A Compact Broadband Circularly Polarized Antenna with a Backed Cavity for UHF RFID Applications

JunLong Li[1], Hui Liu [1], Shuai Zhang[2], Yuan Zhang[1], Sailing He [1,3*]

[1] Centre for Optical and Electromagnetic Research, South China Academy of Advanced Optoelectronics, South China Normal University (SCNU), Guangzhou, Guangdong, People's Republic of China
[2] the Antennas, Propagation and Millimeter-wave Systems section at the Department of Electronic Systems, Aalborg University, 9220, Denmark
[3] Department of Electromagnetic Engineering, KTH Royal Institute of Technology, SE-100 44 Stockholm, Sweden
[*] sailing@kth.se

Abstract: A compact broadband circularly polarized antenna is designed with a novel method for universal ultra-high-frequency (UHF) radio-frequency identification (RFID) readers. It is composed of a compact ring–shaped patch which aims to decrease the size of the antenna. A quadrature 3 dB coupler placed below the ground plane creates 90° phase differences to generate the circularly polarized radiation of the antenna. To improve the performance of the proposed antenna and minimize its size, coupling feeding methods, an FR4 dielectric slab, and a metal cavity are used in this antenna. The coupled feeding is implemented to improve the gain over the operational band. Introduction of an FR4 dielectric slab and a cavity reduce the operating frequency and improve the impedance matching and axial ratio (AR) bandwidth. The antenna with a backed cavity can increase the front to back ratio remarkably and further enhance the gain. The measured results show that the antenna with a low profile ($0.45\lambda_0\times0.45\lambda_0\times0.06\lambda_0$ at 915 MHz) has the impedance bandwidth of 30.8% (730-990MHz) and 3-dB AR bandwidth of 24.2% (760-970MHz). Both the impedance and the AR bandwidth cover the worldwide UHF RFID band, over entire RFID band.

1. Introduction

Radio frequency identification (RFID) is a wireless communication technology that can exchange information between two objects using electromagnetic waves. It relies on a tag and a reader. RFID systems typically operate in low-frequency (LF), high-frequency (HF), ultra-high frequency (UHF), and microwave frequency bands. The UHF band has received great attention in many applications because of its faster recognition rate, lager data capacity, and longer reading distance. It is mostly used in applications such as logistics management, goods tracking, and electronic payment. However, the frequencies for UHF RFID applications are not the same in different countries and regions. For example, the UHF frequencies for RFID applications are 840.5–844.5 MHz and 920.5–924.5 MHz in China, 852–855 MHz and 950–956 MHz in Japan, and 902–928 MHz in North America [1]. Therefore, RFID systems should cover all UHF frequencies from 840 to 960MHz, for universal performance worldwide, with the additional benefits of simplifying the configuration and reducing costs.

In general, an RFID system consists of tags with the product information and readers to receive the data. Since RFID tag antennas are normally linearly polarized, and the orientations of the tags are arbitrary, circularly-polarized (CP) antennas are widely used in RFID reader antennas to avoid polarization mismatch between the readers and the tags [2]. The patch antenna is one of the most commonly used to generate CP radiation. CP radiation can be generated by exciting two orthogonal modes of equal magnitude and a 90◦ phase offset in space. [3]. The design of a CP reader antenna has played an important role in RFID systems. Many patch antennas with circular polarization are presented in the literature. CP patch antennas are commonly designed with current perturbations because of the compact profile and easy fabrication [4]-[7]. However, the impedance bandwidth and CP bandwidth of these patch antennas are relatively narrow, and are therefore unable to cover the entire UHF RFID frequency range from 840 to 960 MHz In order to further produce broadband CP radiation, stacked architectures of the RFID reader antennas are designed, which have the required broad impedance and AR bandwidth [1], [8]–[14].

However, the reported overall sizes of the stacked RFID universal reader antennas are relatively large [1], exceeding $0.76\lambda_0\times0.76\lambda_0\times0.18\lambda_0$ (λ_0 is the free-space wavelength at 915MHz), which may not meet the miniaturization requirements for modern distribution logistics RFID systems and electronic payment systems. The design of a compact RFID universal reader antenna with high gain and wide AR and impedance bandwidth is highly desired. In the past few years, a few miniaturization RFID reader antennas have been proposed. The planar broadband circularly polarized slot antenna covering the UHF band of 860–960 MHz for RFID reader applications was proposed in [13], [14]. There antenna consists of a square slot antenna inserted asymmetric grounded ship and fed by a modified L shaped microstrip line. A CPW-Fed antenna for universal RFID readers was proposed by insetting two L-shaped strip lines into a circular slot in the ground plane and feeding with an L-shaped microstrip line in [15]. Although the planar slot antenna and CPW-Fed antenna are suitable for miniaturization for RFID reader application, there have a bidirectional radiation pattern, limiting the scope of application.

