Progress In Electromagnetics Research C, Vol. 65, 121–129, 2016

CPW-Fed Circularly Polarized Square Slot Antenna with Enhanced Bandwidth and Reduced Size for Wideband Wireless Applications

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Abstract—A coplanar waveguide-fed circularly polarized square slot antenna with the feasibility of obtaining a wider bandwidth and a relatively smaller size is proposed and demonstrated. The proposed antenna, consisting of a stepped feeding strip, a modified grounded L-shaped radiating patch, an inverted-L grounded strip and an asymmetric ground with an L-shaped slot as well as two horizontal slots, is designed, analyzed and fabricated. Good agreement between simulated and measured results is observed. Simulation and measurement results reveal that the proposed antenna can provide an impedance bandwidth of 106.3% (2.3–7.52 GHz) and a 3-dB axial ratio (AR) bandwidth of 90.2% (2.25–5.95 GHz). Additionally, within the effective circular polarization (CP) bandwidth of 88.5% (2.3–5.95 GHz), the proposed antenna has gains from 1.9 dBic to 5.2 dBic with an average gain of 3.9 dBic.

1. INTRODUCTION

Coplanar waveguide-fed circularly polarized slot antennas have attracted great attention due to their merits of simple structure, low profile, light weight, low fabrication cost, broad bandwidth, capabilities of reducing polarization mismatch, suppressing multipath interferences, and suitability for integration with microwave circuits [1–10]. Meanwhile, since the feature of broad 3-dB axial ratio (AR) bandwidth is becoming increasingly necessary due to the high data rate and multimedia required by modern services, many newly published techniques in [6–10] focus on the realization of broad circular polarization (CP) bandwidth with various coplanar waveguide-fed (CPW-fed) circularly polarized square slot antenna structures. In [6], by protruding a symmetric T-type strip from the CPW feedline and introducing a nesting-L slot structure in the ground, the CP antenna produces a CP bandwidth of 60.9%. An asymmetric CPW-fed CP monopole antenna utilizing two L-shaped grounded strips combined with an open rectangular ring presented in [7] realizes an effective 3-dB AR bandwidth of 69.4% and it is compact in size. In [8], two inverted L-shaped strips and a 45° blended strips are added at the corners of the square slot to get a wide CP bandwidth of 64.7%. Moreover, a check-shaped strip with its vertex connected to the protruded strip of the CPW is used to achieve a wide CP bandwidth of 48% in [9]. In addition, by adding three inverted L-shaped strips around the corners of the square slot, the antenna proposed in [10] obtains a CP bandwidth of 85.7%, whereas its size is not compact.

In this paper, a relatively compact CP antenna with an effective CP bandwidth of 88.5% is presented. The proposed antenna is based on a square slot antenna. And the modified L-shaped radiation patch and inverted-L grounded strip mainly account for its CP radiation. By connecting one end of the L-shaped patch with the ground via a tapered slot, the 3-dB AR bandwidth can be greatly enhanced. To further enhance the AR performance, a longer horizontal slot, an L-shaped slot and a shorter horizontal slot are etched on the ground to adjust the AR performance at lower, middle

Received 9 May 2016, Accepted 15 June 2016, Scheduled 26 June 2016

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and upper frequencies, respectively. Meanwhile, a meandered arc-shaped slot is loaded on the L-shaped radiation patch, which facilitates the shift of the operating frequency band towards the lower band, thus contributing to a relatively compact size. Finally, three parasitic rectangular slots are symmetrically etched at the edges of the ground plane so as to further improve the AR performance. For demonstration, the proposed antenna is fabricated and measured. The measured results have a reasonable agreement with the simulated ones.

2. ANTENNA CONFIGURATION

Figure 1 shows the geometry of the proposed CPW-fed circularly polarized square slot antenna, which is printed on a square substrate with a size of $40\,\text{mm} \times 45\,\text{mm} \times 1.5\,\text{mm}$, relative dielectric constant of 4.4 and loss tangent of 0.02. A square slot of $25.2\,\text{mm} \times 27.27\,\text{mm}$ is asymmetrically etched on the front-side

