Design of UHF RFID Reader Antennas Using Coupled Line Power Divider and Narrow Bandpass Filter

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Abstract **─** In this paper, a Circularly Polarised (CP) universal Ultra-High-Frequency (UHF) RFID reader antenna based on coupled line power divider is firstly proposed. The antenna features compact size, simple structure and low-cost and achieves Return Loss (RL)≥25.5 dB, gain≥5.5 dBic and Axial Ratio (AR)≤1.8 dB, over the universal UHF RFID band of 840 to 955 MHz and the 3-dB AR beam-width is more than 110°. Then, an improved bandpass filter based on coupled lines and a ring resonator is proposed for achieving extremely narrow frequency response. A CP filter reader antenna using this narrow bandpass filter is proposed for enhancing the reliability of the communication and reducing the cost of the microwave front end in RFID system. The filter antenna exhibits the measured 1-dB gain (gain>6.4 dBic) bandwidth from 905 to 930 MHz and RL≥15 dB, AR≤1.4 dB in the band.

Index Terms **─** Circularly Polarised (CP), coupled line, filter antenna, RF Identification (RFID) and Ultra-High-Frequency (UHF).

I. INTRODUCTION

RF Identification (RFID) is a paste a tag antenna on goods, animal, or person for the purpose of identification and tracking by radio, which has been rapidly developed and widely applied to many manufacturing companies, logistics systems, service industries, government agencies and public service organizations in the last several years. Compared with Linear Polarised (LP) antenna, Circularly Polarised (CP) antenna features greater flexibility in orientation angle between reader and tag, better weather penetration and so on. Therefore, CP reader antenna has been widely used in RFID systems. On the one hand, the Ultra-High-Frequencies (UHF) designated for RFID applications are different in different countries, but almost all countries allocate it within the band from 840 to 955 MHz [1]. Hence, a reader antenna operating in the universal UHF RFID band would be beneficial for RFID system implementation and cost reduction. On the other hand, the adjacent band interference signals come from wireless communication systems reducing the reliability of UHF RFID systems. For example, China allocates UHF RFID frequencies within the band from 920.5 to 924.5 MHz and designate partial frequencies of Personal Communication System (PCS) in the range of 825-915 MHz and 935-954 MHz. The adjacent band interference signals from PCS often lead to incorrect reading and writing in the UHF RFID systems. However, this problem can be solved with the aid of high selectivity and narrow bandpass filter. Moreover, Integration of CP reader antenna and filter in one module is one of the ways to achieve miniaturization and cost reduction of microwave front end of RFID systems.

There have been some studies in the literature on RFID reader antenna [2-7]. A compact printed end-fire UHF RFID antenna is proposed for handheld application [2]. However, the disadvantages are the LP and the narrow operation band that are unable to cover the universal UHF RFID band. The CP antennas using microstrip-to-

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slotline transition, slot loaded circular patch and a coplanar waveguide feed are respectively proposed in literatures [3-5]. Unfortunately, the 3-dB Axial Ratio (AR) bandwidth of the antennas in [3] and [4] are no more than 3.72% and 3.2%, respectively. Moreover, the fatal weakness of the antennas in [3] and [5] is the lower gains, because of the bi-directional radiation pattern, which is unable to be applied to the direction RFID application. A sequentially four probes feed structure and a horizontally meandered strip feed technique are respectively proposed in literatures [6] and [7] for CP reader antenna. But the structures and optimizations of these two antennas are somewhat complicated and the volumes are large. These disadvantages are not satisfactory for widespread RFID application. On the other side, several structures have been proposed for integrating the filter and the linear polarised antenna into one module [8, 9], yet very few investigations have been reported on the CP filter antenna.

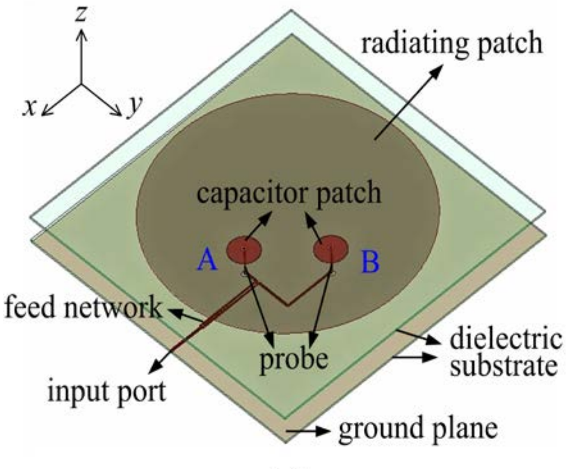
In this paper, a CP universal UHF RFID reader antenna features compact size, simple structure and low-cost is firstly proposed. It is implemented by a coupled line Wilkinson power divider [10] and dual capacitively coupled feeds. Then, a bandpass filter using coupled lines and a ring resonator is improved for achieving extremely narrow frequency response. A CP filter reader antennas based on this narrow bandpass filter is proposed for enhancing the reliability of the communication between RFID reader and tag.