In this paper, the traditional double feed ring-shaped patch antenna was studied in the RFID band, which has the wide AR and impedance bandwidth. However, this design is not preferred in miniaturization applications, since the gain of this design on the low frequency band is very low. Therefore, a novel technique is introduced to maintain the compact structure, while the CP and impedance bandwidth of antenna cover the entire UHF RFID band, and the gain is stable. Here, the coupling feeding scheme was introduced to eliminate mismatching between the long probe and ring-shaped patch, enhancing the gain on the low frequency. Dielectric slab inserting in the air gap between the coupled patch and ground plane was used to reduce the operating frequency, and to improve the AR and return loss performance effectively. A metal cavity utilized in the ring-shaped patch antenna can increase the front-to-backed ratios of radiation and improve the CP performance furtherly. The final compact design has broadband circularly polarized radiation and a stable gain. The antenna structure and the design process is presented in Section 2. The measured results and analyses are presented in Section 3. Conclusions are given in Section 4. The proposed compact broadband circular polarization antenna is simulated with HFSS software, which is verified with measurements.

2. Antenna design and analysis

2.1. *Antenna configuration*

Fig. 1 shows the configuration of the proposed low profile antenna, which consists of four layers of conductors and a metal cavity. The four conducting layers include a ring-shaped patch, two same square coupling feeding patches, a finite-size ground plane, and the 3dB branch line coupler. The proposed antenna has three layers of substrates. A ring- shape patch is fabricated on the top surface of the upper FR4 substrate ($\varepsilon_r = 4.4, \tan\delta = 0.02, h2$) and two identical small square coupling patches are printed on the

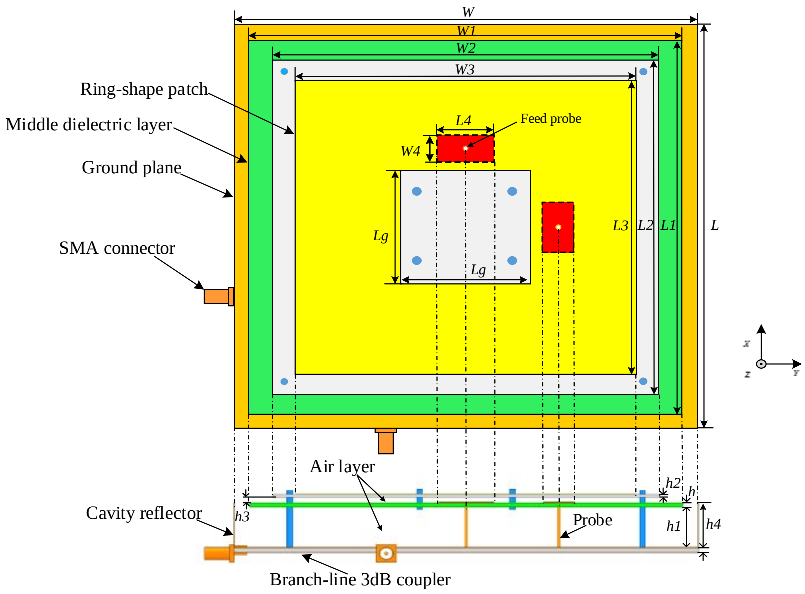


Fig. 1. *Configuration of the proposed antenna*

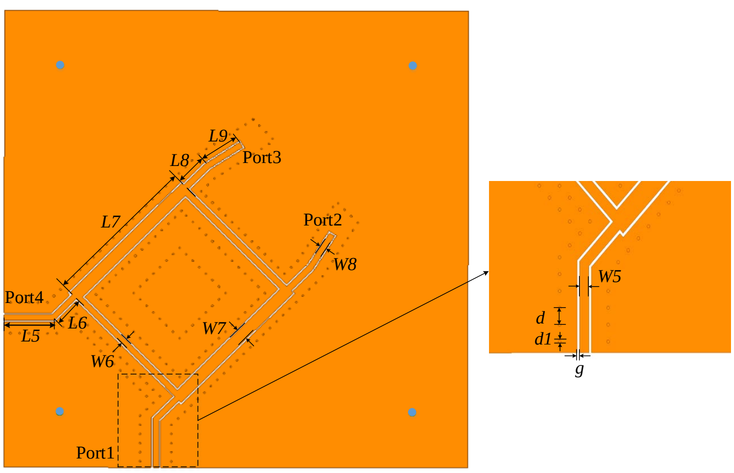


Fig. 2. *Branch line coupler substructure designed with CPWG*

Table 1 Dimension of the proposed antenna

Symbol	Value(mm)	Symbol	Value(mm)
L	150	*W3*	110
L1	140	*W4*	10
L2	120	*W5*	1.95
L3	110	*W6*	1.95
L4	18	*W7*	3.85
L5	16.3	*W8*	1.95
L6	10	*h*	1.5
L7	51	*h1*	15
L8	10	*h2*	1
L9	13	*h3*	2
Lg	42	*h4*	16.5
W	150	*d*	3
W1	140	*d1*	0.6
W2	120	*g*	0.5

top of the middle FR4 substrate($\varepsilon_r = 4.4, \tan\delta = 0.02, h$). A 3dB branch-line coupler is fabricated beneath the bottom FR4 substrate($\varepsilon_r = 4.4, \tan\delta = 0.02, h$). Between the middle and the bottom FR4 substrates, an air gap with height h1 is introduced, and between the middle and the upper FR4 substrates, there is an air gap with height h3. The structure of the 3dB branch line coupler below the ground plane is shown in Fig. 2, which is designed by CPWG (Coplanar Waveguide Ground). SMA connectors are soldered to port1 and port4 of the branch-line coupler. Two long probes are soldered to port2 and port3. Two same square coupled patches on the middle substrate are soldered to the probe directly. Furthermore, a cavity with height h4 is utilized in this antenna, which is composed of four metal walls and the ground plane. The dimensions of the proposed antenna are summarized in Table 1.