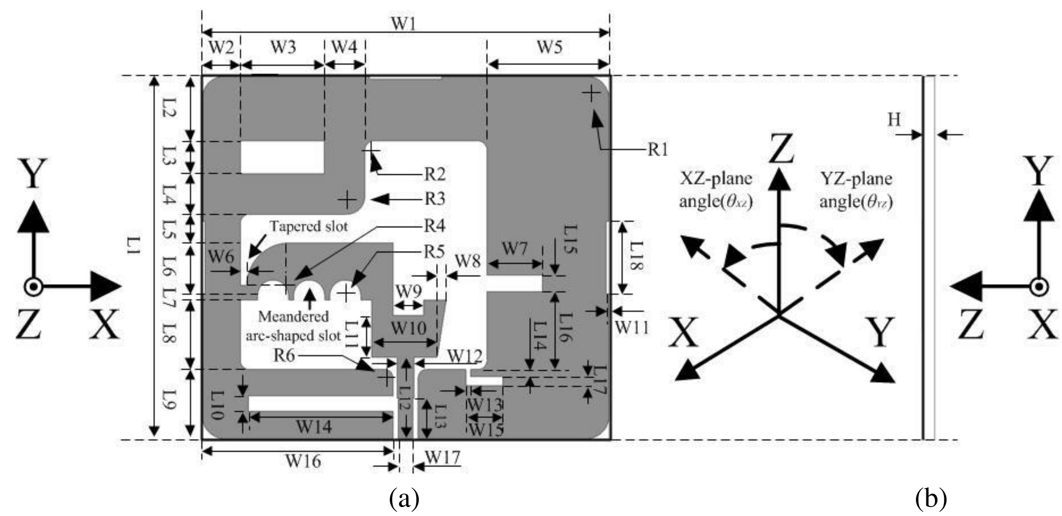

Figure 1. Configuration of the proposed antenna. (a) Front view; (b) side view.

Table 1. Dimensions of the proposed antenna.

Parameter	Value (mm)	Parameter	Value (mm)	Parameter	Value (mm)
$L1$	40	$L15$	1.8	$W11$	0.3
$L2$	7.15	$L16$	2.34	$W12$	1.9
$L3$	3.6	$L17$	1	$W13$	0.54
$L4$	4.5	$L18$	8	$W14$	16
$L5$	3.15	$W1$	45	$W15$	4.1
$L6$	5.8	$W2$	4.23	$W16$	21.1
$L7$	0.5	$W3$	9.27	$W17$	1.6
$L8$	7.65	$W4$	4.5	$R1$	2.5
$L9$	7.65	$W5$	13.5	$R2$	1
$L10$	1.7	$W6$	0.7	$R3$	2
$L11$	4.63	$W7$	6.1	$R4$	4.7
$L12$	9	$W8$	1	$R5$	1.7
$L13$	4.5	$W9$	3.38	$R6$	0.9
$L14$	0.81	$W10$	7.26	H	1.5

ground plane, and it is fed by a 50-Ω CPW having a feeding strip with two-stage stepped structure. The sizes of the two-stage stepped feeding strips are 4.5 mm × 1.6 mm and 4.5 mm × 1.9 mm, respectively. Simultaneously, the widths of the corresponding two-stage gap between the two-stage feeding strip and ground are 0.6 mm and 0.45 mm, respectively. The feeding strip of the CPW protruded into the square slot is 1.35 mm × 1.9 mm in size. Moreover, a modified L-shaped patch is chosen as the main radiator. One end of the L-shaped patch is connected to the ground plane with a rectangular patch of 1.6 mm × 0.7 mm via a tapered slot with radius of 4.7 mm. Meanwhile, a meandered slot composed of three identical arc-shaped slots is loaded on the modified L-shaped patch. The radius of the arc-shaped slot is 1.7 mm. Furthermore, an inverted-L strip is added to one corner (upper left corner) of the square slot, which is capable of generating two orthogonal resonant modes for CP radiation. The width of the inverted-L strip is 4.5 mm. And then a shorter horizontal slot, an L-shaped slot and a longer horizontal slot are etched out from the ground plane, and their sizes are 6.1 mm × 1.8 mm, 4.1 mm × 1.81 mm and 16 mm × 1.7 mm, respectively. In addition, three rectangular slots with a same size of 8 mm × 0.3 mm are symmetrically loaded at the edges of the ground plane to adjust the AR performance. Finally, all the vertices of the ground plane employ square-to-round filleting transition to further improve the antenna performance, and they have different filleting radii of 0.9 mm, 1 mm, 2 mm and 2.5 mm. The detailed geometry and dimensions of the proposed antenna are given in Figure 1 and Table 1.