II. CONFIGURATION OF THE CP UNIVERSAL UHF RFID READER ANTENNA

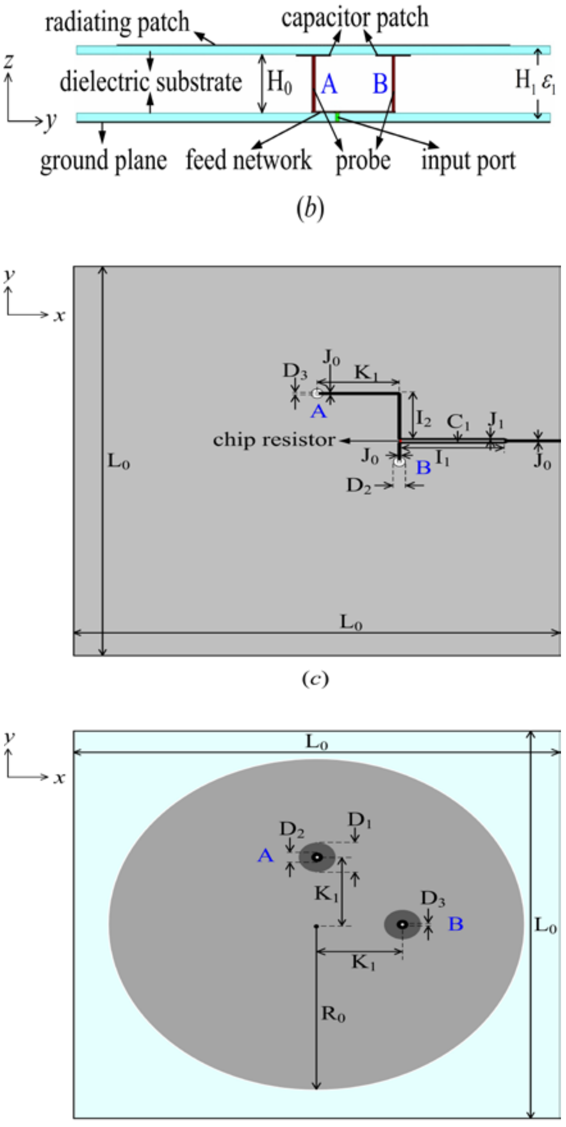
The configuration of the proposed CP universal UHF RFID reader antenna and coordinate system are shown in Fig. 1. For achieving compact size and simple structure, the feed network has been implemented by the use of a coupled line Wilkinson power divider [10] and a quarter-wavelength delay line 90° phase shifter, as shown in Fig. 1 (c). The two output ports provide two ways of equal amplitude signals with 90° phase difference. Here, the signal of port A lags behind that of port B. Therefore, the antenna achieves a Right-Hand CP (RHCP) wave.

A 100 ohm chip resistor is welded on the coupled line power divider for attaining isolation between the two feeds. The radiating circular patch with semi-diameter R_0 is capacitively excited by the two capacitor patches with same diameter D_1. The two capacitor patches are respectively loaded on the two probes A and B and their center points are oriented in orthogonal directions with a same perpendicular distance of K_1, away from the center axis of the radiating patch.

The feed network and ground plane are printed on the bottom FR4 substrate. The radiating patch and the two capacitor patches are printed on the upper FR4 substrate. The two substrates with distance H_0 were fixed by plastic posts. Air substrate is used to achieve broader bandwidth, higher gain and lower cost. Note, that the FR4 substrates have thickness H_1=0.8 mm, relative permittivity ε_1=4.4 and loss tangent $\tan\delta_1$=0.02. The ends of the probe A and B are welded to the four via-holes inside, which are manufactured on the two substrates. The four via-holes with diameter D_3 locate at the outputs of the feed network and the centers of the capacitor patches, respectively. For welding probes conveniently, four circular slots with same diameter D_2 are etched on the ground plane and the radiating patch, as shown in Figs. 1 (c) and 1 (d), separately.