2.2. *Antenna Analysis and Design Procedure*

Fig. 3 shows the design process of the proposed antenna, which involves four antenna prototypes. The reflection coefficients, axial ratios, and boresight gains of the four antenna prototypes are shown in Fig. 4. In the proposed antenna, the ring-shaped patch on top of the upper substrate is introduced. The use of the ring-shaped patch can reduce the size of the CP patch antenna. This is because using a square ring leads to a larger electrical length of the patch compared to that of the square patch [20]. Fig. 4(a) shows that because of introducing a 3dB quadrature branch line coupler, Ant.1 resonates at 850MHz and 900MHz, therefore its impendence bandwidth can cover the entire UHF RFID band. However, if the square ring-shaped patch is directly fed by the probe, the input impedance is high and the currents at the feed point are very weak. [21]. As can be seen from Fig. 4(c), if the ring-shaped patch antenna is directly excited by two probes, the boresight gain of Ant.1 is very low on the low band of UHF RFID frequencies and the gain at 840MHz is 1.6dBic. The reason is that the probe-fed ring-shaped patch antenna in Ant. 1 is mismatched at low frequency band. Ant.1 is not preferred in miniaturization applications. Hence, to overcome this problem, a parallel coupled scheme is introduced to feed the ring–shaped patch antenna in Ant.2. Two coupled patches are inserted into the

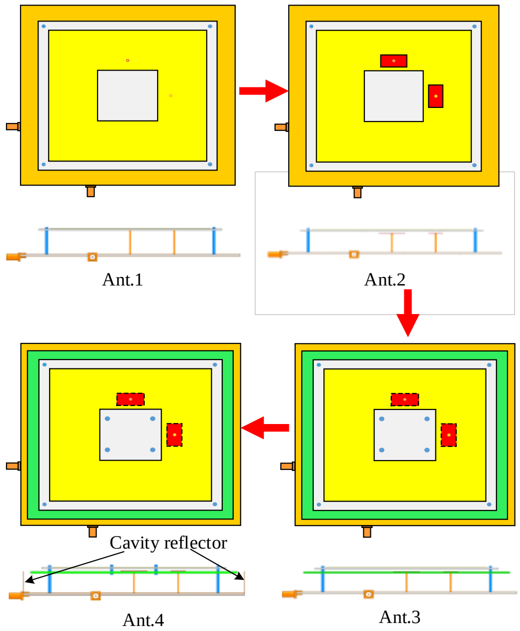


Fig.3. *Design procedure*

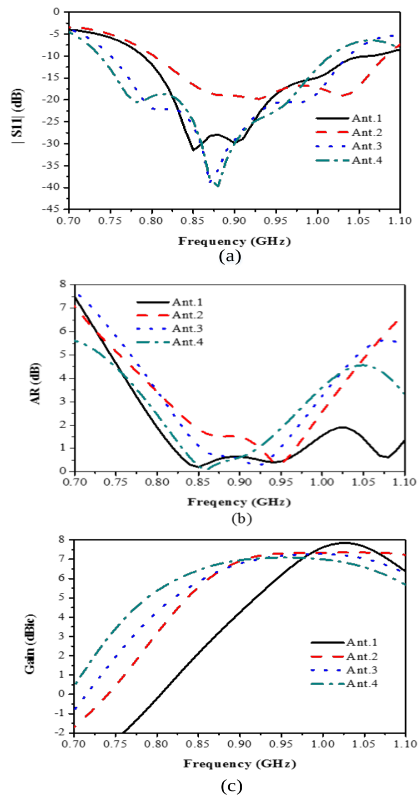


Fig. 4. *Comparison of different antennas: (a) reflection coefficients, (b) AR, and (c) gain.*