3. ANTENNA DESIGN

The physical operating mechanism of the proposed patch antenna can be explained in [11–16] with exact analytical solutions utilizing semi-analytical methods. The feeding strip of the CPW employs two-stage stepped structure to get a better impedance matching. Meanwhile, since the square slot is asymmetrically etched on the ground plane, which equivalently transforms the proposed antenna to an asymmetric-CPW-fed square slot antenna, the bandwidth of the proposed antenna can be effectively enhanced [17]. In general, CP is generated by two orthogonal E vectors with equal amplitude and a phase difference of 90°, namely horizontal and vertical electric field components along the X- and Y-axes respectively. The modified L-shaped patch and the inverted-L grounded strip are utilized to generate two orthogonal modes and they mainly account for the CP operation of the proposed antenna. Meanwhile, the main purpose of introducing two horizontal slots and an L-shaped slot on the ground is to break the surface current distribution balance. When properly tuning the dimensions of these slots, the vertical fields generated by them will compensate and equate the amplitudes of the two orthogonal modes at their corresponding frequencies. Meanwhile, proper placement of these slots is essential to have a phase quadrature between the two orthogonal modes. Furthermore, the meandered line etched on the modified L-shaped patch provides a slightly longer pathway for the current within a same total physical size, which equivalently miniaturizes the antenna size [18]. Both two ends of the L-shaped patch employ tapered structure, hereby getting a better AR performance. In addition, three rectangular slots symmetrically loaded at the edges of the ground plane and the vertices of the ground plane employing square-to-round filleting transition act as a perturbation structure to further improve the antenna performance in AR and impedance matching.

4. SIMULATED AND MEASURED RESULTS

Figure 2 shows the simulated surface vector current distributions on the square slot antenna at 4 GHz viewed in $+Z(\theta = 0°)$ direction for different time phases of 0°, 90°, 180° and 270°, respectively. When the phase is equal to 0°/90°/180°/270°, the dominant surface current is in the $-135°/-45°/45°/135°$ direction with reference to X-axis. In other words, after one quarter-period, the current vector at 4 GHz rotates in the right-hand direction by 90° when viewed in $+Z$ direction, which satisfies the requirement of spatial/temporal quadrature for circular polarization.

The measured and simulated VSWRs of the proposed antenna are depicted in Figure 3. Good agreement between the simulated and measured results is obtained. With reference to the figure, the simulated and measured impedance bandwidths (VSWR $\leq$ 2) of the proposed antenna are 105.6% (2.3–7.45 GHz) and 106.3% (2.3–7.52 GHz), respectively.

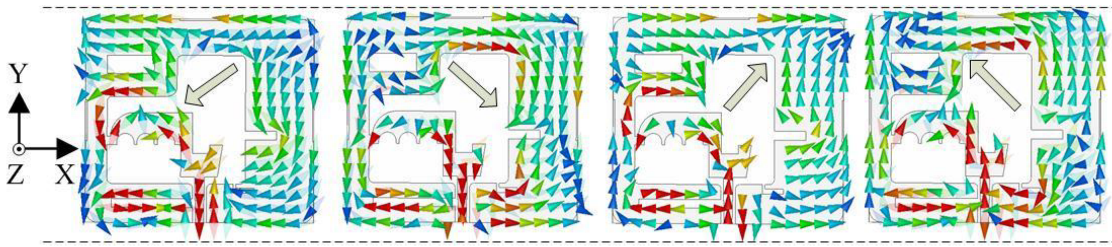

Figure 2. Simulated surface vector current distributions of proposed antenna at 4 GHz for four phases. (a) 0°, (b) 90°, (c) 180°, (d) 270°.

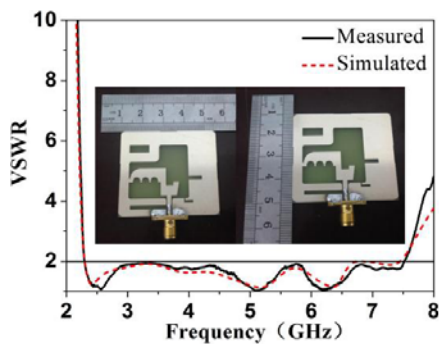

Figure 3. Simulated and measured VSWRs and the photographs of the fabricated antenna.

Figure 4 shows the simulated and measured normalized radiation patterns in the XZ-planes ($\varphi = 0°$) and YZ-planes ($\varphi = 90°$) at 2.5, 4 and 5.5 GHz. Without a metal reflector, the proposed printed slot antenna would radiate bidirectional patterns (both sides around the slot), namely radiating right-hand CP waves in $+Z$ direction and left-hand CP waves in $-Z$ direction. In Figure 5, the measured gains are from 1.9 dBic to 5.2 dBic with an average gain of 3.9 dBic. Meanwhile, the simulated and measured 3-dB AR bandwidths (AR $\leq$ 3) of the proposed antenna are 90.6% (2.24–5.95 GHz) and 90.2% (2.25–5.95 GHz), respectively. It should be noted that the discrepancy between

Table 2. Performance comparisons between the proposed and referenced antennas. (BW1: Impedance bandwidth, BW2: 3-dB AR bandwidth, BW3: Effective CP bandwidth).

