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Design of Broadband Circularly Polarized Square Slot Antenna for UHF RFID Applications

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Abstract—A novel circularly polarized (CP) square slot antenna for covering the universal ultrahigh-frequency (UHF) radio frequency identification (RFID) band is proposed. The antenna uses low-cost FR4 material as the dielectric substrate and coplanar waveguide (CPW) to feed. Circularly polarized radiation can be realized by embedding two symmetrical rectangular grounded planes with L-shaped slits in opposite corners of the square slot. The widened vertical tuning stub at the end of the signal line fed by CPW can improve the CP and impedance matching operation, and finally realizes broadband characteristic. The measured 10 dB impedance bandwidth and 3 dB axial ratio (AR) bandwidth are 1250 MHz (710–1960 MHz) and 180 MHz (840–1020 MHz), respectively. The measured peak gain is about 3.4 dBi in the whole UHF RFID frequency band (0.84–0.96 GHz). The dimension of the CP square slot antenna is $116 \times 116 \times 1.6\,\text{mm}^3$. The proposed antenna has the advantage of simple structure, is easy to be processed, can exhibit dual CP radiation characteristic, and covers the broadband frequency range, which can be applied to the UHF RFID handheld reader environment.

1. INTRODUCTION

Radio frequency identification (RFID) is a non-contact automatic identification technology that uses radio frequency to identify and track objects [1, 2]. Due to the advantages of high data rate, long reading distance, strong reliability, and high security, RFID technology has been used in many applications, such as transportation, logistics, medical care, and public safety. The RFID system mainly consists of an electronic tag, a reader device, and a management system. The reader device includes a reader antenna. In practical applications, the RFID tag antenna is linearly polarized (LP) and can only receive electromagnetic waves parallel or perpendicular to the direction of the electric field. In order to reduce the loss caused by polarization mismatch and the multipath effect between the reader and tag antenna, the reader antenna is usually designed as a circularly polarized (CP) antenna [3, 4]. The frequency bands of the RFID system include low frequency (LF), high frequency (HF), ultra-high frequency (UHF), and microwave (MW) frequency bands [5]. Different countries and regions have assigned different frequency ranges in the UHF RFID frequency range. The operation frequency range of UHF RFID is 840–845 MHz and 920–925 MHz in China, 902–928 MHz in America, 952–955 MHz in Japan, and 866–869 MHz and 923–925 MHz in Singapore [2]. Therefore, the research on antennas covering the universal UHF RFID frequency band is the current focus.

In recent years, many CP microstrip antennas [6–11] applied to the UHF RFID frequency band have been proposed, but these antennas have a large dimension, narrow impedance bandwidth and axial ratio bandwidth. Square slot antennas [12–18] have the advantages of small size, easy manufacture, and wide operation bandwidth. CP can be achieved by inserting an arc-shaped strip into the square slot in [19], and the antenna has a wide operation frequency bandwidth. In [20], a cross-strip is embedded

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into an X-shaped slot to produce CP radiation, and it can obtain the impedance bandwidth about 3.0% and axial-ratio (AR) bandwidth about 1.3%. A novel CP slot antenna is proposed [21], by insetting a stick-shaped shorted strip to generate CP radiation. Impedance bandwidth and axial ratio bandwidth do not cover the universal UHF RFID frequency range from 840 to 960 MHz.

In this paper, a novel square slot antenna covering the global UHF RFID frequency range is proposed. A pair of symmetrical rectangular grounded planes with L-shaped slits is embedded in the diagonal corners of the square slot, which can generate CP radiation by exciting two orthogonal LP modes with 90° phase difference. The wide slot structure increases the impedance bandwidth by coupling with the feed structure. The widened vertical tuning stub at the end of the feedline improves the impedance matching and circular polarization characteristics. Finally, the proposed antenna achieves broadband characteristic. The experimental results show that the 10 dB impedance bandwidth of the proposed antenna can achieve about 1250 MHz (710–1960 MHz) and the 3 dB axial ratio bandwidth about 180 MHz (840–1020 MHz), covering the universal UHF RFID frequency band. Additionally, gain is a very important parameter of the antenna, and it is required that the gain should not be too low, so this paper requires the minimum requirement of the antenna gain to be -1 dBi. The measured peak gain of the proposed broadband circularly polarized square slot antenna is about 3.4 dBi, which is 4.4 dBi higher than the minimum requirement. Compared with the antennas presented in previous researches, the proposed antenna has a simple structure, wide impedance bandwidth and AR bandwidth.

2. ANTENNA DESIGN

The geometry of the proposed CP square slot antenna is shown in Fig. 1. The proposed antenna is fabricated on the top side of a square FR4 substrate with the dimension of $116 \times 116\,\text{mm}^2$, a thickness ($H$) of 1.6 mm, a relative permittivity (ε_r) of 4.4, and a loss tangent ($\tan\delta$) of 0.02. The ground plane and feeding structure are on the same side of the dielectric substrate, and a single-sided printing method is adopted. A wide square slot with a side length of 100 mm is etched on the ground plane. The antenna is fed by a signal line with a width of 2 mm and the gap width (g_1) of 0.5 mm, which is connected to a $50\,\Omega$