air gaps between the ground plane and the ring-patch. The boresight gain of Ant.2 is significantly increased to an average value of 6.2 dBic over the entire UHF RFID operation bandwidth. The boresight gain at 840MHz is increased from 1.6dBic to 5.1dBic in Ant.2 because of the introduction of coupling between the two coupled patches and the square ring patch with reference to Fig. 4(c), in which a gain enhancement of 3.5dBi is achieved. However, though a wide impendence bandwidth is yielded, the reflection coefficients of Ant.2 is poor in the entire UHF RFID band compared to Ant.1. There are some deteriorations in the 3-dB AR bandwidths, especially in the low band. To further improve the impendence and AR bandwidth, a middle layer with an FR4 dielectric slab is utilized in Ant.3. In [22], the introduction of a dielectric slab to a crossed-dipole antenna can efficiently improve the antenna gain and the AR bandwidth at low operating frequencies. By applying the FR4 dielectric slab in Ant.3, the impedance bandwidth shifts downward from 800-1080MHz to 750-1040MHz with improved impedance matching between the feed network and the ring-shaped antenna. Moreover, the boresight gains and AR in the low band are also further improved compared with Ant.2. In order to minimize the antenna size, it is necessary to reduce the size of the ground plane. However, a small ground plane of the ring-shaped patch antenna leads to a poor front-back ratio. A metal cavity is utilized in Ant.4, which can concentrate energy in the forward direction by restraining the back and side radiation. The cavity is mainly used to improve the gain at low frequencies. The cavity can also be optimized to improve the peak gain, but our final purpose is to maximize the overall performance instead of one frequency. From the simulations, the front-to-back ratio has been improved from 7.9dB in Ant.3 to 13.5 dB in Ant. 4 at 915MHz. Moreover, as can be seen in Fig. 4, the impedance bandwidth of Ant.4 is further broadened to 740-1020MHz. Ant.4 has a wide AR bandwidth of 790-980MHz (21%) and an average enhanced gain (especially at low frequencies) of 6.65dBic for the entire UHF RFID band.

The design procedure is summarized as follows:

(i) The introduction of the coupling feeding to the ring-shaped patch antenna enhances the gain in the low band remarkably.

(ii) The FR4 dielectric slab inserted into the air gaps can shift the resonant frequency to the lower band and simultaneously improve the impedance matching and AR bandwidth efficiently.

(iii) The metal cavity is utilized in this antenna to increase the front to back ratio and further to improve impedance matching and AR bandwidth.

If two orthogonal modes of equal amplitude for the antenna are excited with a 90 phase offset, the CP radiation is achieved. A hybrid feed is usually adopted to excite the CP radiation because it features a wide impendence and AR bandwidth [1]. As is known, a feed network designed with Coplanar Waveguide Ground (CPWG) can reduce the loss in the RF system. Therefore, the 3dB hybrid coupler designed with CPWG is used to feed our ring-shape patch antenna. The designed frequency of this hybrid coupler is at 915MHz. When port1 is excited, the surface current distributions on the ring-shaped patch at 915 MHz are as plotted in Fig. 5 for different time phases: t=0 (0°), T/4 (90°), T/2 (180°), and 3T/4 (270°), where T represents a cycle. It is observed that the current on the ring-shaped patch flows in the anticlockwise direction as t increases, which leads to right-hand circularly polarized (RHCP) radiation. Obviously, the electrical length of the ring-shaped patch is longer than that of the square patch with the same size. The surface

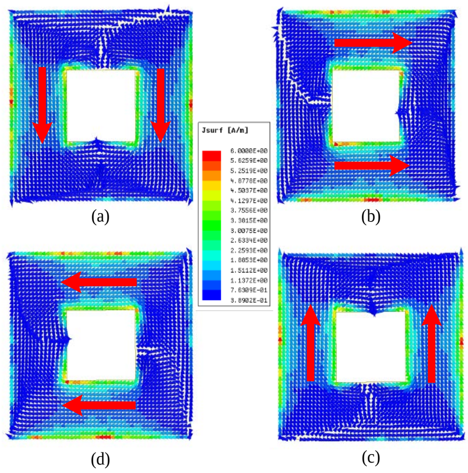


Fig. 5. *Current distribution on the ring-shaped patch in the different time at 915MHz: (a)t=0T, (b)=T/4, (c) t=T/2 and (d)t=3T/4.*

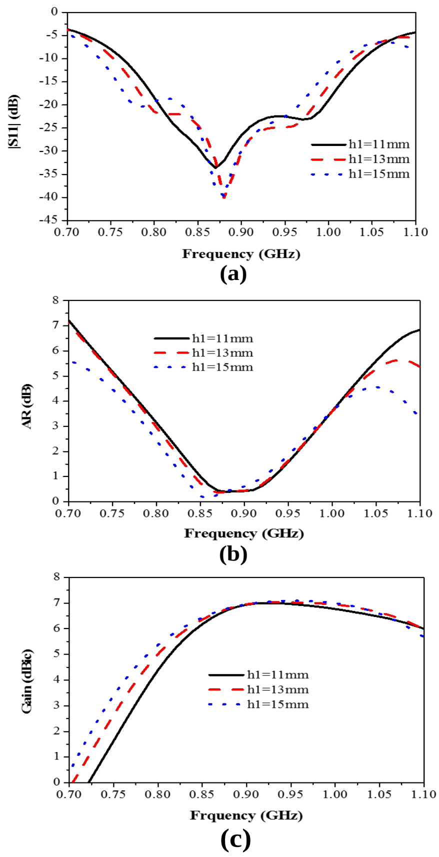
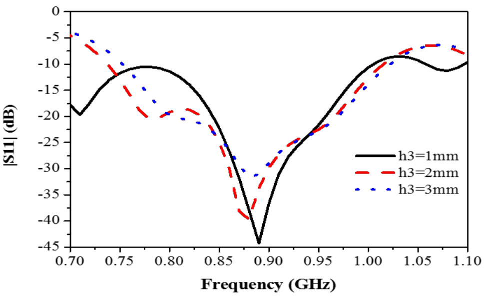
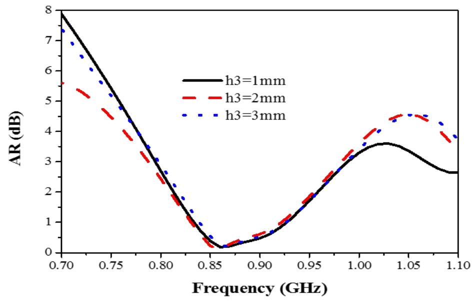


