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Broadband Design of Planar Circularly Polarized Annular-Ring Antenna for RFID Applications

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Abstract—By introducing the Wilkinson divider and dual L-shaped strips as a feeding network, broadband design of planar circularly polarized (CP) annual-ring antenna for ultra-high frequency (UHF) RFID system is proposed and experimentally studied. The proposed broadband CP antenna can provide the impedance bandwidth ($RL \geqq 10$ dB) of about 246 MHz (25.0% @ 985 MHz) and the 3 dB axial-ratio (AR) bandwidth of about 180 MHz (19.5% @ 925 MHz) to meet the worldwide UHF RFID band (860 $\sim$ 960 MHz). Meanwhile, with unidirectional pattern in the XZ- and YZ-planes, the measured peak gain and radiation efficiency are about 7.7 dBic and 70% across the operating band, respectively.

1. INTRODUCTION

In the recently years, by placing in the door reader to read the data of warehouse management on the cartons or stack board, the transparency problem on the goods entering the logistics warehousing center can be solved. Therefore, the radio frequency identification (RFID) system is widely used in the plant material inventory, logistics and vendor market. Meanwhile, due to the merits of longer reading distance, fast reading speed and large information storage capability UHF (860–960 MHz) band radio-frequency identification (RFID) system has gained tremendous attentions for many industrial services such as supply chain, tracking, inventory management and bioengineering applications than those operated in the low- and high- frequency (LF and HF) bands. The RFID reader antenna is one of the important components in RFID system and should be designed with CP operation to receive the RF signal that emanates from arbitrarily oriented tag antennas for improving the reliability of communications between readers and tags. Moreover, in the presence of environmental reflections which results in the multi-path effect, the transmitted and received plane waves undergo polarization direction changes. This will reduce the communication quality between the tag and reader antenna. Therefore, polarization diversity has to be utilized, requiring the use of circularly polarized antennas. 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 11.0%) 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. In a microstrip CP antenna, two orthogonal resonant modes whose initial phase is offset by 90° need to be excited with equal magnitude. The electric field distributions of the orthogonal modes are determined by boundary conditions determined by the configuration of patch antennas. Numerous pioneer works on CP microstrip patch 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

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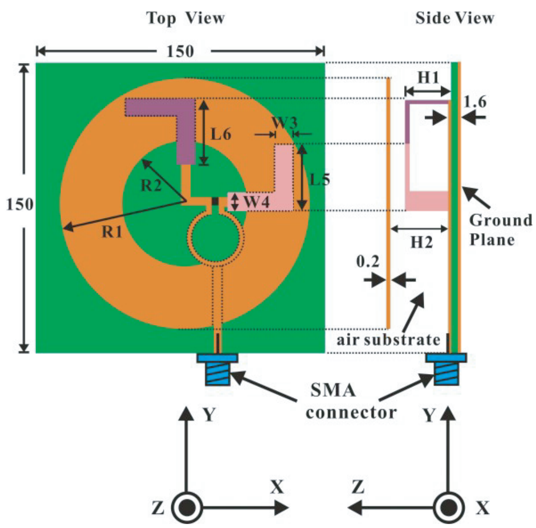
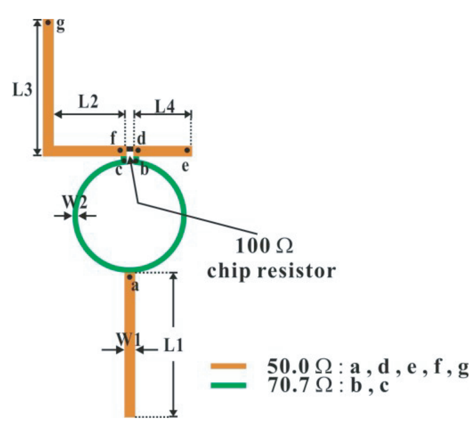
by an open circular ring microstrip line through multiple slots [4], asymmetric-circular shaped slotted microstrip antenna [5], a circularly polarized patch antenna fed by four probes connecting with the phase shifters of 90 or 180 degrees [6], a square microstrip antenna with a pair of quarter-wavelength transmission line capable of coupling to radio waves having rotational polarization [7], a circularly polarized patch antenna with multiple arc-shaped and semi-circular slots [8]. And, in many practical applications, air-filled CP patch antennas are frequently used due to their low manufacturing cost, free of surface waves, low dielectric loss, as well as higher gain and broad bandwidth by having a large height. This is particularly true for low frequency applications, such as a passive UHF RFID reader antenna, where the physical size of patch is too large to print on a circuit board. To overcome the disadvantage of bulky volume [1, 3, 4] or complex structure [2, 6, 8], in this article, we present a novel CP design of planar broadband UHF RFID reader antenna with unidirectional reading pattern. This planar annual-ring antenna is fed by the Wilkinson divider and dual L-shaped strips to obtain the broadband CP operation. The obtained impedance bandwidth across the operating band can reach about 246 MHz (25.0% centered at 985 MHz) and the 3 dB axial-ratio (AR) bandwidth of about 180 MHz (19.5% centered at 925 MHz). With unidirectional reading pattern, the maximum antenna peak gain and radiation efficiency across the operating band are about 7.7 dBic and 70%, respectively. The design concept of this model and its CP performances (including both simulated results and actual measured data) are described and discussed in this paper.