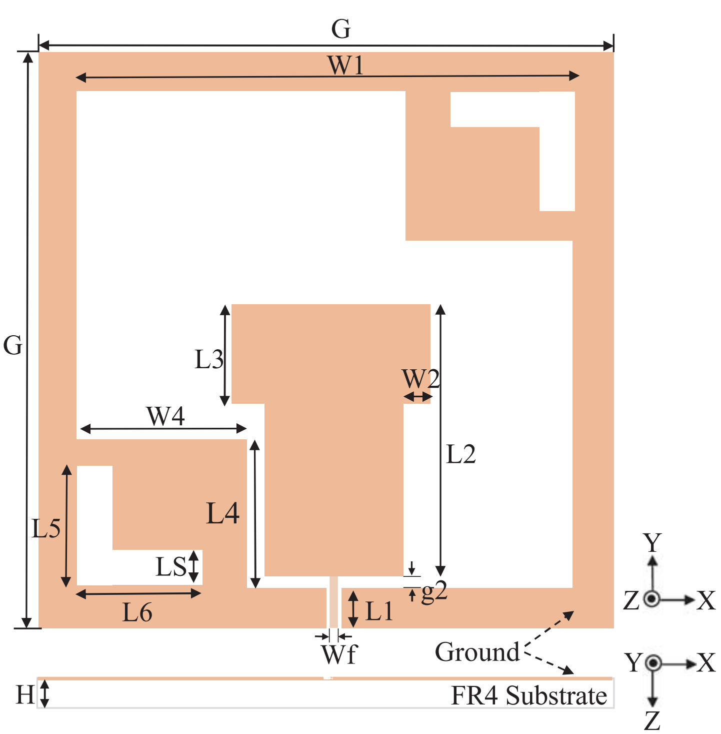


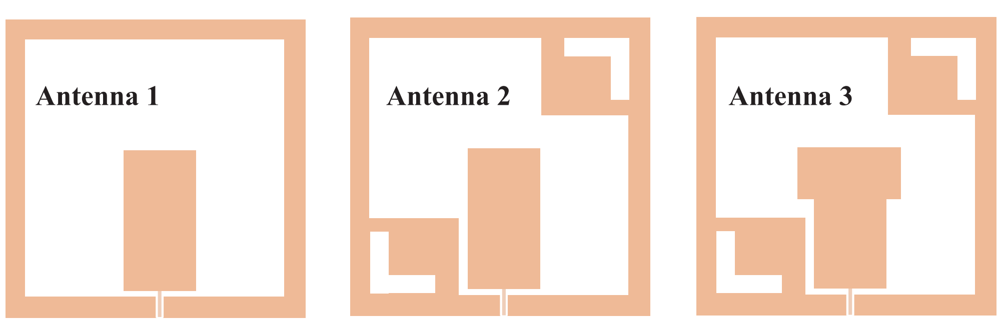
Figure 1. Geometry of the proposed CP square slot antenna.

SMA coaxial connector. The widened signal line with a length (L_2) of 60 mm and width (W_3) of 28 mm is embedded in a square slot, and vertical tuning stubs with the length (L_3) of 20 mm and width (W_2) of 6 mm are respectively embedded along the X axis at the end of the widened signal line to optimize impedance matching and axis ratio characteristics. A pair of symmetrical rectangular grounded planes with the length of 30 mm and width of 34 mm embedded respectively a pair of L-shaped slots with side lengths of 24 mm and 25 mm and a slot width (L_S) of 7 mm to disturb the electric field distribution on the square slot, resulting in two equal amplitudes, approximately orthogonal linear resonant modes (TE_{01} and TE_{10} modes) with a phase difference of 90°, achieving circular polarization. By adjusting the parameters of the L-shaped slot, the 3 dB AR bandwidth can be optimized to meet the required axial ratio bandwidth requirements. The antenna proposed in this paper is simulated and optimized by Ansoft HFSS 18.0 electromagnetic simulation software. Table 1 shows the optimal dimensions of the proposed broadband CP square slot antenna.

Table 1. Optimal values of antenna parameters.

G	L_1	L_2	L_3	L_4	L_5
116	8	60	20	30	24
L_6	L_S	W_1	W_2	W_3	W_4
25	7	100	6	28	34
W_f	g_1	g_2	H		
2	0.5	2	1.6		

The design process of the proposed antenna can be described by the three prototypes from Antenna 1 to Antenna 3 shown in Fig. 2. The simulation results of the reflection coefficient S_{11}, AR, and gain for Antenna 1, Antenna 2, and Antenna 3 are shown in Fig. 3. Antenna 1 is designed as a simple square slot structure, and a single widened signal line is used as the feedline. From the simulation results of S_{11}, it is found that Antenna 1 has good impedance matching, with 10 dB impedance bandwidth from 0.96 GHz to 1.17 GHz, and the resonance frequency is 1.06 GHz. The AR simulation results show that the AR of Antenna 1 in the entire UHF RFID frequency band is about 51 dB, which is much greater than 3 dB. Therefore, Antenna 1 radiates linearly polarized waves and does not achieve circular polarization characteristic. From simulated results of the gain, it is found that the gain of Antenna 1 fluctuates within 1.9–2.9 dBi in the frequency range from 0.7 GHz to 1.1 GHz, which meets the minimum requirement of the gain, but is still low. Antenna 2 is compared with Antenna 1 in structure. Antenna 2 is embedded with a pair of symmetrical rectangular planes with L-shaped slits at the opposite corners of the square slots and is connected to the ground plane. From the simulated results of Antenna 2, it can be found that the impedance matching, circular polarization, and gain performance are improved. In the entire UHF RFID frequency band, S_{11} is less than 10 dB, and the impedance bandwidth is from 0.82 GHz



(a) (b) (c)

Figure 2. Three prototypes of the proposed antenna.

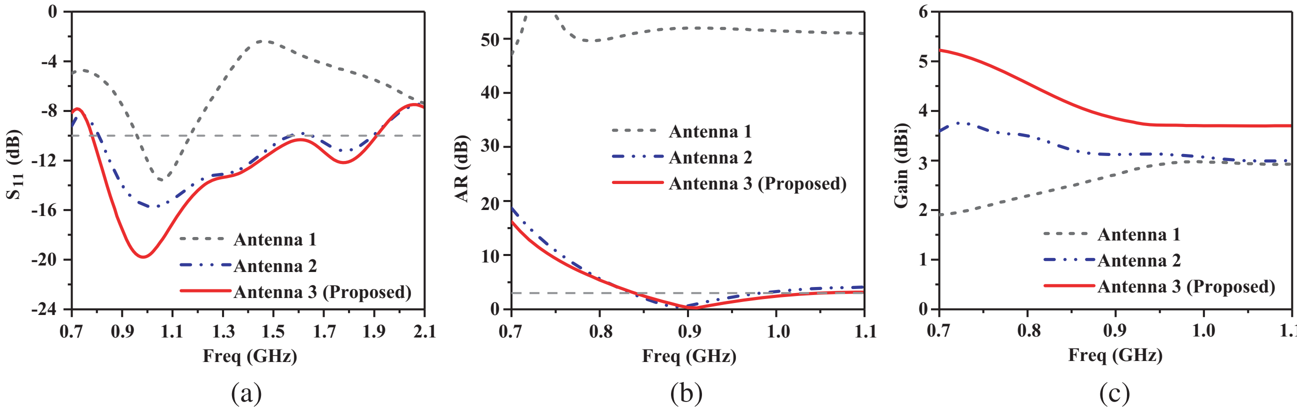


Figure 3. Simulated results for Antenna 1–3. (a) Reflection coefficient. (b) Axial ratio. (c) Gain.