Fig. 6. *Simulated antenna performance with different h1: (a) reflection coefficients, (b) AR, and (c) gain.*

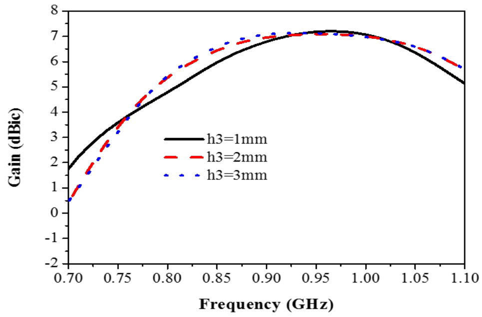
current behaviour from 840MHz to 960MHz is very similar to that of the 915MHz case. If port4 is excited, the rotation of the current is opposite to that of port1, which generate LHCP. Hence, the designed antenna can realize dual circular



(a)



(b)



(c)

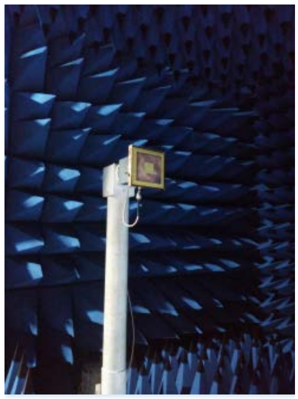
Fig. 7. *Simulated antenna performance with different h3: (a) reflection coefficients, (b) AR, and (c) gain.*

polarization.

2.3. Parameter study

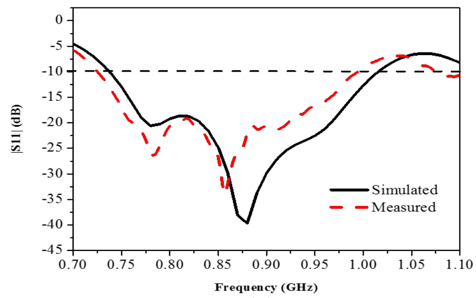
Parametric analyses of important parameters that can affect the performance of the antenna are investigated by the simulations. Two parameters, h1 and h3, are presented here. As shown in Fig. 6, when the distance h1 between the middle substrate and the ground plane increases, the boresight gain, impedance bandwidth, and axial ratio bandwidth are all enhanced. When the parameter h1 is chosen to be 15 mm, the value of AR is very low. There is a trade-off between the antenna height and total size. Finally, we choose the height h1 to be 15 mm in order to preserve the compactness of the design. Fig. 7 shows the effects of parameter h3 (height between the middle FR4 substrate and the upper FR4 substrate). Obviously, tuning h3 will affect the distance between the two coupled patches and the ring-shaped patch. As displayed in Fig. 7, a linear increase in h3 leads to a slightly enhanced gain in the low-frequency range. Furthermore, increasing h3 improves the AR bandwidth and impedance matching in UHF frequency band. Therefore, we can use different values of h1 and h3 to optimize the gain and AR characteristics of the antenna.

(a)

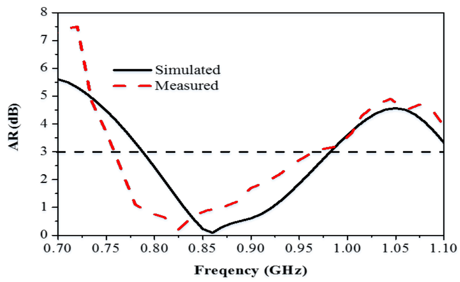


(b)

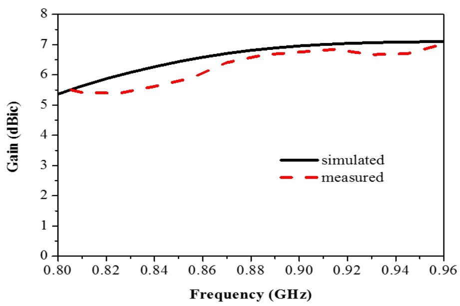
Fig. 8. *Photographs of the experiment setups: (a) Agilent N5247A vector network analyser and (b) an anechoic chamber.*



(a)



(b)



(c)

Fig.9. *Simulated and measured results of: (a) reflection coefficients, (b) AR, and (c) gain.*

3. Experimental results

To verify the proposed antenna, a prototype is fabricated and measured. The square ring is printed on the upper substrate and two coupling patches are printed on the middle substrate. The feeding network is fabricated on the lower substrate, into which six Teflon posts are introduced to fix the three substrates of the antenna. The cavity-backed reflector is composed of the ground plane and four copper plates. SMA connectors are used at port1 and port4 to feed the 3dB coupler. When port1 of the branch line coupler is excited, port 4 is terminated with a 50Ω load. The N5247A network analyzer is used to measure the reflection coefficients of the antenna. Gain, AR, and radiation patterns are obtained in an anechoic chamber. The detailed experiment setups are shown in Fig. 8.