(a)


(b)



(c)

Figure 1. Geometry of the proposed planar broadband circularly polarized antenna for UHF RFID reader. (a) Geometry. (b) Photograph. (c) The Wilkinson divider.

2. ANTENNA DESIGN

The geometrical configuration and photograph of the proposed broadband circularly polarized antenna are illustrated in Figure 1. The circularly polarized annular-ring antenna with the outer and inner radii of $R1$ and $R2$, respectively is arranged with the height of $H2$ (28.6 mm in this study) above an printed FR4 substrate ($150 \times 150\,\text{mm}^2$, $\varepsilon_r = 4.4$, thickness $= 1.6$ mm and loss tangent $= 0.0245$) as the ground plane. First, to gain equal magnitude of two orthogonal resonant modes, a Wilkinson divider [9] is introduced with two output ports along x- and y-axes, respectively. However, in Fig. 1(c), the length difference of section fg and de is set up to be 46 mm, which is equal to the guided quarter-wavelength at the operating frequency of 900 MHz band to generate 90 degrees phase difference. Next, a vertical strip with the size of $8 \times 17\,\text{mm}^2$ is used to connect the right-angle corners of dual L-shaped strip at point e and g, respectively. For a wider CP operating bandwidth at UHF band, the above annular-ring patch antenna with an air substrate is coupled-feed by dual L-shaped strips to excite TM_{11} mode. The dual L-shaped coupled-feed strips with the same dimensions of $L5 \times W3$ and $L6 \times W4$ are arranged with the height of $H1$ (17 mm in this study) above the printed FR4 ground substrate as shown in Figure 1(a). Furthermore, to demonstrate and examine the accuracy of this simulated results, the electromagnetic simulator HFSS, which is on the principle of the finite element method [10], is utilized in the design of the proposed CP antenna. An Agilent Vector Network Analyzer E5071C is utilized to measure the input impedance of the proposed reader antenna. As a result, Figure 1 shows the calculated values of design parameters throughout the presented strategy above. Particularly, from those results we are simultaneously optimizing them by using Ansoft HFSS as we set $L1 = 41$ mm, $L2 = 22$ mm, $L3 = 39$ mm, $L4 = 15$ mm, $L5 = 33$ mm, $L6 = 30$ mm, $W1 = 3$ mm, $W2 = 1.6$ mm, $W3 = 9$ mm, $W4 = 9$ mm, $R1 = 65$ mm, $R2 = 30$ mm, $H1 = 17$ mm, $H2 = 28.6$ mm.