to 1.57 GHz and from 1.66 GHz to 1.89 GHz. The symmetrical rectangular grounded plane structure excites near-degenerated resonant modes with a phase shift of 90°, so that Antenna 2 can achieve circular polarization performance, and the 3 dB axial ratio bandwidth is from 0.84 GHz to 0.98 GHz. In the radiation band range from 0.7 GHz to 1.1 GHz, the gain of Antenna 2 is higher than that of Antenna 1, and the trend is smoother. In order to increase the impedance bandwidth, 3 dB axial ratio bandwidth, and gain, and to further optimize the impedance matching, circular polarization, and gain characteristics, Antenna 3 is presented. In Antenna 3, the end of feedline with a length of 20 mm along the $-Y$ axis is respectively widened by the width of 6 mm towards the $\pm X$ axis direction. It is found from the simulated results that both the 10 dB impedance bandwidth and 3 dB axial ratio bandwidth have been widened, and the gain has been further increased. The 10 dB impedance bandwidth is from 0.79 GHz to 1.92 GHz, and the 3 dB axial ratio bandwidth is from 0.84 GHz to 1.05 GHz. The bandwidth meets the frequency band requirements and covers a wide frequency range. The gain fluctuates in the range of 3.7–4.2 dBi within the entire 3 dB axial ratio bandwidth, meeting the minimum requirements.

To illustrate the CP radiation mechanism, Fig. 4 shows the surface current distributions with different phases of 0°, 90°, 180°, and 270° on the ground plane and feedline at 900 MHz. At a phase angle of 0°, the current flows mainly in the $+X$ and $+Y$ directions, and the arrow direction is the vector sum of the current components in the $+X$ and $+Y$ directions. At a phase angle of 90°, the current mainly flows in the $+X$ and$-Y$ directions, and the current direction is orthogonal to the direction at the phase angle of 0°. The current directions with phase angles of 180° and 270° are opposite to the phase angles of 0° and 90°, respectively. As the phase angle increases by 90°, the current rotates in a clockwise direction. Therefore, the proposed antenna excites left-hand circular polarization (LHCP) radiation in the $+Z$ direction. When the rectangular ground planes with an L-shaped slot are respectively embedded in the other two opposite corners of the square slot, right-hand circular polarization (RHCP) radiation is excited in the $+Z$ direction. The proposed broadband rectangular slot antenna has dual circular polarization characteristic.

3. PARAMETERS STUDIES AND OPTIMIZATION

To obtain the desired results of impedance matching and circular polarization characteristics, Ansoft HFSS 18.0 is used to simulate and optimize the significant parameters of the proposed antenna. The simulation results illustrate the influence of different parameters on the reflection coefficient S_{11} and AR. When optimizing the parameters, make sure that the value of one parameter is tuned while the values of other parameters are fixed.

3.1. Influence of the Width of L-Shaped Slits L_S

Figure 5 shows the influence of the L-shaped slit width (L_S) on the S_{11}, AR, and gain. It can be seen from Fig. 5(a) that when L_S takes different values, the resonant frequencies of the S_{11} do not change,

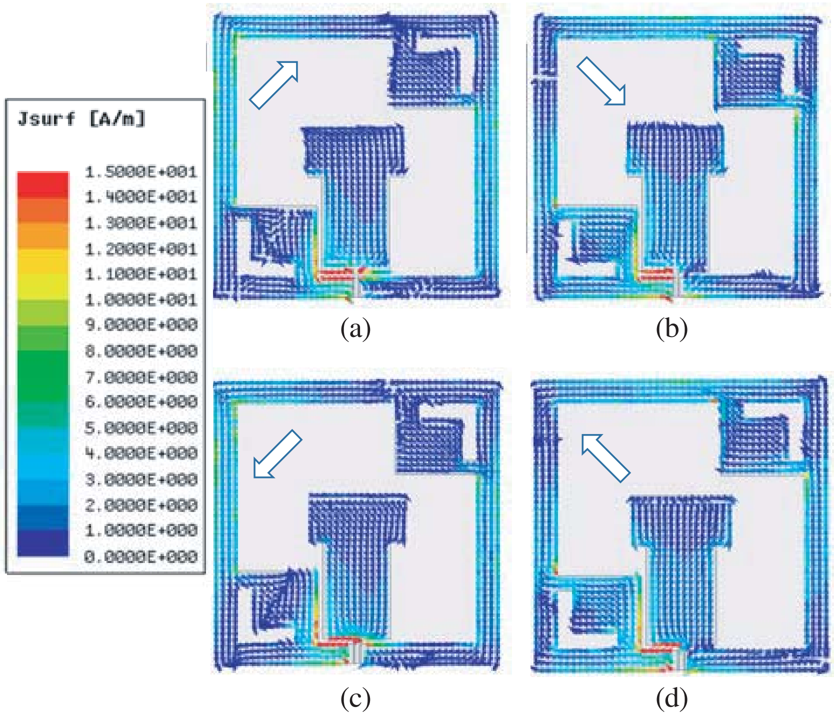


Figure 4. Surface current distributions at 900 MHz for four phases angles. (a) 0°. (b) 90°. (c) 180°. (d) 270°.