In Fig. 9(a), the measured and simulated S parameters of the proposed antenna are compared. The measured impedance bandwidth for S11<-10 dB is 730-990MHz (30.2%) which covers the entire universal UHF RFID band of 840-960MHz. Good agreement between the simulation and measurement is obtained. As shown in Fig.9(b), the measured antenna can offer a 3-dB AR over the UHF band of 760–970MHz, or 24.2% centred at 865 MHz, with a minimum axial ratio of 0.2 dB at 825 MHz. In the Fig.10, it is confirmed that the measured realized gain is stable, with a maximum of 5.6 dBic within the entire RFID bandwidth. There is a slight difference between the simulated and measured realized gains, which could be due to the inaccuracy of the dielectric constant of the substrate and the loss of branch line coupler. It should be reminded that the gain in Fig. 9 (c) and the above analyses is the one defined by IEEE, where the mutual coupling between the two input ports of the quadrature coupler is not included (the isolation at the central frequency is over 10 dB). This is mainly due to the easier comparison between the proposed antenna and the ones in the previous literature which can only realize one polarization and have a single port. The simulated and measured radiation patterns of the proposed antenna at 840MHz , 915MHz.and 960MHz are respectively showed in Fig.11, Fig12, and Fig.13. The proposed antenna can realize both RHCP and LHCP. Since the antenna configuration is symmetric, only the RHCP case is given here. The front-to-back ratio at 915MHz can be as high as 14dB. The cross-polarization of the antenna is over 15 dB lower than the co-polarization at most of the frequencies within the operating band. In addition, the simulated radiation efficiency is over 70-82% within the operating frequencies.

A comprehensive comparison between previously reported antennas for UHF RFID readers and our proposed antenna is summarized in Table 2. Although the gains of the antennas in [1][8]–[11] are higher than that of the proposed antenna, their sizes are much larger than the proposed one. Notably, the antenna in [12] has similar small size to our proposed antenna. However, it has a narrow impedance and AR bandwidth, and it cannot cover the entire UHF band from 840MHz to 960MHz. This indicates that the proposed antenna has a low profile, a wide AR and impedance bandwidth over the entire UHF RFID band. The gain of proposed antenna is less than the gain of antenna in reference [12], because a branch line coupler using in circular polarization antenna will generate large loss if isolation of port1 and port4 is low. However, the designed antenna can realize dual circular polarization. It will increase the freedom of RFID system. Although, some stacked patch antennas were proposed in the open lecture, it is different methods to improve the impedance and AR performance from our works. The stacked patch antenna on the open report are unable to explain the effect of dielectric substrate inserting air gap of the ground plane and drive patch. The Ring-Slot antenna above an open cavity loaded with an artificial magnetic conducting reflector, is presented in [18]. However, the artificial magnetic conducting reflector of slot antenna need larger dimension. This antenna not suitable to broad circular polarization application because of the narrow AR bandwidth (4.0%). In proposed antenna, the metal cavity can make the ring-shape patch antenna to generate better unidirectional radiation and improve the impedance and AR bandwidth.

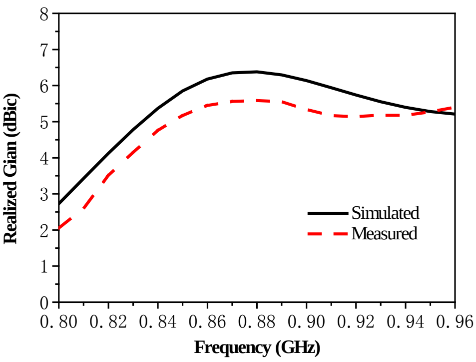


***Fig.**10. Simulated and measured realized gain.*

4. conclusion

A compact, broadband circularly polarized RFID reader antenna covering the entire UHF RFID band has been presented. The antenna has a ring-shaped radiating patch, two coupling square patches, and a 3dB branch coupler underneath the ground. The ring-shaped patch is coupled by two small square patches on the top of the middle substrate. Good impedance matching, axial ratio, and CP gain performance from 840MHz to 960MHz have been achieved in the simulated and measured results. Moreover, the measured results show that the proposed antenna has an impedance bandwidth (S11<-10dB) of 30.8%, or 730–990 MHz, a 3-dB AR bandwidth of 24.2%, or 760–970 MHz, a stable gain with an average gain of 5.3dBic, and a front-to-back ratio of at least 13dB over the entire RFID band. The prototype can generate RHCP at 915 MHz, and it can also create LHCP by interchanging port1 and port4. The proposed antenna is very suitable for UHF RFID reader applications. Since the proposed antenna requires more manufacturing procedure for four layer of conductors and a cavity. it is difficult for mass production. However, it is an effective design method to retain compact structure for circular polarized antenna. Some work to reduce the Complexity of proposed antenna will be done in our future work.