3. RESULTS AND DISCUSSIONS

Figure 2 illustrates the related simulated and experimental results of the return loss and axial ratio (in the boresight direction) for the proposed CP antenna of Figure 1, respectively. The related results are listed in Table 1 as comparison where f_L and f_H, respectively, represents the lower and higher cutoff frequency ($RL = 10$ dB or $AR = 3$ dB). From the related results, the measured impedance bandwidth across the operating band can reach about 246 MHz (25.0% centered at 985 MHz) and the 3 dB axial-ratio (AR) bandwidth of about 180 MHz (19.5% centered at 925 MHz), which covers the entire UHF RFID band. The above measured results show the satisfactory agreement with the simulated ones for

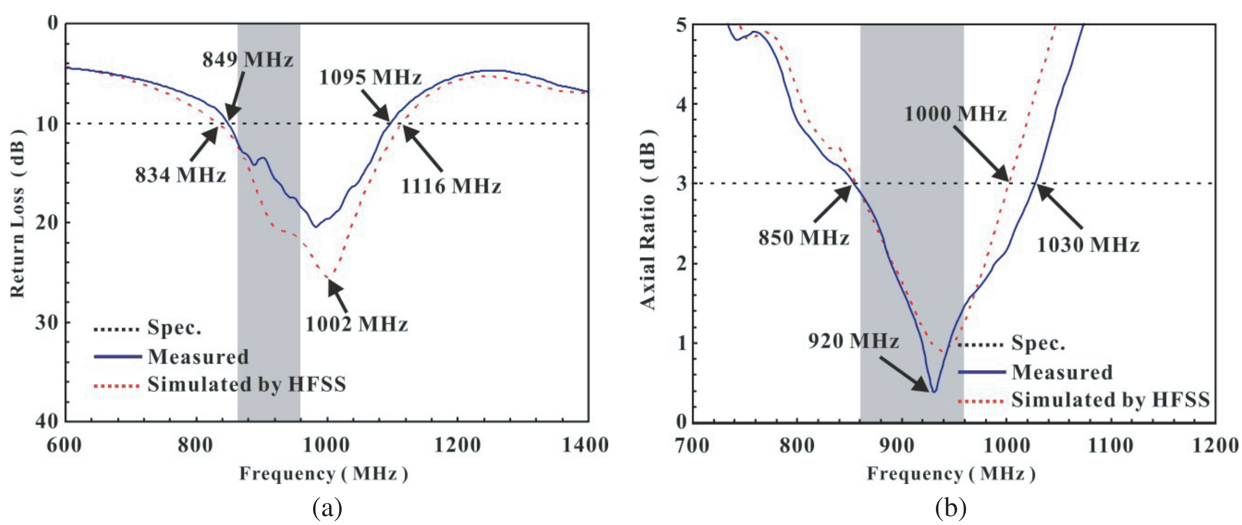


Figure 2. Simulated and measured results against frequency for the proposed planar broadband circularly polarized antenna. (a) Return loss. (b) Axial ratio.

Table 1. Simulated and measured return losses and axial ratios against frequency for the proposed broadband circularly polarized annual-ring antenna.

The proposed CP Antenna		Simulated	Measured
Return Loss	$f_L \sim f_H$ (MHz)	$834 \sim 1116$	$849 \sim 1095$
	BW (MHz/%)	282/28.1	246/25.0
Axial Ratio	$f_L \sim f_H$ (MHz)	$860 \sim 1000$	$850 \sim 1030$
	BW (MHz/%)	140/14.8	180/19.5