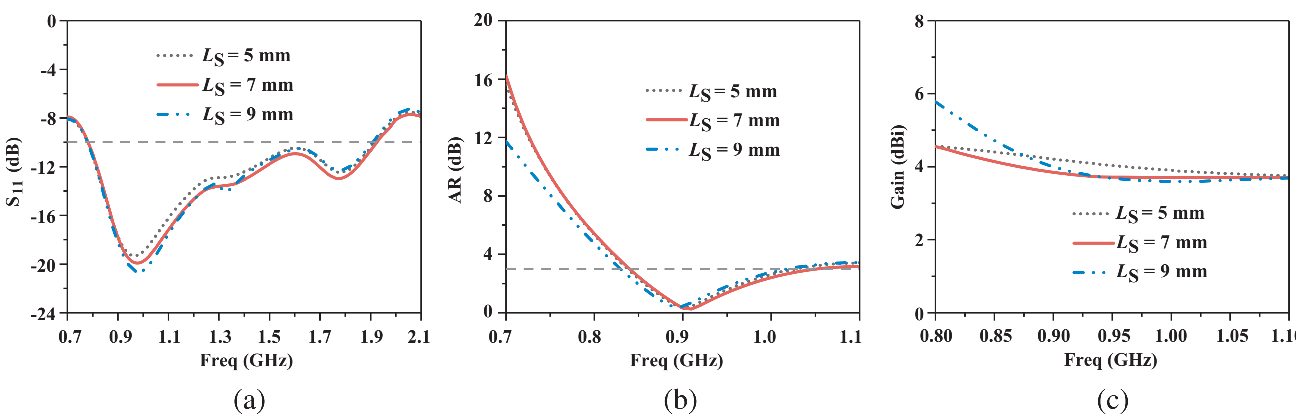


Figure 5. Simulated results of different L-shaped slit widths (L_S). (a) S_{11}. (b) Axial ratio. (c) Gain.

and the starting frequencies are the same, both at 0.78 GHz. When L_S is 7 mm, the stop frequency is the largest, and the 10 dB impedance bandwidth is the widest. The influence of L_S on the AR bandwidth is shown in Fig. 5(b). When L_S is 9 mm, compared with L_S of 5 mm and 7 mm, the resonant frequency, start frequency, and stop frequency are all slightly shifted to lower frequencies. When L_S is 7 mm, the 3 dB axial ratio bandwidth is the widest, from 0.84 GHz to 1.05 GHz, covering the UHF RFID frequency band, and the AR performance is the best. The influence of L_S on the gain is shown in Fig. 5(c). Within the entire radiation band from 0.8 GHz to 1.1 GHz, when L_S is 5 mm, the gain is greater than that when L_S is 7 mm, but the difference is not large. When L_S is 9 mm, the gain curve is the least smooth. Therefore, considering the influence of L_S on the impedance bandwidth, axial ratio bandwidth, and gain, the optimal value of L_S is 7 mm.

3.2. Influence of the Feedline Parameters $\mathbf{W_2}$ and $\mathbf{g_2}$

The effect of the widened width of W_2 at the end of the feedline on the antenna performance is demonstrated in Fig. 6. The value of W_2 has little effect on the start frequency and stop frequency of the impedance bandwidth, and has almost no effect on the resonance frequencies of the reflection coefficient S_{11}. The larger the value of W_2 is, the better the impedance matching performance is in the whole UHF RFID frequency range. Fig. 6(b) shows the effect of W_2 on the axial ratio performance. As the value of W_2 increases, the resonance frequency shifts to higher frequencies. When W_2 is 8 mm, the axial ratio bandwidth is the widest, but the starting frequency is 0.85 GHz, which does not cover the universal UHF RFID frequency range. The axial ratio bandwidth of W_2 of 6 mm is second only to the bandwidth of W_2 of 8 mm. It is found from Fig. 6(c) that the gain of all values of W_2 meets the minimum requirement. Except for $W_2 = 8$ mm, as the value of W_2 increases, the gain decreases in the entire radiation frequency range. The gain when W_2 is 2 mm is very similar to the gain when W_2 is 4 mm.

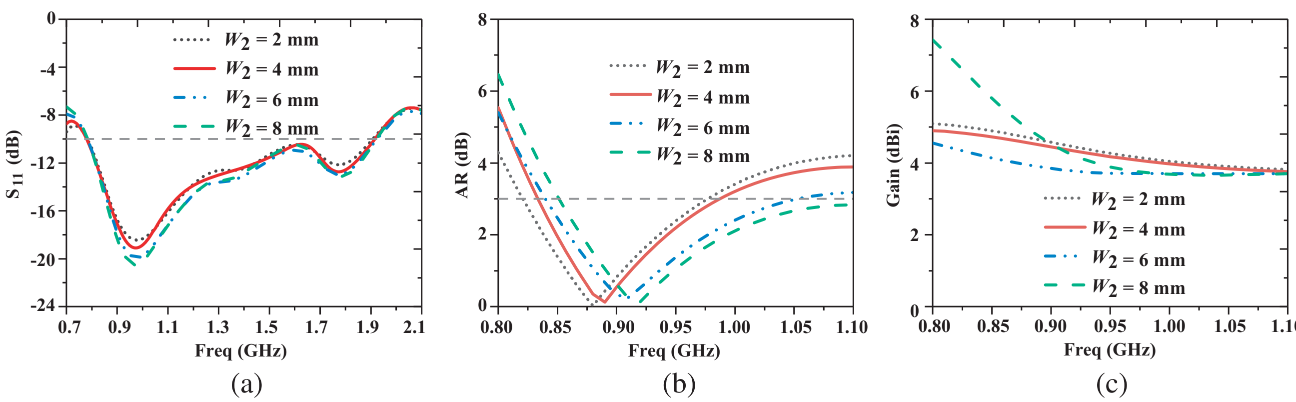


Figure 6. Simulated results of different widened feedline widths (W_2). (a) S_{11}. (b) Axial ratio. (c) Gain.

Figure 7 shows the effect of parameter g_2 on the return loss, AR, and gain characteristics of the proposed antenna, and parameter g_2 is the gap width between the feedline and ground plane. From the change curve of the influence of g_2 on the reflection coefficient S_{11}, it is found that g_2 has a greater influence on the low-frequency resonance point, and the resonance frequency can be adjusted by changing the value of g_2. As g_2 increases, the low-frequency resonance point shifts to lower frequency, and the high-frequency resonance point hardly changes. When g_2 is 2 mm, the 10 dB impedance bandwidth is the widest. Except for $g_2 = 1$ mm, the 10 dB impedance bandwidth decreases as g_2 increases. Different

