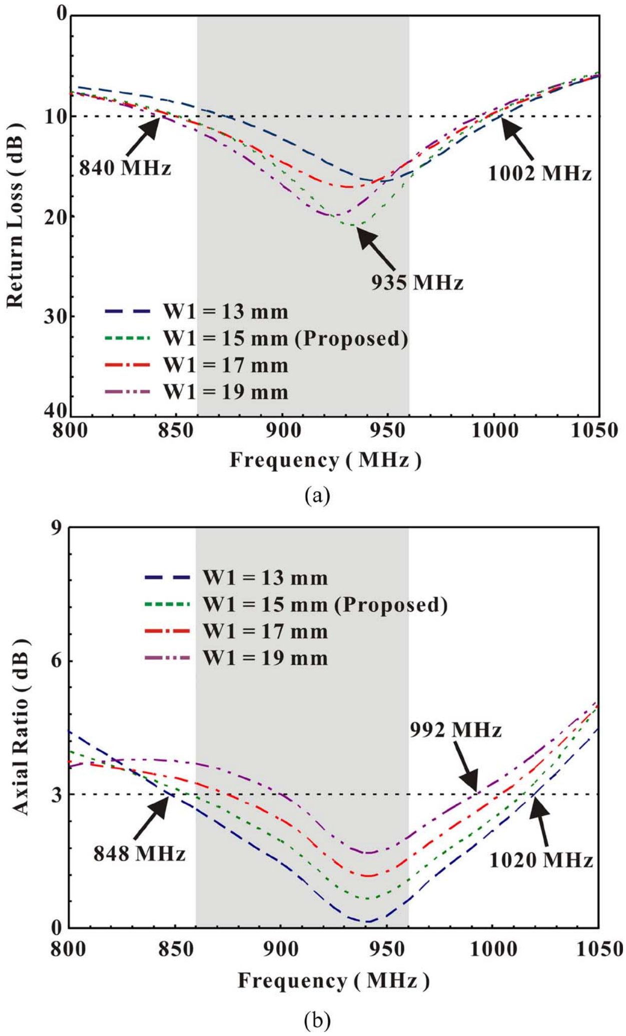

Fig. 9. Simulated results against frequency for the proposed planar broadband CP antenna with various widths (W1) of the ring ground plane. (a) Return Loss. (b) Axial Ratio.

introducing Tagformance Lite Measurement System from Voyantic Company (shown in Fig. 12) for discussing the detection range. A standard tag with Higgs - 3 UHF RFID IC (ALN-9640) [27] for EPC Class1 Gen2 operating at 900 MHz is introduced for the measurement system. A commercial UHF RFID reader with the output power of EIRP 3.28 W connected to the LP antenna with peak gain of 8.5 dBi and the dimension of $200 \times 190 \times 40$ mm^3 as the reference antenna. In Fig. 11, the comparison of the detection ranges between the proposed CP antenna and the reference reader antenna can be observed to realize the performance sensitivity. It is easily found that the maximum reading distance for the proposed CP antenna is about 5.5 m and nearly the same as that of the reference reader antenna. Meanwhile, this proposed CP antenna has smaller volume than that of the reference antenna. Moreover, miniaturization is an important issue as we consider dexterity. Because of its low profile, the proposed CP antenna can provide compact operation with broadband operation.

Furthermore, the measured peak gain was obtained using the gain transfer method where a standard gain horn antenna was used as a reference. The radiation efficiency can be calculated from the ratio of the radiated power to the total power supplied