Reference Designs	**BW1 (GHz)**	**BW2 (GHz)**	**BW3 (GHz)**	**Antenna size (mm3) (length × width × height)**	**Peak gain (dBic)**
Proposed Antenna	2.3–7.52 (106.3%)	2.25–5.95 (90.2%)	2.3–5.95 (88.5%)	40 × 45 × 1.5 ($0.55\lambda_0 \times 0.62\lambda_0 \times 0.02\lambda_0$)	5.2 dBic at 5.95 GHz
Li et al. [6]	1.77–6.06 (110%)	3.2–6 (60.9%)	3.2–6 (60.9%)	60 × 60 × 1 ($0.92\lambda_0 \times 0.92\lambda_0 \times 0.02\lambda_0$)	4.4 dBic at 3.5 GHz
Zhang et al. [7]	1.89–3.9 (69.4%)	1.85–3.95 (72.4%)	1.89–3.9 (69.4%)	50 × 50 × 0.8 ($0.48\lambda_0 \times 0.48\lambda_0 \times 0.01\lambda_0$)	4.8 dBic at 3.4 GHz
Rezaeieh et al. [8]	2.25–6.75 (100%)	3.172–6.211 (64.7%)	3.172–6.211 (64.7%)	40 × 40 × 0.8 ($0.63\lambda_0 \times 0.63\lambda_0 \times 0.01\lambda_0$)	5.0 dBic at 5.08 GHz
Liu et al. [9]	1.45–3.15 (73.9%)	1.9–3.1 (48%)	1.9–3.1 (48%)	85 × 80 × 1.6 ($0.71\lambda_0 \times 0.67\lambda_0 \times 0.01\lambda_0$)	4.2 dBic at 2.1 GHz
Felegari et al. [10]	2–7 (111.1%)	2–5 (85.7%)	2–5 (85.7%)	60 × 60 × 0.8 ($0.7\lambda_0 \times 0.7\lambda_0 \times 0.01\lambda_0$)	4.5 dBic at 5.0 GHz

the simulated and measured results may be caused by the imperfect testing environment. Furthermore, the error in the process of fabrication and the presence of the SMA connector interfering with the radiated field may be taken into account as well. In addition, the measured effective CP bandwidth of nearly 88.5% (2.3–5.95 GHz) not only meets the need for certain Wi-Fi (2.4/5.2/5.8 GHz) or WiMAX (2.5/3.5/5.5 GHz) band communication application, but also provides the potential to implement multiservice transmission.

A comparison of the proposed antenna with previous work is made in terms of impedance bandwidth, 3-dB AR bandwidth, effective CP bandwidth, antenna size and peak gain with results presented in Table 2. The selection criteria for inclusion in this comparison are newly published wideband CPW-fed circularly polarized square slot antennas. All the substrates of the compared antenna are with relative dielectric constant of 4.4 and loss tangent of 0.02. Compared with the wideband CPW-fed circularly polarized square slot antennas proposed in [6, 8, 9] and [10], a surface area size reduction of 148.2%/16.4%/39.5%/43.7% and an effective CP bandwidth increase of 45.3%/36.8%/84.4%/3.3% have been obtained. Thus, the proposed antenna occupies a smaller surface area size and simultaneously yields a wider effective CP bandwidth compared to those in references [6, 8, 9] and [10]. Meanwhile, comparisons between the proposed antenna and the wideband