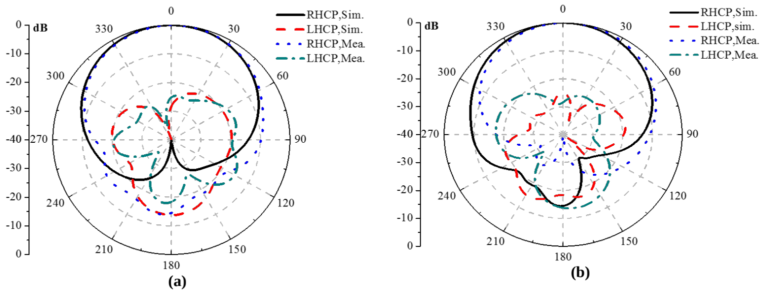


Fig. 11. *Measured and simulated radiation patterns at 840MHz in: (a)xoz plane, (b)yoz plane*

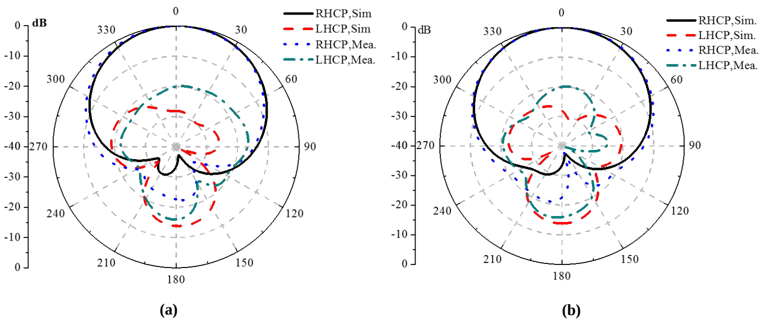


Fig.12. *Measured and simulated radiation patterns at 915MHz in: (a)xoz plane, (b)yoz plane*

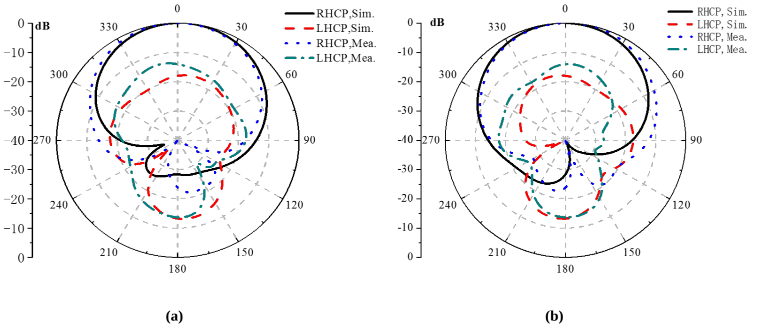


Fig.13. *Measured and simulated radiation patterns at 960MHz in: (a)xoz plane, (b)yoz plane*

Table 2 Return loss bands, CP bands, gain and sizes of some wideband UHF RFID reader antennas

Refs.	Frequency range ($\lvert S11\rvert \leq$ -10dB)	AR(3dB)	Max gain (dBic)	Dimension Size $L \times W \times H$ (mm)
[1]	760-963MHz, 23.56%	818-964MHz, 16.9%	9.3	250×250×35
[8]	797-965MHz, 19.1%	833-962MHz, 14.4%	9.8	250×250×39
[9]	685-1125MHz, 48.6%	836-986MHz, 16%	8.6	250×250×60
[10]	833-1033MHz, 21.4%	835-955MHz, 13.4%	7.0	200×200×29.8
[11]	835-1150MHz, 31.7%	839-968MHz, 14.2%	7.6	170×190×45
[12]	854-1102MHz, 25.4%	902-929MHz, 3.0%	6.77	150×150×34
This work	730-990MHz, 30.8%	760-970MHz, 24.2%	5.6	150×150×21

5. Acknowledgments

This work was supported by the National Natural Science Foundation of China (11621101, 61108022), the Guangdong Innovative Research Team Program (201001D0104799318), partially the National High Technology Research and Development Program (863 Program) of China (No. 2012AA030402)

6. References

[1] Chen, Z.N., Qing, X., Chung, H.L.: 'A universal UHF RFID reader antenna', IEEE Trans. Microw. Theory Tech., 2009., 57, (5), pp.1275–1282

[2] Mireles, E. Sharma, S.K.: 'A novel wideband circularly polarized antenna for worldwide UHF band RFID reader applications', og. Electromagn. Res. B, 2012, 42, pp. 23–44

[3] Balanis, C.A.: 'Antenna Theory: Analysis and Design' (Wiley, New York, 2005, 3nd edn.)