(a)



(*b*)

(*c*)

(*d*)

Fig. 1. The configuration of the proposed universal UHF RFID reader antenna: (a) 3D view, (b) side view, (c) layout of the feed network and ground plane on the bottom substrate and (d) layout of the radiating patch and the two capacitor patches on the upper substrate.

III. ANALYSIS OF THE NARROW BANDPASS FILTER AND CONFIGURATION OF THE CP FILTER UHF RFID READER ANTENNA

A. The narrow bandpass filter

Figure 2 shows the circuit structure of the improved narrow bandpass filter with high selectivity, which is composed of two identical coupled lines and two different transmission lines. The even and odd-mode characteristic impedances of the coupled lines are Z_e and Z_o and the characteristic impedances of the two different transmission lines are Z_1 and Z_2, respectively. The terminated impedances for the ports 1 and 2 are Z_0=50 Ω and the electrical length of all transmission lines are $\theta=0.5\pi$. Therefore, the length of the ring resonator equals one guided wavelength at the center operating frequency of the filter. It should be mentioned that if setting the impedances Z_1 and Z_2 equal to Z_e and Z_o, respectively, the complexity of the circuit analysis can be reduced greatly. Meanwhile, the perfect Return Loss (RL) and Insertion Loss (IL) can be obtained automatically.

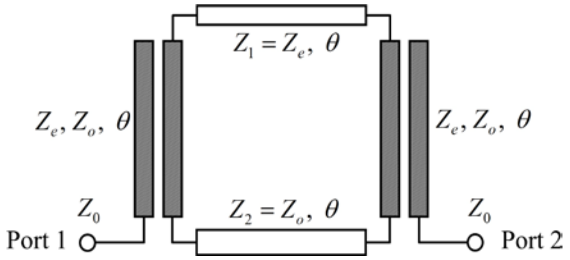


Fig. 2. The structure of the narrow bandpass filter.

In order to obtain the mathematical relations between the scattering parameters (S-parameters) and the circuit parameters Z_e and Z_o, the graph-transformation method is employed for analyzing the improved narrow bandpass filter. The equivalent circuits shown in Fig. 3 is attained after using this method on the three port coupled line sections [11]. The transfer matrix A_Y of the unit Y is given by [12]:

$$A_Y = \begin{bmatrix} \cos\theta & j\sin\theta/Y \\ jY\sin\theta & \cos\theta \end{bmatrix}, \tag{1}$$

where

$$\theta = (\pi f)/(2 f_0), \tag{2}$$

$$\begin{cases} Y = Y_{11} - Y_{12}^2 / Y_{11} \\ Y_{11} = (Y_o + Y_e)/2, \\ Y_{12} = (Y_o - Y_e)/2 \end{cases} \tag{3}$$

$$\begin{cases} Y_o = 1/Z_o \\ Y_e = 1/Z_e \end{cases}. \tag{4}$$

In addition, the equivalent capacitor Y_C and the transformer 1, N in Fig. 3 can be written as follows:

$$Y_c = jY_{11}\tan\theta, \tag{5}$$

$$N = Y_{11} / Y_{12}. \tag{6}$$

To analyze the frequency response of the filter, the ring resonator comprising the two units of Y and the two transmission line sections can be simplified to the equivalent unit Y_m, as shown in Fig. 4. The equivalent admittance matrix can be written as [12]:

$$Y_m = \begin{bmatrix} Y_{m11} & Y_{m12} \\ Y_{m21} & Y_{m22} \end{bmatrix}, \tag{7}$$

where

$$Y_{m12} = Y_{m21} = \frac{YZ_eZ_o + (YZ_e+1)^2\cos^2\theta - 1}{-jZ_2\sin\theta[(YZ_e+1)^2\cos^2\theta - 1]}. \tag{8}$$

The transmission zeros f_z are determined as setting Y_{m12}=0. Thus, the equation (9) can be derived from (8):

$$(YZ_e+1)^2\cos^2\theta + YZ_eZ_o - 1 = 0. \tag{9}$$

When (9) is solved for the electrical length of the transmission zeros in terms of the circuit parameters, it is found that,

$$\theta_z = \arccos\left(\sqrt{\frac{1-Y^2Z_eZ_o}{(1+YZ_e)^2}}\right). \tag{10}$$