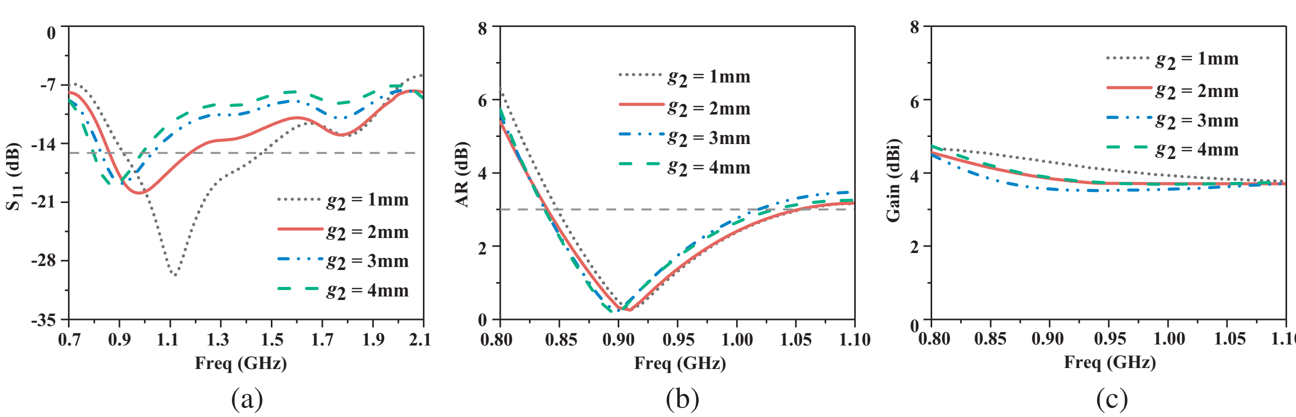


Figure 7. Simulated results of different gap widths (g_2). (a) S_{11}. (b) Axial ratio. (c) Gain.

values of g_2 have almost no effect on the 3 dB axial ratio bandwidth and resonant frequency. The small effect of the parameter g_2 on the 3 dB axial ratio bandwidth shows that g_2 has strong manufacture tolerance for the broadband circularly polarized antennas. Fig. 7(c) shows the effect of parameter g_2 on the gain of the antenna. It is found that g_2 has little effect on the gain.

3.3. Influence of the Width of Square Slot W_1

Figure 8 illustrates the effect of the square slot width (W_1) on the performance of the broadband circularly polarized antenna. The low resonance frequency of impedance matching shifts to lower frequencies as W_1 increases. Except for $W_1 = 98$ mm, the high resonance frequency hardly shifts, and the impedance bandwidth decreases with the increase of W_1. When W_1 is 104 mm, the impedance bandwidth is the widest, but the 3 dB axial ratio bandwidth is from 0.86 GHz to 1.06 GHz, which does not meet the bandwidth requirements. When W_1 is 102 mm, compared with other values of W_1, the gain is the largest in the entire radiation frequency range, but the gain trend is not smooth. Therefore, when W_1 is 100 mm, the proposed antenna has good impedance matching characteristic, satisfies the coverage of UHF RFID frequency band, and has a smooth curve of the gain in the UHF RFID frequency band, so that the antenna has stable performance.

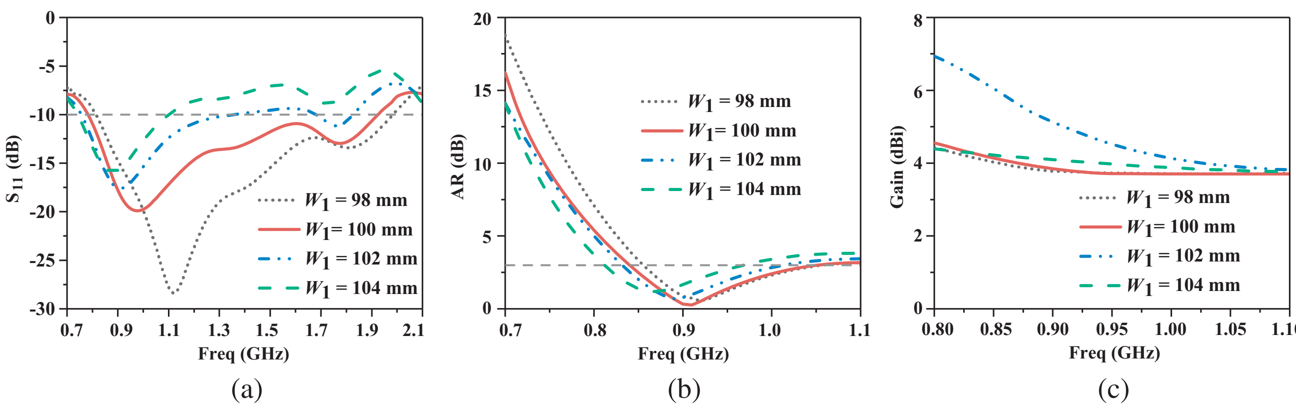
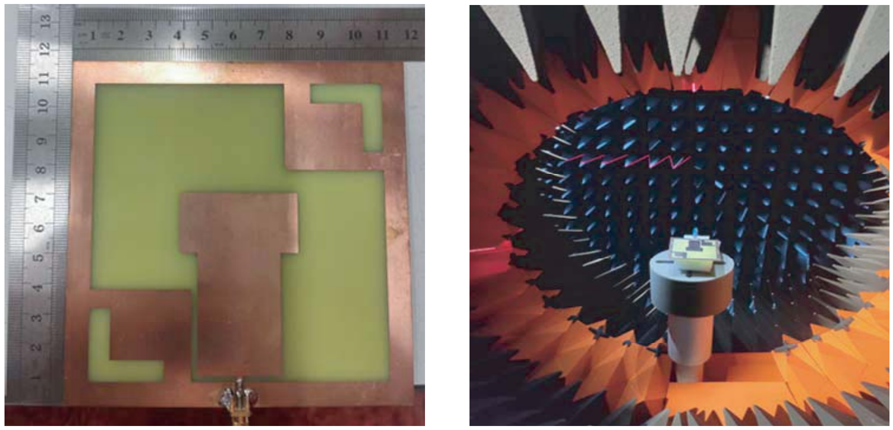


Figure 8. Simulated results of different square slot widths (W_1). (a) S_{11}. (b) Axial ratio. (c) Gain.