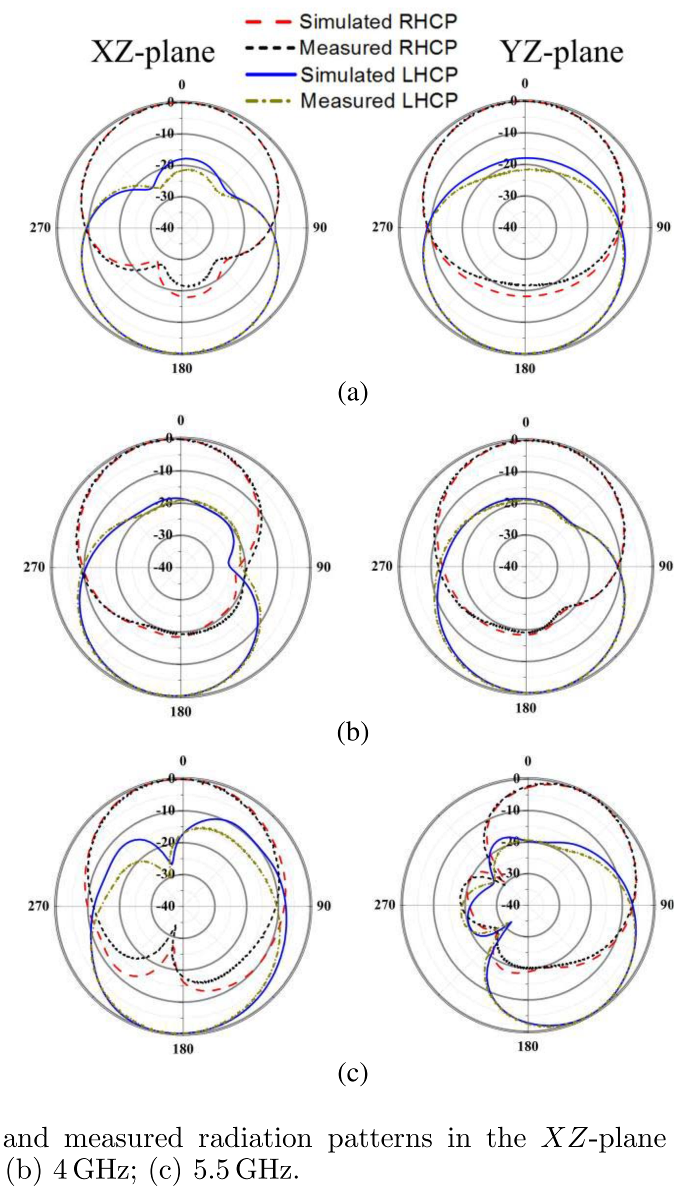

Figure 4. Simulated and measured radiation patterns in the XZ-plane ($\varphi = 0°$) and YZ-plane ($\varphi = 90°$). (a) 2.5 GHz; (b) 4 GHz; (c) 5.5 GHz.

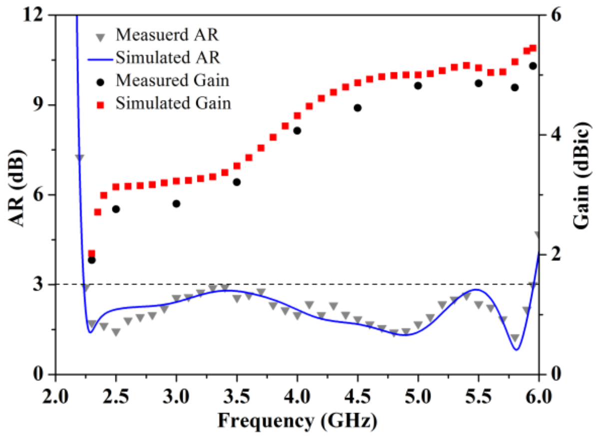

Figure 5. Simulated and measured ARs and gains of the proposed antenna.

CPW-fed circularly polarized square slot antenna in [7] indicate that the effective CP bandwidth have been improved by 27.5%, with the price of an increase of 48.0% in surface area size. Consequently, from Table 2, it could be seen that the proposed antenna provides either a wider operating bandwidth or a relatively reduced size. Actually, it obtains a better performance with a favorable compromise between operating bandwidth and antenna size.

5. PARAMETRIC STUDY

All critical parameters, such as $W15$, $W14$, $W7$, $R4$, $W8$, $W4$, $R5$ and $W11$, should be adjusted carefully to achieve a good performance. The effects of these parameters on impedance and AR bandwidths are examined herein to facilitate the design of a same or homogeneous antenna. During this process, all the other parameters not mentioned stay constant as shown in Table 1.

5.1. Effect of L-Shaped Slot and Two Horizontal Slots ($W15$, $W14$ and $W7$)

The effects of the lengths of the longer horizontal slot, L-shaped slot and shorter horizontal slot ($W14$, $W15$ and $W7$) on the impedance and AR bandwidths are shown in Figure 6, Figure 7 and Figure 8, respectively. The results indicate that $W14$, $W15$ and $W7$ have significant influence on the lower, middle and upper operating frequencies respectively in AR performance. While for the impedance performance,

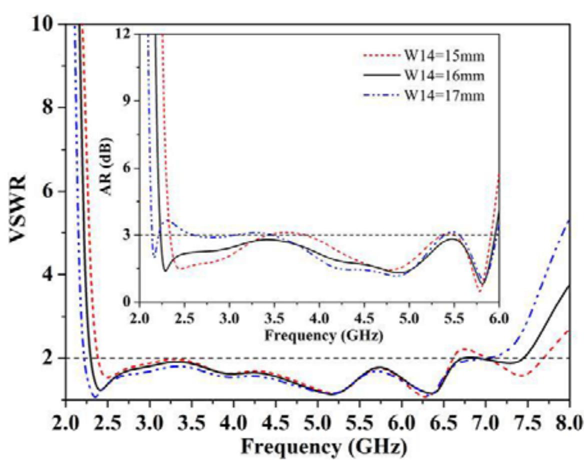

Figure 6. VSWRs and ARs with varied $W14$.