Moreover, from formula (3) and (4), Y can be presented as follows:

$$Y = 2/(Z_e+Z_o). \tag{11}$$

Apply (11) to (10) and (10) is rewrite as:

$$\theta_z = \arccos\left(\frac{Z_e - Z_o}{3Z_e + Z_o}\right). \tag{12}$$

In addition, the electrical length for the frequency f_z can be calculated by the relationship:

$$\theta_z = (\pi f_z)/(2f_0). \tag{13}$$

It can be concluded that Z_e and Z_o are the key parameters for deciding values of the transmission zeros, that is, the frequency response of the narrow bandpass filter.

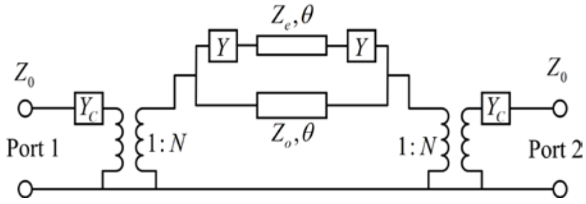


Fig. 3. The equivalent circuits of the filter.

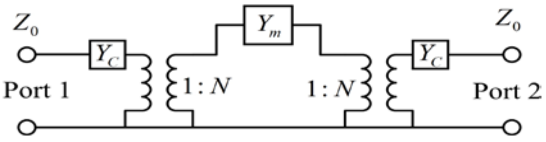


Fig. 4. The simplified diagram of the filter.

There is tradeoff between the narrower bandwidth and the IL for the filter. If chosen the specific bandwidth for the condition of IL≤0.1 dB and RL≥20 dB as objective function, the circuit parameters of the filter can be obtained by simple design process. Figure 5 shows the ideal and full wave Electromagnetic (EM) simulated S-parameters as the improved filter achieving the extremely narrow frequency response and the circuit parameters are Z_e=96 Ω and Z_o=46 Ω.

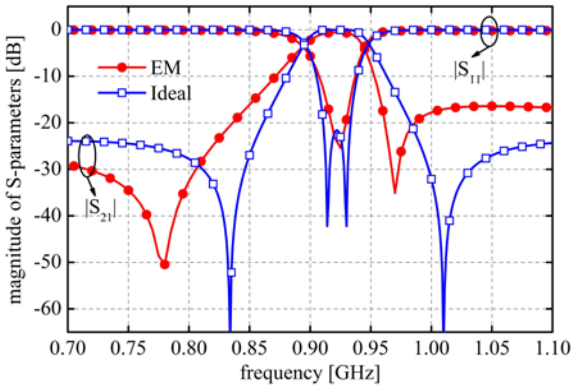
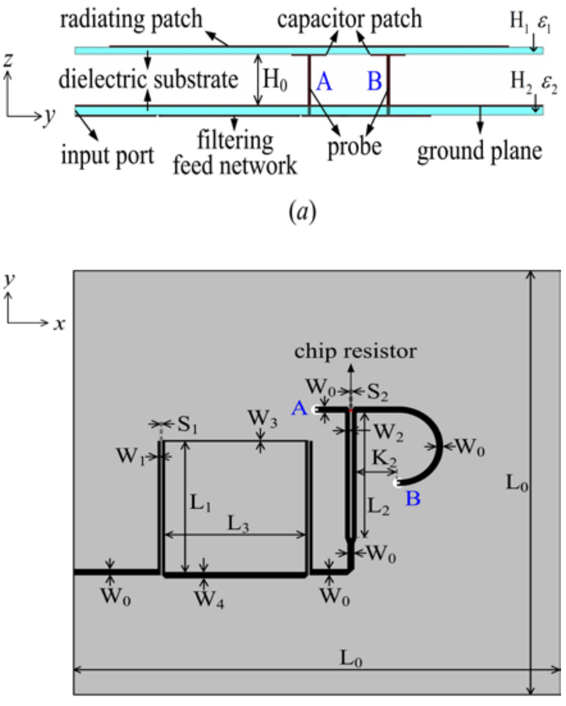


Fig. 5. The ideal and full wave Electromagnetic (EM) simulated results of the filter.