4. RESULTS AND DISCUSSION

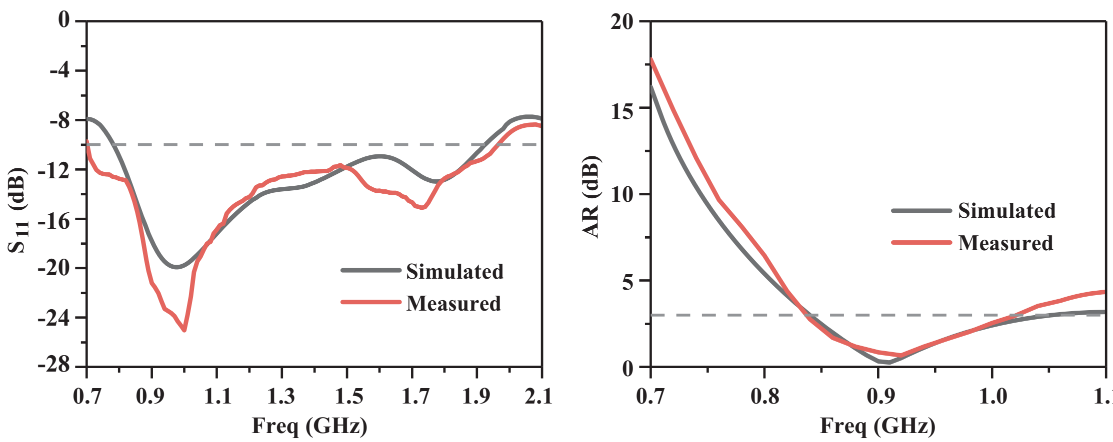
The manufactured prototype and far-field measurement diagram of the proposed broadband CP square slot antenna are shown in Fig. 9. The reflection coefficient S_{11} is tested by an Agilent E5071C vector network analyzer, and the far-field performance of the antenna is measured in an anechoic chamber using a SATIMO measurement system. Fig. 10 illustrates the simulated and experimental results of S_{11} and AR of the proposed antenna. From Fig. 10, compared with the simulated impedance bandwidth, the measured impedance bandwidth is wider, but the trend of the curves is generally similar. The simulated 10 dB impedance bandwidth is 1130 MHz (0.79–1.92 GHz), and the measured 10 dB impedance bandwidth is 1250 MHz (0.71–1.96 GHz). The axial ratio, gain, efficiency, and 2D radiation pattern of the proposed antenna are all measured in the anechoic chamber. The simulated and measured AR bandwidths are in good agreement. The tested 3 dB AR bandwidth is 180 MHz (840–1020 MHz), and the relative bandwidth is about 20.0% at the operating frequency of 900 MHz. The measured impedance bandwidth and axial ratio bandwidth have wide bandwidth coverage, covering the universal UHF RFID frequency range.

The experimental results of peak gain and radiation efficiency are shown in Fig. 11. In the frequency range of 840 MHz to 960 MHz, the peak gain fluctuates within 3.0–3.5 dBi, and the radiation efficiency reaches about 95%. The measured peak gain and radiation efficiency results are lower than the simulated results, and the slight difference between simulated and measured results of peak gain and radiation



(a) (b)

Figure 9. Photographs of the proposed broadband CP square slot antenna. (a) Manufactured prototype. (b) Far-field measurement.



(a) (b)

Figure 10. Simulated and measured results. (a) S_{11}. (b) Axial ratio.

efficiency is mainly due to manufacturing tolerances. Fig. 12 depicts the simulated and measured 2D radiation patterns for both x-o-z plane and y-o-z plane at the working frequency of 900 MHz. The measured results show that the proposed antenna has good bidirectional radiation symmetry in the x-o-z and y-o-z planes and generates LHCP radiation waves in the bore-sight direction ($+Z$ direction), which is consistent with the above analysis results. When the center frequency is 900 MHz, the measured 3 dB beamwidths in the x-o-z and y-o-z planes are about 102° ($-46° \sim 56°$) and 99° ($-55° \sim 44°$), respectively, and the range of beamwidth is wide. The wide beamwidth of the proposed antenna in RFID system can effectively reduce the number of readers.

Figure 13 illustrates the measured reading distance of the proposed broadband CP square slot antenna. The proposed antenna is connected to a UHF RFID reader module (JR2010) with the operating frequency band of 920–925 MHz and a low output power of 26 dBm. The UHF RFID reader module is connected to the computer through the USB cable. The reading distance is measured by rotating the monopole-like tag (Alien 9640) with dimensions of 94.8 mm × 8.15 mm along the $\pm z$ axis direction. The measured results show that the maximum reading distance in free space is in the range from 1.85 to 2.30 m. In the bore-sight direction ($+Z$ direction), the measured reading distance is the farthest.

The comparison between the proposed broadband circularly polarized square slot antenna and

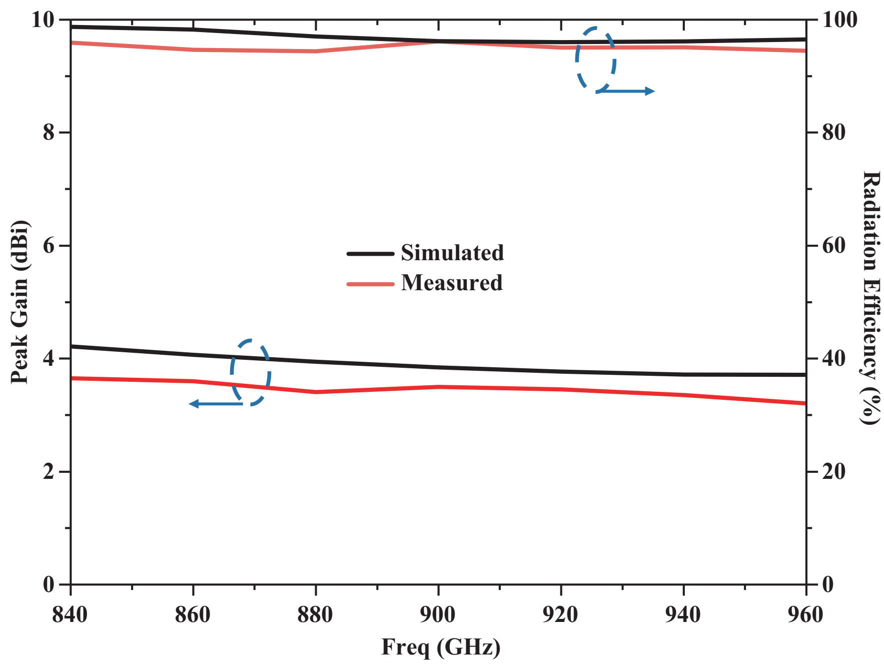


Figure 11. Simulated and measured peak gain and radiation efficiency of the proposed antenna.