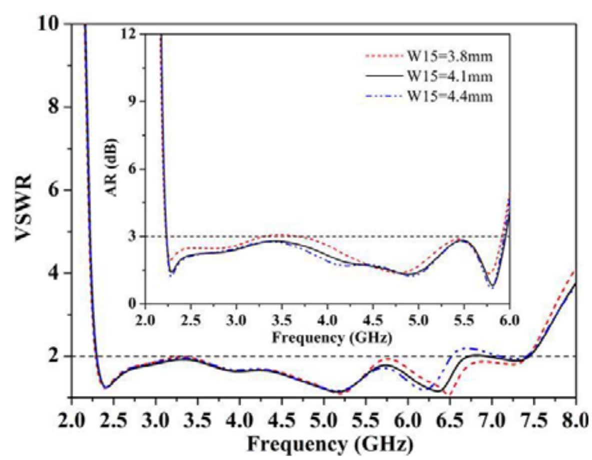

Figure 7. VSWRs and ARs with varied $W15$.

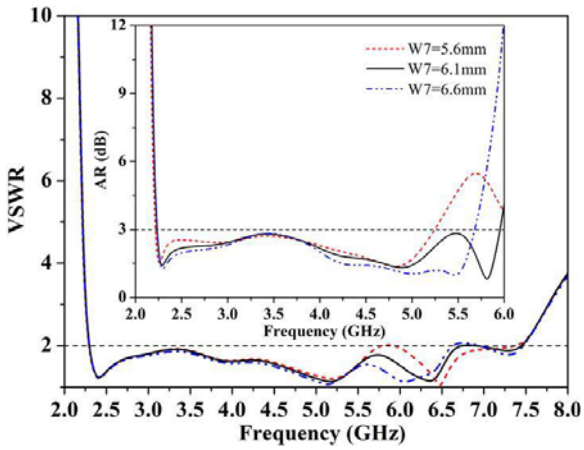

Figure 8. VSWRs and ARs with varied $W7$.

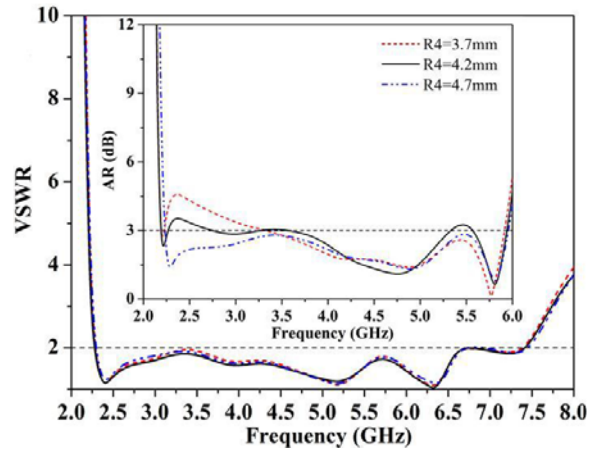

Figure 9. VSWRs and ARs with varied $R4$.

both $W15$ and $W7$ have great influence on the upper operating frequencies and $W14$ have great effect on the lower operating frequencies. To obtain good impedance matching and AR performance, $W14$, $W15$ and $W7$ are set as 16 mm, 4.1 mm and 6.1 mm, respectively.

5.2. Effect of Two Tapered Structures for the Modified L-Shaped Patch ($R4$ and $W8$)

Figure 9 and Figure 10 reveal the influence of two tapered structures for the modified L-shaped patch on the impedance and AR bandwidths, respectively. As $R4$ increases, the AR performance at lower frequencies will be significantly improved while the impedance performance almost stays the same. Hence, with this tapered structure, the AR bandwidth of the proposed antenna is greatly enhanced. Meanwhile, when $W8$ varies, though it has little influence on the impedance performance, the AR performance at higher frequencies will be deteriorated, whether the value increases or decreases. To obtain good impedance matching and AR performance, $R4$ and $W8$ are set to 4.7 mm and 1 mm, respectively.

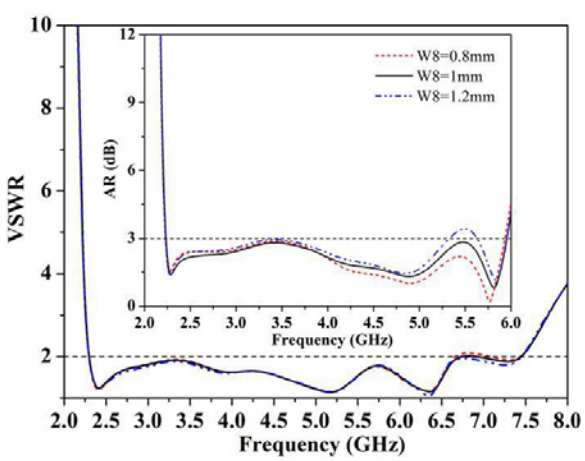

Figure 10. VSWRs and ARs with varied $W8$.

