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MODIFIED SQUARE SLOT ANTENNAS FOR BROADBAND CIRCULAR POLARIZATION

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Abstract—Square slot antennas with modified edges for broadband circular polarization are presented. Slots with only stubs or notches are studied and it is found that the axial ratio (AR) bandwidth is quite sensitive to the perturbations of the stubs and notches. To further enhance the AR bandwidth, slot antennas with combination of stubs and notches are proposed and wide 3-dB AR bandwidth of 15.5% (2.45–2.86 GHz) is obtained. By placing a conducting reflector at the rear of the slot, another modified square slot antenna is designed for practical applications, which achieves a 3-dB AR bandwidth of 6.5% (2.38–2.54 GHz) and peak gain of 8.7 dBic. Agreement between simulated and measured results is satisfactory.

1. INTRODUCTION

Circularly polarized (CP) antennas have been receiving much attention due to their abilities to eliminate the arising multipath effects and allow flexible orientation of the transmitter and the receiver. As far as single-fed microstrip antennas are concerned, circular polarization can be generated with perturbation technologies such as using a nearly square patch [1], truncating patch corners [2], adding stubs or cutting notches along two opposite edges [3] and embedding a diagonal slot [4]. However, the simple single-fed CP antennas have inherently narrow 3-dB axial-ratio (AR) bandwidth of less than 2% [5].

Generally speaking, slot antennas have larger bandwidth (BW) than the microstrip antennas because of their lower quality factors due to the bidirectional radiation characteristics. According to the Babinet Principle, slot antennas are complementary structures to the

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microstrip antennas. Therefore, the perturbation technologies can also be applied to slot antennas for CP operations [6, 7]. Moreover, for the conventional CP patches, the CP AR is very sensitive to the dimensions of the perturbation segments. However, slot antennas can mitigate the manufacturing tolerances of perturbation segments. Consequently, slot antennas with perturbations are more suitable to design broadband CP antennas than patch antennas.

Additionally, CP radiation can also be achieved by using an L-shaped feeding strip when no perturbations are added to slots [8–10]. Though wide AR bandwidths of 40% [8], 2.6% [9] and 6% [10] are obtained, the capacitance value between the bent strip and ground is very critical to obtain a low axial ratio and good impedance matching [8]. In literature [11], a pair of hat-shaped patches is added to the ring slot for CP and the bent feeding line is deformed for impedance matching. A CPW-fed square slot antenna with lightening-shaped feeding and two symmetrical F-shaped slit embedded in opposite corners for wide CP bandwidth is proposed in [12]. The complex antenna has numbers of parameters to control and the design procedure is complicated though wide AR bandwidth of 51.7% is obtained. A parasitic patch embedded in the wide-slot antenna can enhance the bandwidth [13] and when a rectangular patch [14] or a cross-shaped patch [15] is loaded in the square slot, wide AR bandwidths of 12% and 12.4% are obtained. In [16], four unequal linear slots are located around the annular-slot and the 3-dB AR bandwidths for the dual-frequency bands with inverse CP are about 6%. The slot antenna with two inverted-L grounded strips around two opposite corners of the slot [17] and another diamond-shaped slot [18] antenna achieve AR bandwidths of 25% and 68%, respectively. The two mentioned antennas can be regarded as slots with perturbations on edges. But the wide bandwidths may be mainly due to the CPW feeding technique in some way and the radiation patterns are unsatisfactory.

In this paper, a systematic study of AR bandwidths for slots with the stub and notch perturbations is presented firstly. Slots with a combination perturbation of stubs and notches are proposed and wider AR bandwidths are obtained compared with those with only stubs or notches. Since unidirectional patterns are required in some wireless communication systems, a modified slot with conducting reflector is proposed. The measured results show that a CP bandwidth of 6.5% (2.37–2.54 GHz) and peak gain of 8.7 dBic are achieved in this design. The introduction of stubs and notches perturbations is proved to be an effective technique to generate circular polarization and wide AR bandwidth for slot antennas.

2. ANTENNA DESIGN

A diagonal-fed square patch with a pair of stubs or notches along the two opposite edges can radiate CP waves. The perturbations of stub and notch can be also applied to slot antennas for CP operations. Two orthogonal modes of the same magnitude are excited when the slot edges are modified and the feeding position is properly selected so that the two modes are excited with phase difference of 90°. Circular polarization can also be obtained when only one edge is modified, but the configuration is asymmetrical. Due to the fact that the area of the stub or the notch is very critical to yield lower AR value, the performance of one-edge-modified patch is similar to that of a two-edge-modified patch. The advantage of the stubs or notches configurations is that the fine-tuning can be easily done by trimming the dimensions of the stubs or notches.

A pair of stubs or notches with different dimensions is firstly introduced in Case 1 and 2, in which one stub (notch) is designed to obtained low CP AR and another stub (notch) is adopted to affect the impedance bandwidth. Though the positions of the stubs and notches in Case 1 and 2 are the same, right hand circular polarization (RHCP) and left hand circular polarization (LHCP) are obtained, respectively. Then in Case 3 to 5, two stubs and two notches are embedded along orthogonal edges. Wider AR bandwidths are achieved and slot antennas with differently sized grounds are investigated. In Case 6, modified square slot antenna with reflecting conducting plate is proposed for 802.11 b/g (2400–2485 MHz) applications. All the simulated results are carried out by using Ansoft high-frequency structure simulator (HFSS 13) software.