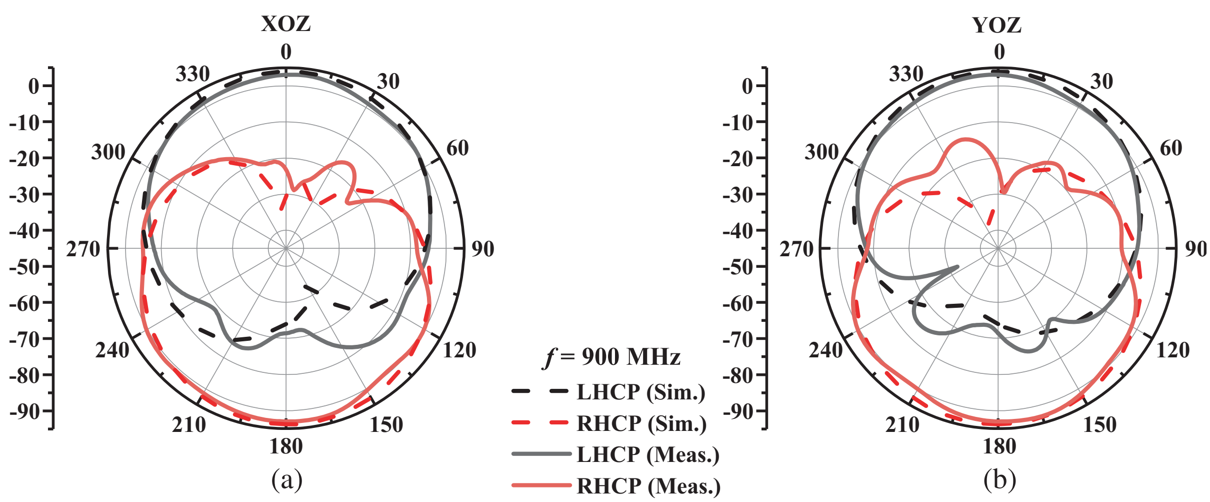


Figure 12. Simulated and measured 2D radiation patterns of the proposed broadband CP square slot antenna at 900 MHz. (a) *x-o-z* plane. (b) *y-o-z* plane.

the other circularly polarized antennas in references is shown in Table 2. It can be found that the proposed antenna has a wide bandwidth coverage, covering the universal UHF RFID frequency band. The circularly polarized antennas in the literature [7, 9] have a multi-layered complex structure, and the operating bandwidth does not cover the frequency range of 840–960 MHz. The antennas proposed in [11, 21, 22] obtain the advantage of compact size, whereas the corresponding operating bandwidth does not meet the requirements. The AR bandwidth of the antenna in [19] is similar to that of the proposed antenna, but its volume is larger. Since the proposed circularly polarized antenna does not add a reflector and has bidirectional radiation characteristic, the gain is not high.

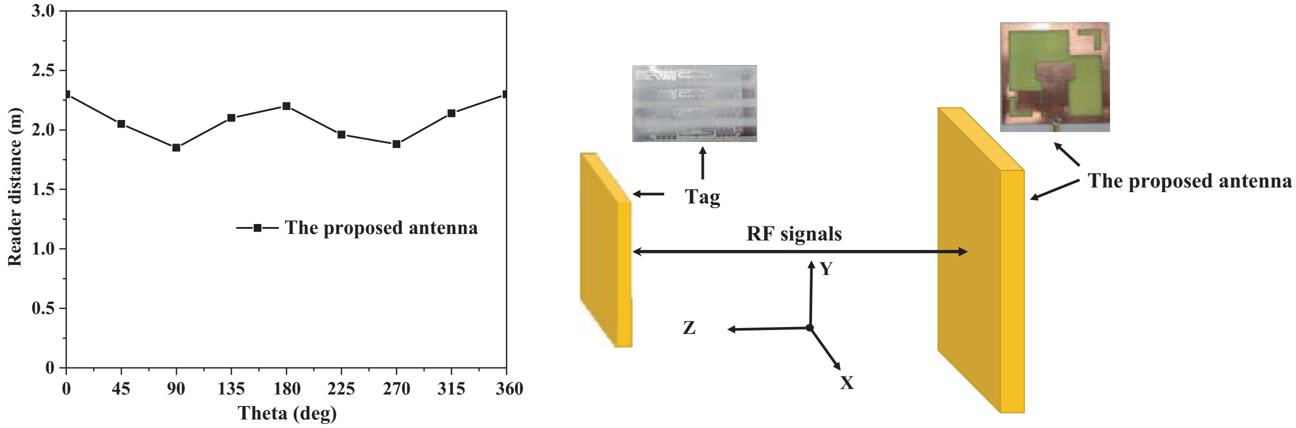


Figure 13. Measured reading distance of the proposed broadband CP square slot antenna by rotating the tag on the $\pm z$ axis.

Table 2. Comparison of the proposed broadband CP square slot antenna with other antennas in references.

Ref.	10 dB IBW (MHz)	3 dB AR BW (MHz)	Maximal gain (dBi)	Dimensions $L \times W \times H$ (mm^3)
[7]	225 (758–983)	121 (838–959)	8.6	$250 \times 250 \times 36.5$
[9]	194 (768–962)	141 (816–957)	9.8	$250 \times 250 \times 35$
[11]	328 (748–1076)	165 (805–970)	3.1	$95 \times 100 \times 13.6$
[19]	142 (860–1002)	166 (857–1023)	6.8	$126 \times 121 \times 0.8$
[21]	136 (894–1030)	60 (910–970)	2.91	$80 \times 80 \times 1.6$
[22]	110 (815–925)	35 (835–870)	5.5	$83 \times 83 \times 1.6$
Proposed	1250 (710–1960)	180 (840–1020)	3.4	$116 \times 116 \times 1.6$

5. CONCLUSION

A broadband circularly polarized square slot antenna covering the universal UHF RFID frequency band (840–960 MHz) is proposed in this paper. The widened signal line is used as a feedline to achieve impedance matching characteristic. Embedding a pair of symmetrical rectangular planes with L-shaped slits at opposite corners of square slot can achieve circular polarization characteristic. The impedance matching and circular polarization characteristics can be improved by adding a vertical tuning stub at the end of the signal line, and finally the proposed antenna obtains wideband characteristic. The measured 10 dB impedance bandwidth and 3 dB axial ratio bandwidth are 1250 MHz and 180 MHz, respectively, which have the advantages of wide impedance bandwidth and axial ratio bandwidth. On the UHF RFID frequency band, the measured average gain is about 3.4 dBi, and the radiation efficiency is about 95%. The proposed antenna has good bidirectional radiation characteristic on the x-o-z plane and y-o-z plane and is suitable for broadband UHF RFID reader applications.