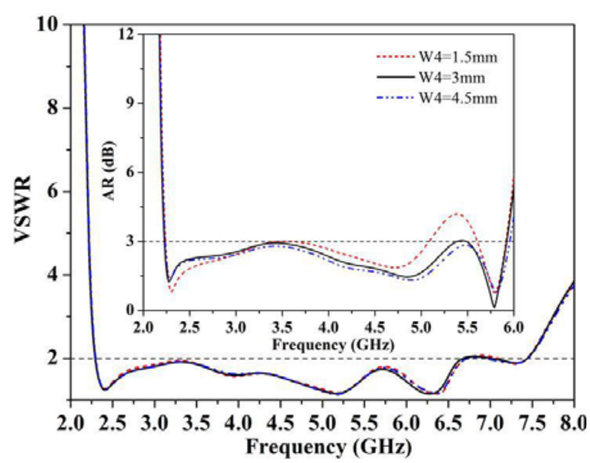

Figure 11. VSWRs and ARs with varied $W4$.

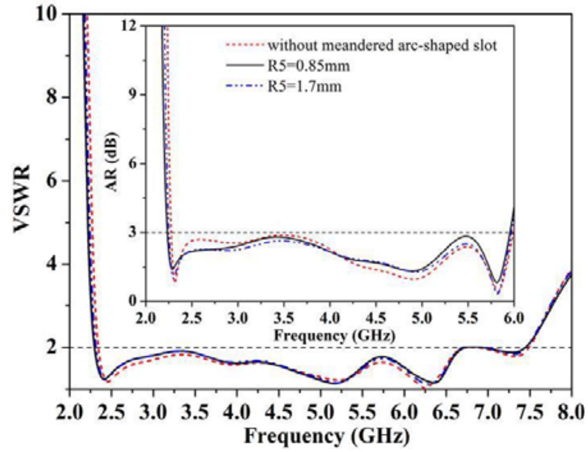

Figure 12. VSWRs and ARs with varied $R5$.

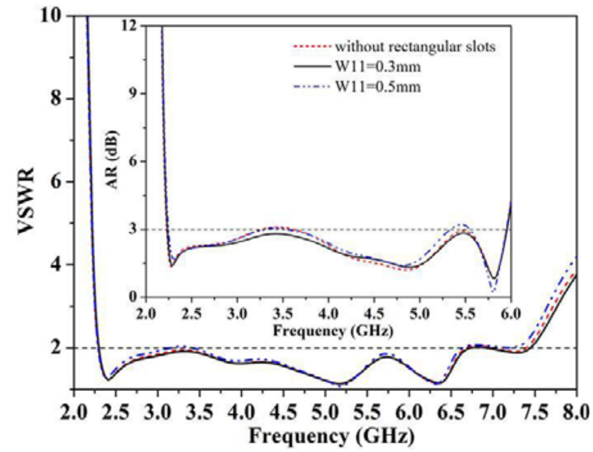

Figure 13. VSWRs and ARs with varied $W11$.

5.3. Effect of the Inverted-L Strip, Meandered Slot and Rectangular Slots ($W4$, $R5$ and $W11$)

The Effects of the inverted-L strip, meandered slot and rectangular slots on the impedance and AR bandwidths are shown in Figure 11, Figure 12 and Figure 13, respectively. $W4$ means the width of the inverted-L grounded strip. As $W4$ increases, the AR performance at higher frequencies will be improved, and the impedance matching across the whole operating band almost stays constant. Moreover, $R5$ means the radius of the meandered slot loaded on the L-shaped radiating patch. As expected, as $R5$ increases, the whole operating band will shift towards lower band, without significant degradation in impedance and AR performances. To obtain good impedance and AR performances, $W4$ and $R5$ are set to 4.5 mm and 1.7 mm, respectively. In addition, as shown in Figure 13, without the rectangular slots loaded at the edges of the ground plane, the values of AR for some frequencies within middle operating frequency band are slightly greater than 3 dB. When the rectangular slots are introduced with discreetly optimized widths of 0.3 mm, the AR performance at these frequencies will be effectively improved.

6. CONCLUSION

A coplanar waveguide-fed circularly polarized square slot antenna with enhanced bandwidth and reduced size has been presented. Simulation and measurement results indicate that with a modified L-shaped radiating patch and an improved ground, the proposed antenna can realize an impedance bandwidth of 106.3% (2.3–7.52 GHz) and a 3-dB AR bandwidth of nearly 90.2% (2.25–5.95 GHz). Meanwhile, within the effective CP bandwidth of 88.5% (2.3–5.95 GHz), relatively moderate gains, ranging from 1.9 dBic to 5.2 dBic with an average gain of 3.9 dBic, are obtained simultaneously. With these inherent characteristics, the proposed antenna can be a good candidate for wideband wireless applications.