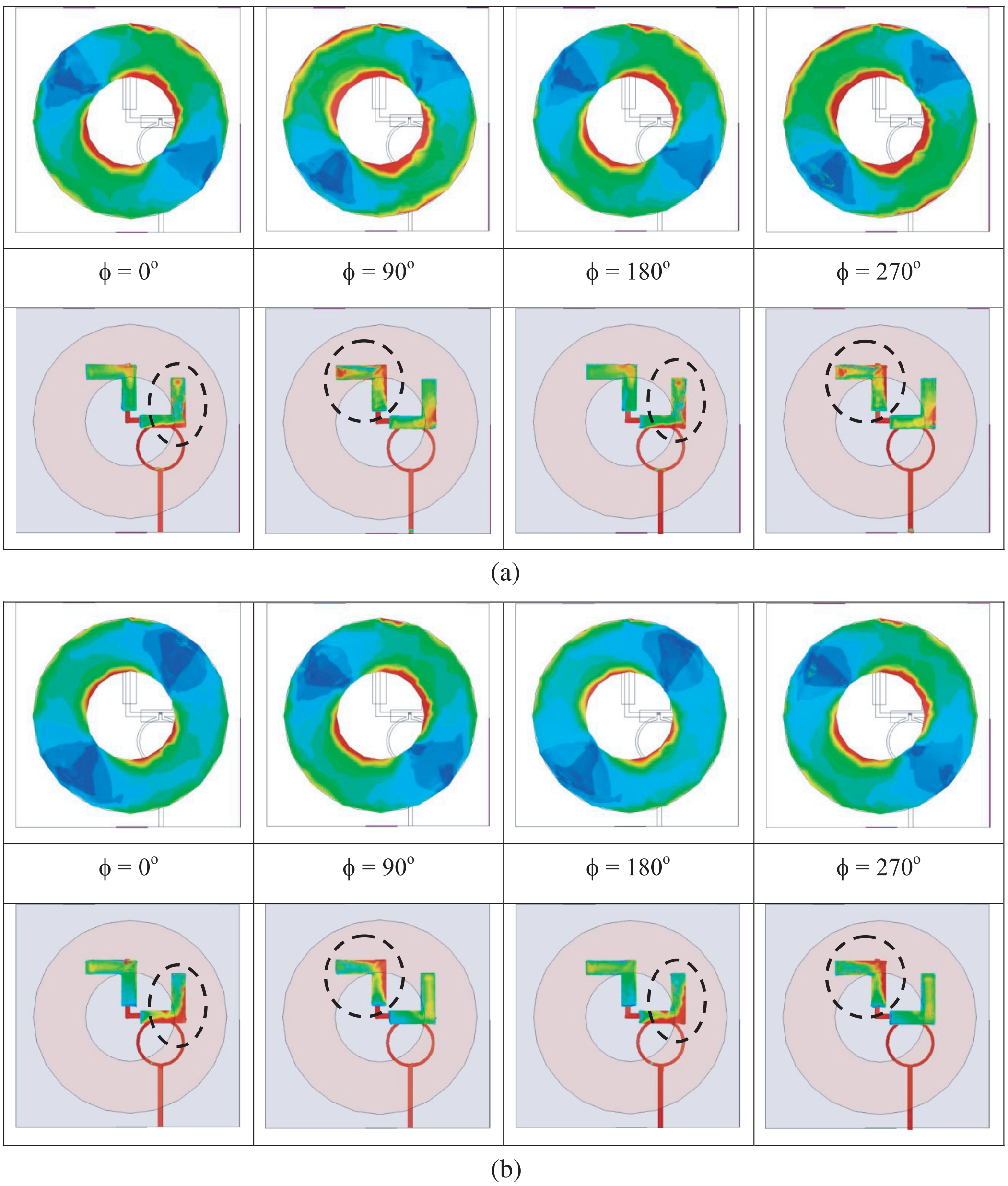


Figure 3. Simulated surface current distributions for the proposed broadband circularly polarized annual-ring antenna shown in Figure 1. (a) $f = 896\,\text{MHz}$. (b) $f = 1001\,\text{MHz}$.

the proposed reader antenna operating at UHF band.