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REFERENCES

1. Wang, B., "A compact antenna design for UHF RFID applications," *Progress In Electromagnetics Research Letters*, Vol. 53, 83–88, 2015.
2. Nasimuddin, Z. Chen, and X. Qing, "Asymmetric-circular shaped slotted microstrip antennas for circular polarization and RFID applications," *IEEE Transactions on Antennas and Propagation*, Vol. 58, 3821–3828, 2010.
3. Yang, L., N.-W. Liu, Z.-Y. Zhang, G. Fu, Q.-Q. Liu, and S.-L. Zuo, "A novel single feed omnidirectional circularly polarizedantenna with wide AR bandwidth," *Progress In Electromagnetics Research C*, Vol. 51, 35–43, 2014.
4. Chen, L., X. Ren, Y. Yin, and Z. Wang, "Broadband CPW-fed circularly polarized antenna with an irregular slot for 2.45 GHz RFID reader," *Progress In Electromagnetics Research Letters*, Vol. 41, 77–86, 2013.
5. Raviteja, C., C. Varadhan, M. Kanagasabai, et al., "A fractal-based circularly polarized UHF RFID reader antenna," *IEEE Antennas and Wireless Propagation Letters*, Vol. 13, 499–502, 2014.
6. Pan, Y.-S. and Y. Dong, "Circularly polarized stack Yagi RFID reader antenna," *IEEE Antennas and Wireless Propagation Letters*, Vol. 19, 1053–1057, 2020.
7. Wang, Z., S. Fang, S. Fu, and S. Jia, "Single-fed broadband circularly polarized stacked patch antenna with horizontally meandered strip for universal UHF RFID applications," *IEEE Trans. Microw. Theory Tech.*, Vol. 59, 1066–1073, 2011.
8. Chang, T.-N. and J.-M. Lin, "Circularly polarized ring-patch antenna," *IEEE Antennas and Wireless Propagation Letters*, Vol. 11, 26–29, 2012.
9. Liu, X. Y., Y. Liu, and M. M. Tentzeris, "A novel circularly polarized antenna with coin-shaped patches and a ring-shaped strip for worldwide UHF RFID applications," *IEEE Antennas and Wireless Propagation Letters*, Vol. 14, 707–710, 2015.
10. Zhang, Y., B. Wang, and J. Huang, "Circularly polarized truncated microstrip antenna for UHF RFID reader," *2019 IEEE 2nd International Conference on Automation, Electronics and Electrical Engineering (AUTEEE)*, 468–471, 2019.
11. Liu, Q., J.-Y. Shen, and H.-L. Liu, "Low-cost compact circularly polarized directional antenna for universal UHF RFID handheld reader applications," *IEEE Antennas Wireless Propagation Letters*, Vol. 14, 1326–1329, 2015.
12. Nosrati, M. and N. Tavassolian, "Miniaturized circularly polarized square slot antenna with enhanced axial-ratio bandwidth using an antipodal Y-strip," *IEEE Antennas and Wireless Propagation Letters*, Vol. 16, 817–820, 2016.
13. Feng, Q.-Y. and W. Abdelrahim, "A compact broadband dual-band circularly polarized antenna for universal UHF RFID handheld reader and GPS applications," *IET Microwaves Antennas and Propagation*, Vol. 13, 1664–1670, 2019.
14. Saini, R. K. and S. Dwari, "A broadband dual circularly polarized square slot antenna," *IEEE Transactions on Antennas and Propagation*, Vol. 64, 290–294, 2016.
15. Xu, R., J.-Y. Li, Y.-X. Qi, G.-W. Yang, and J.-J. Yang, "A design of triple-wideband triple-sense circularly polarized square slot antenna," *IEEE Antennas and Wireless Propagation Letters*, Vol. 16, 1763–1766, 2017.
16. Chen, Y.-Y., Y.-C. Jiao, G. Zhao, F. Zhang, Z.-L. Liao, and Y. Tian, "Dual-band dual-sense circularly polarized slot antenna with a C-shaped grounded strip," *IEEE Antennas and Wireless Propagation Letters*, Vol. 10, 915–918, 2011.
17. Pan, S., J. Sze, and P. Tu, "Circularly polarized square slot antenna with a largely enhanced axial-ratio bandwidth," *IEEE Antennas and Wireless Propagation Letters*, Vol. 11, 969–972, 2012.
18. Xu, Y., Z. Wang, and Y. Dong, " Circularly polarized slot antennas with dual mode elliptic cavity," *IEEE Antennas and Wireless Propagation Letters*, Vol. 19, 715–719, 2020.
19. Lu, J.-H. and S.-F. Wang, "Planar broadband circularly polarized antenna with square slot for UHF RFID reader," *IEEE Transactions on Antennas and Propagation*, Vol. 61, 45–53, 2013.

20. Lin, Y.-F., C.-H. Lee, S.-C. Pan, and H.-M. Chen, "Proximity-fed circularly polarized slotted patch antenna for RFID handheld reader," *IEEE Transactions on Antennas and Propagation*, Vol. 61, 5283–5286, 2013.
21. Pan, C.-Y., C.-C. Su, and W.-L. Yang, "CPW-fed circularly polarized slot antenna with small gap and stick-shaped shorted strip for UHF RFID readers," *Frequenz*, Vol. 6, 181–188, 2018.
22. Pakkathillam, J. K., M. Kanagasabai, and M. G. N. Alsath, "Compact multiservice UHF RFID reader antenna for near-field and far-field operations," *IEEE Antennas and Wireless Propagation Letters*, Vol. 16, 149–152, 2017.