REFERENCES

1. Sze, J.-Y. and C.-C. Chang, "Circularly polarized square slot antenna with a pair of inverted-L grounded strips," *IEEE Antennas Wireless Propag. Lett.*, Vol. 7, 149–151, 2008.
2. Rezaeieh, S.-A., A. Abbosh, and M.-A. Antoniades, "Compact CPW-fed planar monopole antenna with wide circular polarization bandwidth," *IEEE Antennas Wireless Propag. Lett.*, Vol. 12, 1295–1298, 2013.
3. Jan, J.-Y., C.-Y. Pan, K.-Y. Chiu, and H.-M. Chen, "Broadband CPW-fed circularly-polarized slot antenna with an open slot," *IEEE Trans. Antennas Propag.*, Vol. 61, No. 3, 1418–1422, Mar. 2013.

4. Pourahmadazar, J., C. Ghobadi, J. Nourinia, N. Felegari, and H. Shirzad, "Broadband CPW-fed circularly polarized square slot antenna with inverted-L strips for UWB applications," *IEEE Antennas Wireless Propag. Lett.*, Vol. 10, 369–372, 2011.
5. Zhang, L., Y.-C. Jiao, Y. Ding, B. Chen, and Z.-B. Weng, "CPW-fed broadband circularly polarized planar monopole antenna with improved ground-plane structure," *IEEE Trans. Antennas Propag.*, Vol. 61, No. 9, 4824–4828, Sep. 2013.
6. Li, G.-H., H.-Q. Zhai, L. Li, and C.-H. Liang, "A nesting-L slot antenna with enhanced circularly polarized bandwidth and radiation," *IEEE Antennas Wireless Propag. Lett.*, Vol. 13, 225–228, Feb. 2014.
7. Zhang, H., Y.-C. Jiao, T. Ni, and W.-L. Liang, "Broadband circularly polarised antenna with asymmetric ground and L-shaped strips," *Electron. Lett.*, Vol. 50, No. 23, 1660–1662, Nov. 2014.
8. Rezaeieh, S.-A., S. Şimşek, and J. Pourahmadazar, "Design of a compact broadband circularly-polarized slot antenna for wireless applications," *Microwave Opt. Technol. Lett.*, Vol. 55, No. 2, 413–418, Feb. 2013.
9. Liu, Y.-W. and P. Hsu, "Broadband circularly polarised square slot antenna fed by coplanar waveguide," *Electron. Lett.*, Vol. 49, No. 16, 976–977, Aug. 2013.
10. Felegari, N., J. Nourinia, C. Ghobadi, and J. Pourahmadazar, "Broadband CPW-fed circularly polarized square slot antenna with three inverted-L-shape grounded strips," *IEEE Antennas Propag. Lett.*, Vol. 10, 274–277, Apr. 2011.
11. Valagiannopoulos, C.-A., "On smoothening the singular field developed in the vicinity of metallic edges," *International Journal of Applied Electromagnetics and Mechanics*, Vol. 31, 67–77, 2009.
12. Valagiannopoulos, C.-A., "Electromagnetic propagation into parallel-plate waveguide in the presence of a skew metallic surface," *Electromagnetics*, Vol. 31, No. 8, 593–605, Oct. 2011.
13. Unal, G.-S. and M.-I. Aksun, "Bridging the gap between RF and optical patch antenna analysis via the cavity model," *Scientific Reports*, Nov. 2015.
14. Valagiannopoulos, C. A., "High selectivity and controllability of a parallel-plate component with a filled rectangular ridge," *Progress In Electromagnetics Research*, Vol. 119, 497–511, 2011.
15. Valagiannopoulos, C. A., "On examining the influence of a thin dielectric strip posed across the diameter of a penetrable radiating cylinder," *Progress In Electromagnetics Research C*, Vol. 3, 203–214, 2008.
16. Valagiannopoulos, C.-A., "Semi-analytic solution to a cylindrical microstrip with inhomogeneous substrate," *Electromagnetics*, Vol. 27, No. 8, 527–544, Nov. 2007.
17. Han, R.-C and S.-S. Zhong, "Broadband circularly-polarised chifre-shaped monopole antenna with asymmetric feed," *Electron. Lett.*, Vol. 52, No. 4, 256–258, Feb. 2016.
18. Podilchak, S.-K., J.-C. Johnstone, M. Clénet, and Y. M. M. Antar, "A compact wideband dielectric resonator antenna with a meandered slot ring and cavity backing," *IEEE Antennas Wireless Propag. Lett.*, Vol. 15, 909–913, 2016.