Due to dual coupled L-s haped strip along x- and y-axes with 90 degrees phase difference caused by the length difference of section fg and de, an RHCP 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 surface current distributions at 896 and 1001 MHz are illustrated in Figure 3 including the interpretation of CP radiation. We observe that the surface current distributions are located on the surfaces of the annual-ring patch and coupled-feed L-shaped strip, respectively, for four phase angles of 0°, 90°, 180° and 270°, respectively. Every instantaneous phase displayed at every 90 intervals demonstrates a very strong right-handed circularly polarized (RHCP) wave; that is, the surface current flows from the x-axis into the y-axis, becoming a right-handed circular polarization.

4. PARAMETRIC STUDIES AND OPTIMIZATION

In order to achieve the desired impedance matching, we need to slightly modify corresponding parameters in cooperating with the antennas modification from which the circular polarization operation is generated. Return loss and input impedance are mainly affected by the dimensions of the coupled L-shaped strip and the annual-ring patch antenna.

4.1. Effects of the L-Shaped Feeding Line

First, effects of the length ($L6$) and width ($W3$) of the L-shaped feed strip on the antenna performances are shown in Figures 4 and 5, respectively. Slight effects on the impedance matching with various lengths ($L6$) and widths ($W3$) are observed to have more manufacture tolerance for this broadband CP antenna. However, in Figures 4(b) and 5(b), we can find that larger effects on the 3-dB AR bandwidth become significant with the dimension variation of the L-shaped feeding strip. Hence, by properly selecting the length ($L6$) and the width ($W3$) (3 and 9 mm, respectively, in this study), the operating band can be easily adjusted to cover the desired frequency range of 860–960 MHz for UHF band.

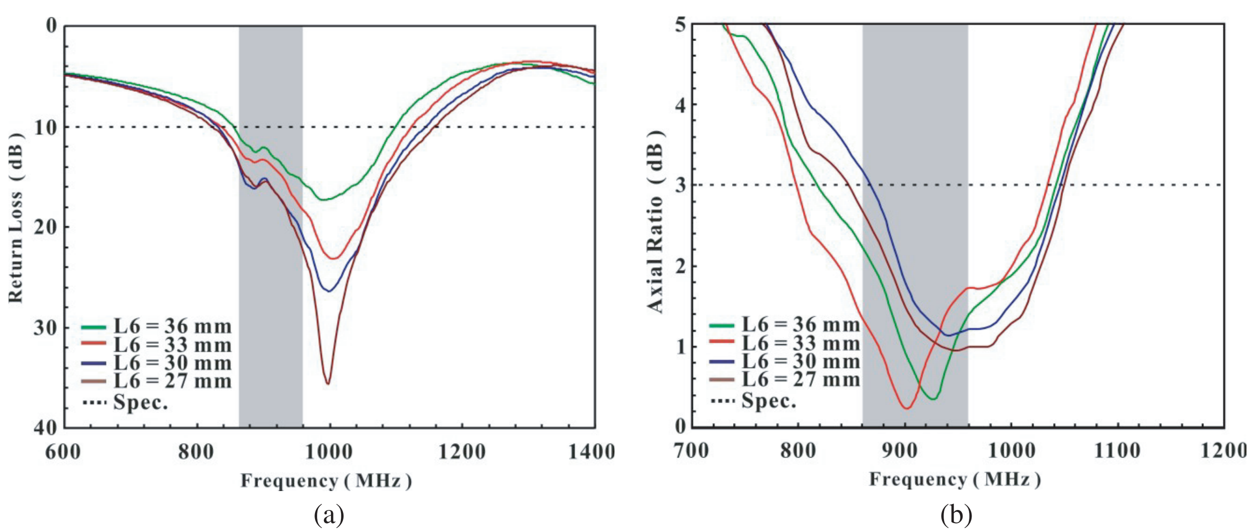


Figure 4. Simulated input impedance and axial ratio against frequency for the proposed broadband circularly polarized annual-ring antenna with various lengths of $L6$. (a) Input impedance. (b) Axial ratio.