The ideal results show that the bandwidth for RL≥20 dB is from 911 to 933 MHz (2.4%), with the IL≤0.03 dB in the band. The EM simulation results show that the RL≥15 dB and IL≤0.9 dB in the band from 913 to 933 MHz (2.2%). Compared with the antecedent filter proposed in literature [13], this improved filter has advantages of low complexity design process and narrower passband response.

B. Configuration of the CP filter UHF RFID reader antenna

The side view and layouts of the feed network and the ground plane of the proposed CP filter UHF RFID reader antenna with coordinate system, are shown in Fig. 6. The layouts of the radiating patch and the two capacitor patches on the upper FR4 substrate are not given, because the configuration and dimensions are the same as the universal reader antenna that have been described in section II. The narrow bandpass filter have been analysed in section III A, is employed in the feed network. It is noted that compared with the universal antenna in Fig. 1 (c), the phase relationship between the ports A and B of the filter antenna in Fig. 6 (b) is reversed and a left-hand CP wave is achieved.



(a)

(b)

Fig. 6. The structure of the proposed CP filter UHF RFID reader antenna: (a) side view and (b) layout of the feed network and ground plane on the bottom F_4B-1/2 substrate.

The feed network and ground plane are printed on the bottom F_4B-1/2 substrate. Note, that the F_4B-1/2 substrate has thickness H_2=1 mm, relative permittivity ε_2=2.65 and loss tangent $\tan\delta_2$=0.001. The same electric parameters and dimensions adopted in the universal reader antenna are used for this upper FR4 substrate. Moreover, the same installation process as the universal reader antenna is employed for the filter reader.

IV. RESULTS

With the aid of EM simulator based on the finite element method, the CP universal UHF RFID reader antenna in section II and the CP filter UHF RFID reader antenna in section III B are modeled and simulated. The RL, gain, AR and bandwidth of the proposed antennas can be achieved by adjusting the semi-diameter R_0 of the radiating circular patch, the diameter D_1 of the capacitor patches, the distance K_1 of the two feeds and the distance H_0 between the upper and bottom substrates. The final design parameters of the proposed antennas are present in Table 1 and the prototypes are implemented as shown in Figs. 7 and 8. Plastic posts are employed to fix the substrates and copper wires are used as the probes to connect the outputs of the feed networks and the center points of the capacitor patches. The inner conductor of the SMA connector is directly welded to the input port of the feed network and the outer conductor of that is soldered to the ground plane, separately.

Table 1: Parameters of the antennas (unit: mm)

H_0	L_0	R_0	D_1	D_2	D_3	J_0	J_1
12	190	81	14	3.6	1	1.5	1
C_1	I_1	W_0	W_1	S_1	L_1	W_2	S_2
0.7	40	2.7	1.3	0.2	55.6	1.91	0.7
L_2	L_3	W_4	K_2	K_1	W_3	I_2	54.7
54.8	3.1	15.9	32	0.8	21.8		

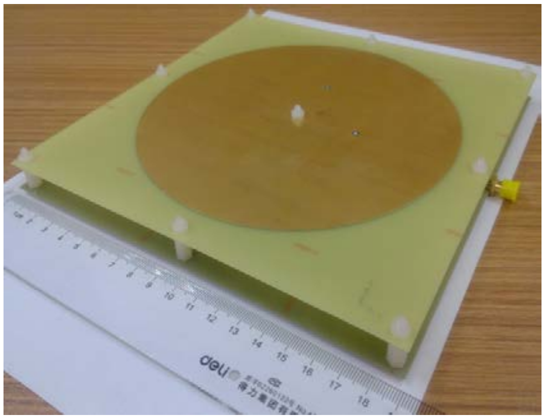


Fig. 7. The photograph of the fabricated CP universal UHF RFID reader antenna.

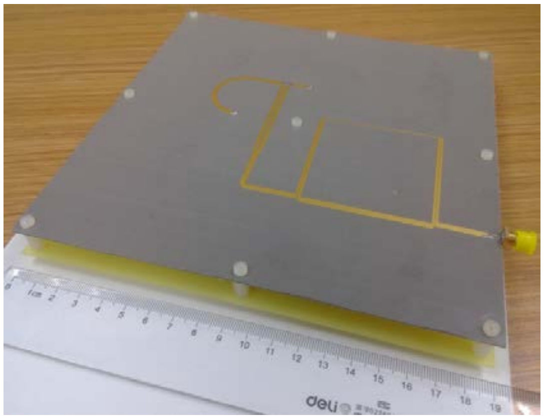


Fig. 8. The photograph of the fabricated CP filter UHF RFID reader antenna.