[4] Randy, O.T., Nasimuddin, Alphones, A.: 'circularly polarized slotted-ground microstrip antennas for radiofrequency identification readers', crow. Opt. Technol. Lett., vol. 2012, 54, (10), pp.2304–2309

[5] Nasimuddin, Qing, X., Chen, Z.N.: 'Compact asymmetric-slit microstrip antennas for circular polarization', IEEE Trans. Antennas Propag., 2011, 59, (1), pp. 285–288

[6] Lin, S.Y., Lin, Y.C.: 'Printed RFID reader antenna with circular polarization for handheld operation'', Microw. Opt. Technol. Lett., 2012, 54, (12), pp. 2728–2730

[7] Chen, J.P., Hsu, P.: 'A spirally complementary split-ring resonators antenna for circular polarization and RFID reader application', in Proc. Antennas Propag. Soc. Int. Symp. (APSURSI), 2012, pp. 1–2.

[8] Liu, X.Y., Liu, Y., Tentzeris, M.M.: 'A Novel Circularly Polarized Antenna with Coin-Shaped Patches and a Ring-Shaped Strip for Worldwide UHF RFID Applications', IEEE Antennas Wireless Propag. Lett., 2014, 14, pp. 707–714

[9] Sim, C.Y.D., Hsu, Y.W., Yang, G.: 'Slits Loaded Circularly Polarized Universal UHF RFID Reader Antenna', IEEE Antennas Wireless Propag. Lett., 2014, 14, pp. 827–830

[10] Nasimuddin, Qing, X., Chen, Z.N.: 'A wideband circularly polarized stacked slotted microstrip patch antenna', IEEE Antennas Propag. Mag., 2013, 55, (6), pp. 84-99

[11] Sim, C.Y.D., Hsu, Y.W., Lin, C.W., et al.: 'Broadband Circularly Polarized Antenna with Moon-Shaped Parasitic Element', Int. J. RF Microw. Comput.-Aided Eng., 2016, 26, (5), pp.387-395

[12] Yeh, C.H., Hsu, Y.W., Sim, C.Y.D., Chi, C.J.: 'Equilateral Triangular Patch Antenna for UHF RFID Applications', Int. J. RF Microw. Comput.-Aided Eng., 2014, 24, (5), pp.580-586

[13] Lu, J.H., Wang, S.F.: 'Planar broadband circularly polarized antenna with square slot for UHF RFID reader', IEEE Trans. Antennas Propag., 2013, 61, (1), pp. 45–53

[14] Xu, B., Zhang, S., Liu, Y. S., *et al.* "Compact broadband circularly polarised slot antenna for universal UHF RFID readers," Electron. Lett., 2015, 51, (11), pp.808–809

[15] Cao, R., Yu, S.C.: 'Wideband Compact CPW-Fed Circularly Polarized Antenna for Universal UHF RFID Reader', IEEE Trans. Antennas Propag., 2015, 63, (9), pp. 4148–4151

[16] Wang, Z.B., Fang, S.J., Fu, S.Q., *et al.*, 'Single-Fed Broadband Circularly Polarized Stacked Patch Antenna with Horizontally Meandered Strip for Universal UHF RFID Applications,' IEEE Transactions on Microwave Theory and Techniques, 2011, 59, (4), pp.1066-1073

[17] Liu, Q., Shen, J. Y., Liu, et al., 'Low-cost compact circularly polarized directional antenna for universal UHF RFID handheld reader applications' IEEE Antennas Wirel. Propag. Lett., 2015, 14, pp.1326–1329

[18] Ferreira, Joubert, J., and Odendaal, J., "A compact dual-circularly polarized cavity-backed ring-slot antenna," IEEE Trans. Antennas Propag., 2017, 65, (1), pp. 364–368

[19] Lai, X.Z., Xie, Z.M., Xie Q.Q., et al.: 'A Dual Circularly Polarized RFID Reader Antenna with Wideband Isolation', IEEE Antennas Wireless Propag. Lett., 2013, 2, pp. 1630–1633.

[20] Gao, S., Luo, Q., Zhu, F.: 'Circularly Polarized Antennas' (Wiley, New York, 2014, 1st edn.), pp.30–33

[21] Li, Y., Sun, S., Yang, F.: 'A Miniaturized Yagi-Uda-Oriented Double Ring Antenna with Circular Polarization and Directional Pattern', IEEE Antennas Wireless Propag. Lett., 2013, 12, pp. 945–948

[22] Yang, W., Pan, Y., Zheng, S., Hu, P., et al.: 'A Low-Profile Wideband Circularly Polarized Crossed-Dipole Antenna', IEEE Antennas Wireless Propag. Lett., 2017, 16, pp. 2126–2129

[23] Li, Y., Tian, B., Xue, J., et al.: 'Compact Dual-Band Circularly Polarized Antenna Design for Navigation Terminals', IEEE Antennas Wireless Propag. Lett., 2015, 15, pp. 802-805

[24] Tran, H.H., Park, I.: 'Wideband Circularly Polarized Cavity-Backed Asymmetric Crossed Bowtie Dipole Antenna', IEEE Antennas Wireless Propag. Lett., 2015, 15, pp. 358–361