4.2. Effects of the Outer Radii of the Annual-Ring Patch Antenna

Furthermore, we come to study the effect of the outer radii of the annual-ring patch antenna. Referring to Figure 6(a), the resonance frequency and impedance levels of the excited mode are significantly

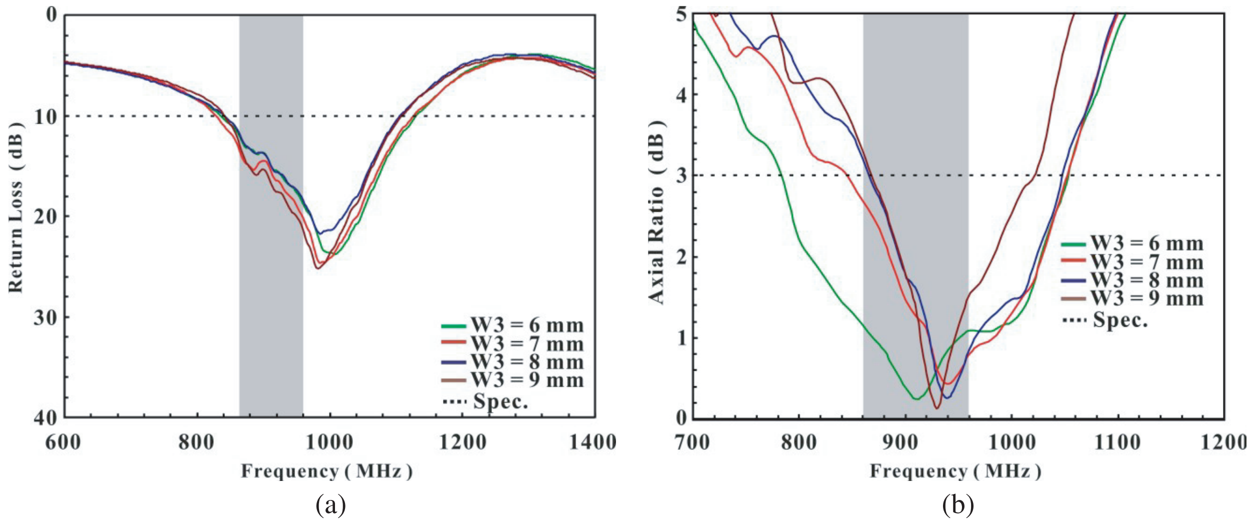


Figure 5. Simulated input impedance and axial ratio loss against frequency for the proposed broadband circularly polarized annual-ring antenna with various widths of $W3$. (a) Input impedance. (b) Axial ratio.