The RL and far-field performance of the prototypes shown in Figs. 9 to 13, were measured by an Agilent E5071C vector network analyzer and the SATIMO SG 24 system in an anechoic chamber, respectively. It should be noted that 'UA' and 'FA' in these figures respectively denote the results of the universal and the filter UHF RFID reader antennas, respectively.

Figure 9 shows the simulated and measured S-parameters of the antennas. The measured RL of the universal antenna is better than 25.5 dB over the universal UHF RFID band from 840 to 955 MHz and of the filter antenna is better than 15 dB in the frequency range of 905 to 930 MHz.

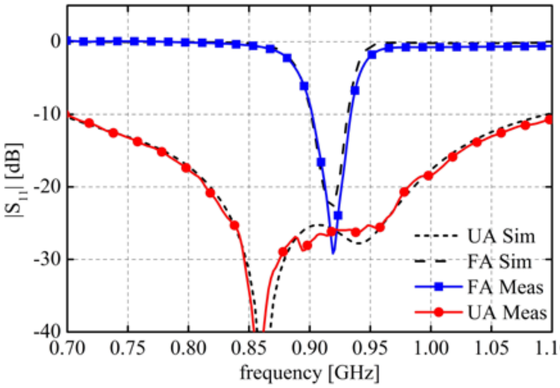


Fig. 9. The simulated and measured S-parameters of the antennas.

The simulated and measured boresight gain and cross-polarisation of the universal and filter reader antennas are illustrated in Fig. 10. Here, 'LHCP' denotes the gain of the left-hand circular polarisation and 'RHCP' denotes the gain of the right-hand circular polarisation. The universal antenna exhibits the measured RHCP gain of more than 5.5 dBic over the universal UHF RFID band, with a peak gain of 8.2 dBic at 915 MHz. The filter antenna exhibits the measured 1-dB gain (LHCP gain>6.4 dBic) bandwidth from 905 to 930 MHz and the peak gain is 7.4 dBic at 920 MHz.

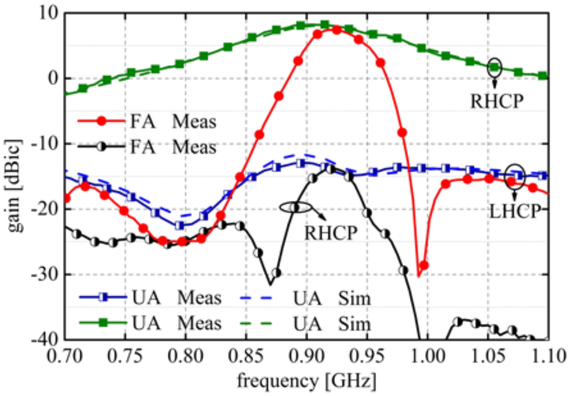


Fig. 10. The simulated and measured boresight gain and cross-polarisation of the antennas.

Figure 11 exhibits the simulated and measured AR of the antennas at boresight. The measured AR of the universal antenna is less than 1.8 dB over the universal UHF RFID band and of the filter antenna is less than 1.4 dB in the 1-dB gain bandwidth. It can be concluded that the measured and simulated RL, gain and AR show good agreement.