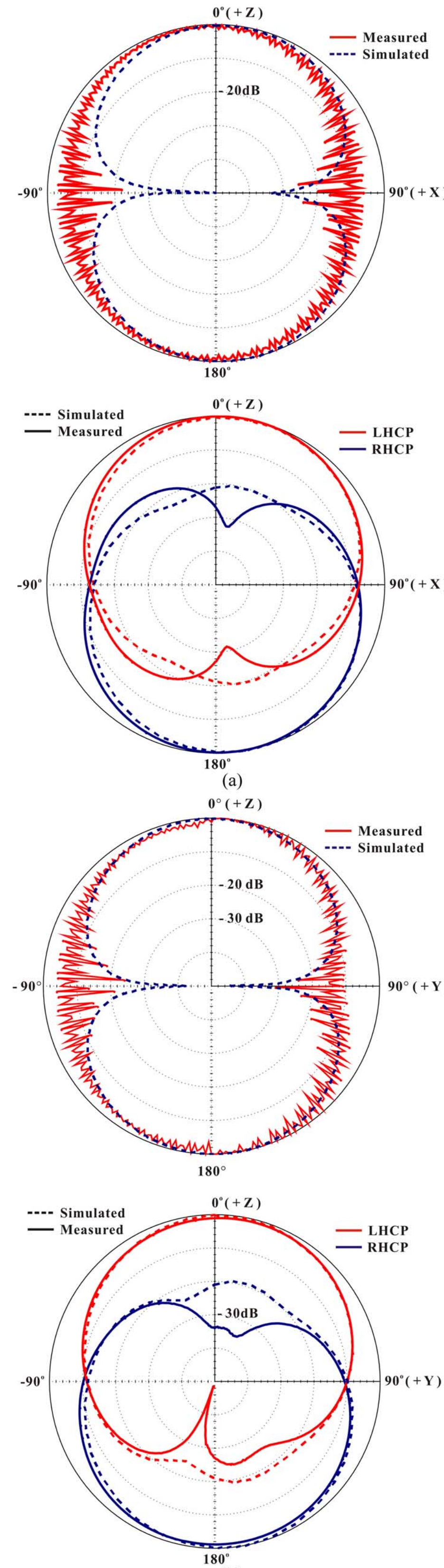

Fig. 10. Simulated and measured normalized LHCP/RHCP radiation patterns for the proposed broadband CP antenna at 940 MHz. (a) X-Z plane. (b) Y-Z plane.

to the radiator at a given frequency [25]. The measured and simulated peak gain and radiation efficiency across the operating

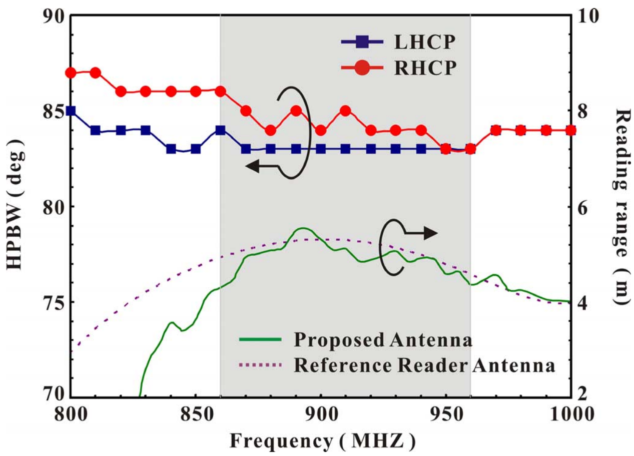

Fig. 11. Measured 3-dB beamwidth and reading range across the operating frequencies for the proposed broadband CP antenna.

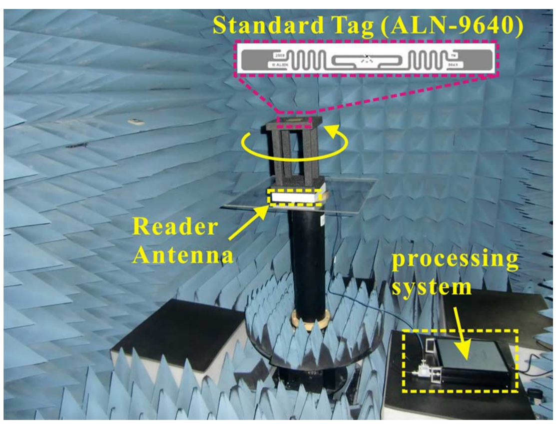

Fig. 12. Measured environment with Tagformance lite Measurement System from Voyantic Company.

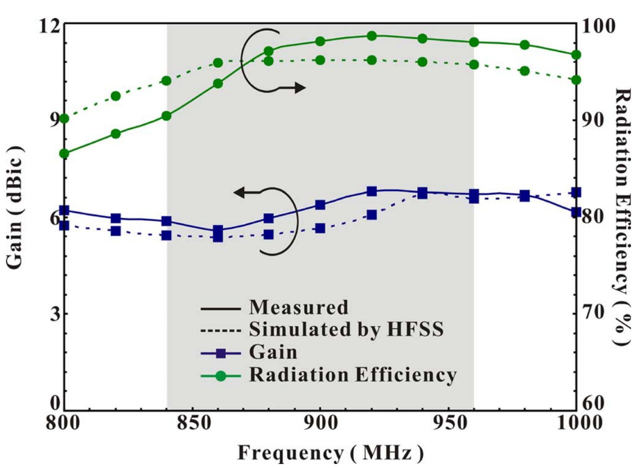

Fig. 13. Measured and simulated peak gain and radiation efficiency across the operating frequencies for the proposed broadband CP antenna.

band are shown in Fig. 13. Good agreement is seen between the measured and simulated results. The maximum measured peak antenna gain and radiation efficiency is 6.8 dBi and 98% across the operating band, respectively, which is more than that of the presented CP antenna design [6]. The gain variations across the desired frequency range of 860–960 MHz for UHF band are within 0.9 dBic.

V. Conclusion

A novel broadband circularly polarized antenna with square slot is proposed for the application of UHF RFID system. The obtained impedance bandwidth across the operating band can reach about 142 MHz (15.3% @ 931 MHz) and the 3 dB axial-ratio bandwidth of about 166 MHz (17.7% @ 940 MHz), which can cover the entire UHF RFID band. The measured peak gain and radiation efficiency are about 6.8 dBic and 98% across the operating band, respectively, with nearly bidirectional pattern in the XZ- and YZ-plane.

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