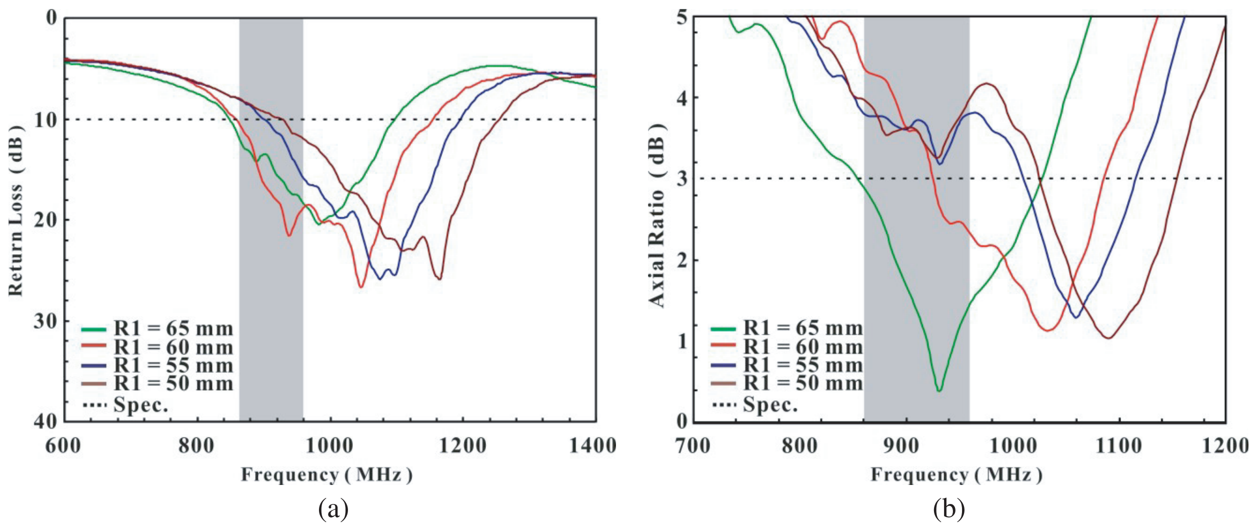


Figure 6. Simulated input impedance and axial ratio against frequency for the proposed broadband circularly polarized annual-ring antenna with various outer radii ($R1$) of the annual-ring. (a) Input impedance. (b) Axial ratio.

affected by the outer radii ($R1$) of the annual-ring patch antenna. Meanwhile, it can be seen from Figure 6(b) that the ARs as the radii ($R1$) size has relatively larger effects on them. With the outer radii ($R1$) of the annual-ring patch antenna decreasing to make the operating frequency increasing, the 3-dB AR bandwidth becomes narrower. By properly selecting the outer radii to be 65 mm (in this study), the operating band can be easily adjusted to cover the desired frequency range of 860–960 MHz for UHF band.

Finally 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 [11], an Agilent N5230A vector network analyzer and a computer workstation running 3D NSI 800F far-field measurement software is employed to study the far-field performance of the proposed broadband CP antenna inside an anechoic chamber (dimension = $6\,\mathrm{m} \times 3\,\mathrm{m} \times 3\,\mathrm{m}$) for UHF RFID system.