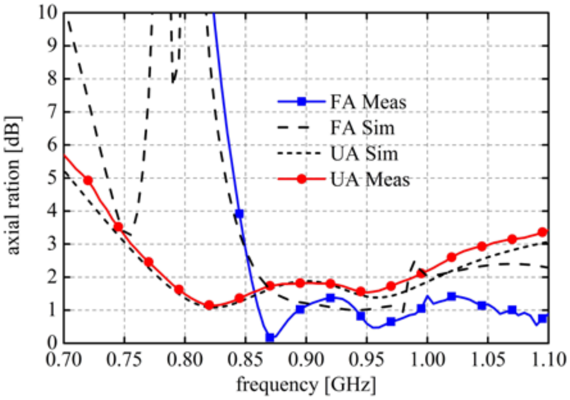
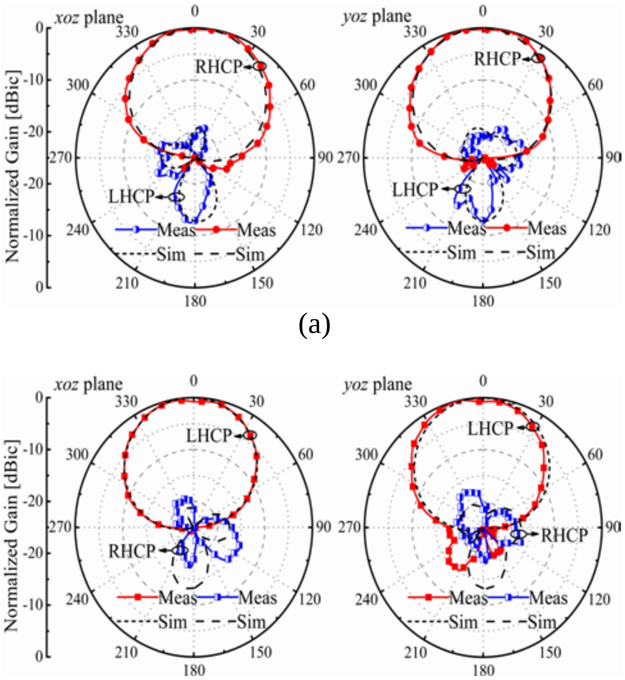


Fig. 11. Simulated and measured AR of the antennas.

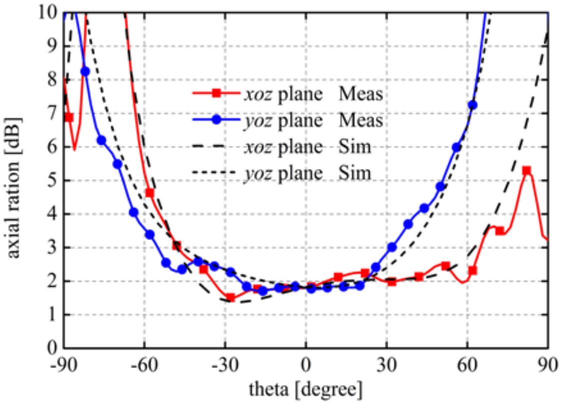
Figures 12 and 13 present the simulated and measured radiation patterns and AR of the antennas in the *xoz* and *yoz* planes at 922 MHz; symmetrical patterns and wide-angle AR characteristics have been observed. The beam-width of 3-dB AR for the universal antenna is more than 110° and for the filter antenna is more than 90°. This shows that these two antennas are fit for wide-coverage RFID applications.



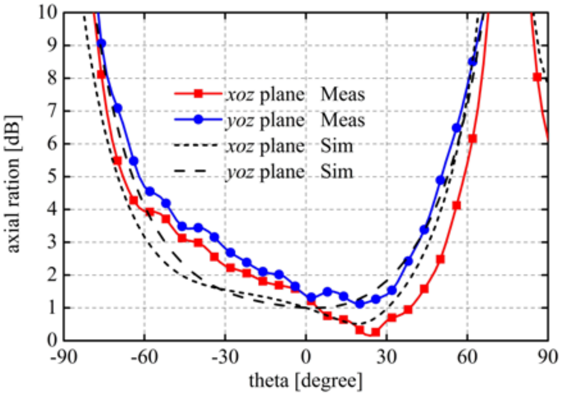
(a)

(b)

Fig. 12. The simulated and measured radiation patterns at 922 MHz of: (a) the universal reader antenna and (b) the filter reader antenna.



(a)



(b)

Fig. 13. The simulated and measured AR at 922 MHz of: (a) the CP universal reader antenna and (b) the CP filter reader antenna.

V. CONCLUSIONS

In this paper, a CP universal reader antenna features compact size, simple structure and low-cost has been firstly proposed for direction UHF RFID application. The experimental results show that the RL≥25.5 dB, the gain≥5.5 dB, the AR≤1.8 dB in the universal UHF RFID band and the beam-width of 3-dB AR is more than 110°. Then, an improved coupled line filter was proposed. It has advantages of low complexity design process and extremely narrow passband response. The CP filter UHF RFID reader antenna using the narrow passband filter was investigated and the experimental results show that the measured 1-dB gain (gain>6.4 dBic) bandwidth from 905 to 930 MHz. The simulation and measurement results are demonstrated that the filter reader antenna can be employed to enhance the reliability of the communication between RFID reader and tag. Moreover, these two antennas are fit for wide-coverage RFID applications.

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