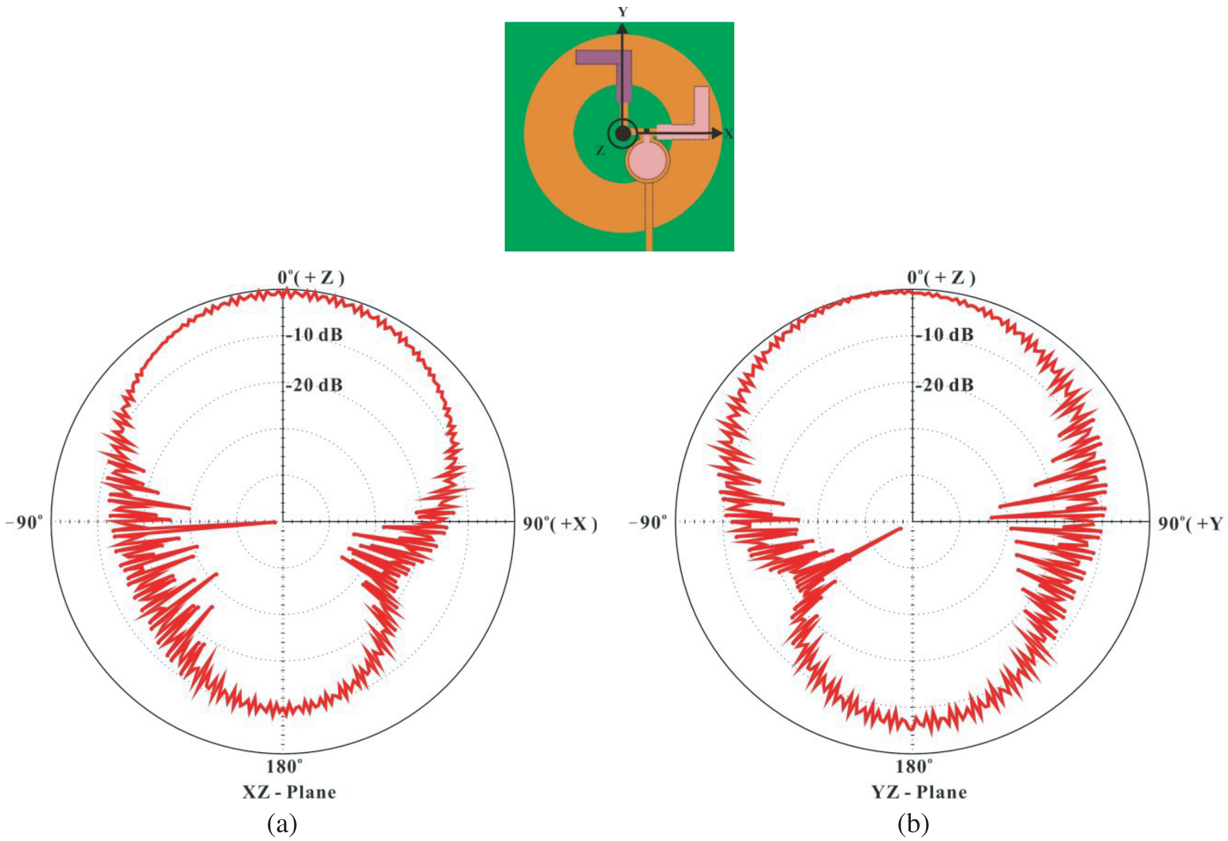


Figure 7. Measured normalized CP radiation patterns for the proposed broadband circularly polarized annual-ring antenna antenna at 920 MHz.

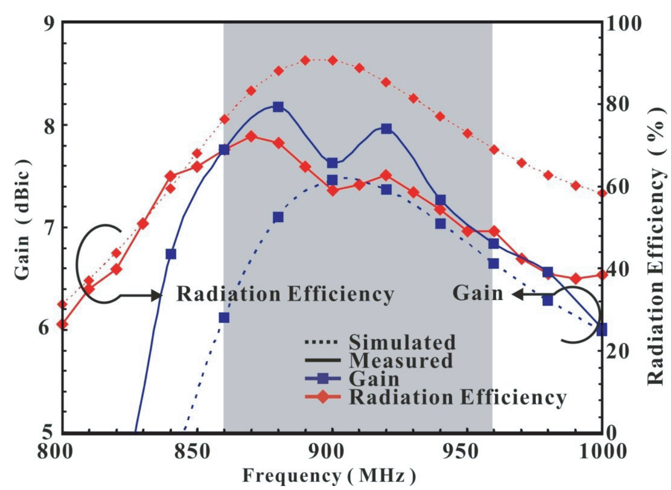


Figure 8. Simulated and measured antenna gain and efficiency for the proposed broadband circularly polarized annual-ring patch antenna studied in Figure 2.

Note that the axial ratio mentioned throughout this paper is measured at broadside by using a linearly-polarized spinning source (a broadband double-ridged horn antenna), and its value is determined by the amount of variation while the source is continuously rotating on the plane [12]. Figure 7 shows the CP radiation pattern measured at 920 MHz with good symmetry of unidirectional radiation. 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 to the radiator at a given frequency [11]. Figure 8 shows the simulated and measured antenna gain and efficiency (mismatching loss included [13]) for the proposed broadband circularly polarized annual-ring antenna. Good agreement is seen between the measured and simulated results. The maximum measured peak antenna gain and radiation efficiency is 7.7 dBic and 70% across the operating band, respectively. The gain variations across the desired frequency range of 860–960 MHz for UHF band are within 0.8 dBic.

5. CONCLUSIONS

A novel broadband circularly polarized antenna fed by the Wilkinson divider and dual L-shaped strips is presented for the application of UHF RFID system. The obtained impedance bandwidth across the operating band can reach about 246 MHz (25.0% @ 985 MHz) and the 3 dB axial-ratio (AR) bandwidth of about 180 MHz (19.5% @ 925 MHz) for UHF RFID applications, which can cover the entire UHF RFID band. The measured peak gain and radiation efficiency are about 7.7 dBic and 70% across the operating band, respectively, with unidirectional pattern in the XZ- and YZ-plane.

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