2.1. Square Slot with Two Stubs (Case 1)

A conventional square patch with two stubs is shown in Figure 1(a). The feed point is along the diagonal line and two small square stubs are added to two opposite edges. LHCP can be achieved for the antenna with the same configuration as Figure 1(a). According to the Babinet Principle, a square slot antenna with two stubs on the FR4 substrate (relative permittivity of 4.4 and dielectric loss of 0.02) is proposed as shown in Figure 1(b). The square slot is rotated by 45° with respect to the square ground and two stubs with same width and different lengths are added to the slot edges. The feed line is printed on the back of the substrate and the stub perturbations are 45° and 135° away from the feeding lines. All the optimized parameters are tabulated in Table 1.

For the conventional modified square patch, the approximate value of the total perturbation area ΔS can be obtained from the following

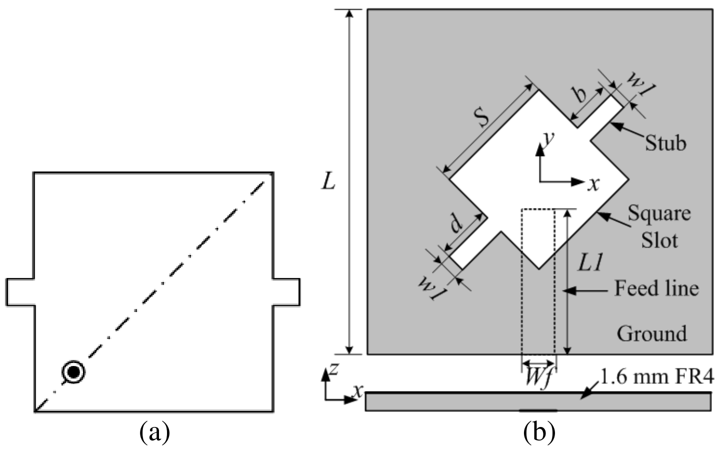


Figure 1. (a) Conventional square patch with two stubs. (b) Square slot with two stubs (Case 1).

Table 1. Dimensions of the slot antennas of Case 1 to 5 (Unit: mm).

Case	L	S	a	b	c	d	W_1	W_f	L_1
1	100	40.2		15.6		19.3	4	3	45.6
2	100	40	7.5		11.5			3	45
3	100	40	8.2	15.6	8	16.3	4	3	45.5
4	90	40	7.4	15.5	8	16.5	4	3.2	40
5	80	38	7.2	14.8	8	16.3	4	3.2	36

relation [5]

$$\left(\frac{\Delta S}{S}\right) Q_0 \approx \frac{1}{2} \tag{1}$$

Where S is the area of the square patch without perturbations, and Q_0 is unloaded quality factor of the patch. Therefore, the dimensions of the perturbation are very critical to yield CP waves during the modified slot antenna design procedure.

The slot antenna with two stubs obtains the impedance bandwidth ($S_{11} < -10\,\text{dB}$) of 53.4% (1.85–3.20 GHz) and the 3-dB RHCP AR bandwidth of 9.6% (2.38–2.62 GHz). Because of the severe influence of the stubs on CP characteristic, the effects of the stubs' lengths b and d on S_{11} and AR are examined as shown in Figure 2. It is clearly seen that the length of the upper-right stub b has little influence on AR while the lower-left stub d mainly determines the AR value at center

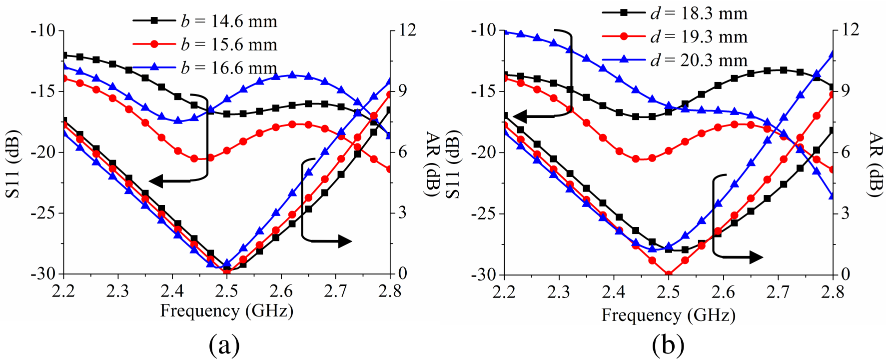


Figure 2. Effects of stubs' parameters on S_{11} and AR characteristics. (a) Effect of the length of the upper-right stub b. (b) Effect of the length of the lower-left stub d.

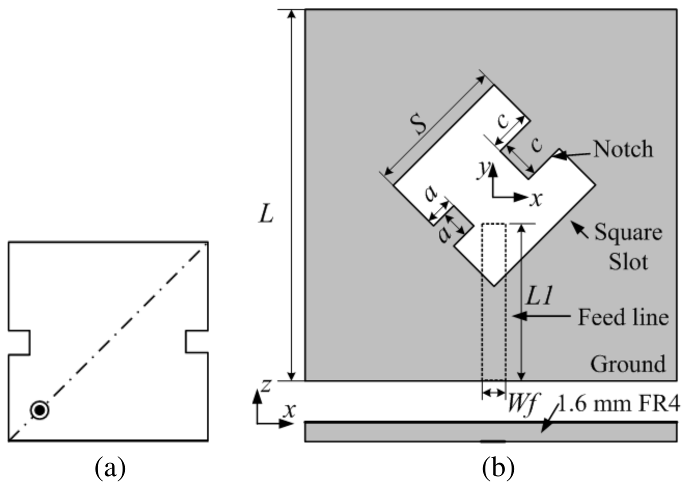


Figure 3. (a) Conventional square patch with two notches. (b) Square slot with two notches (Case 2).

frequency. When designing the slot antenna with stubs, the stub length d is firstly fixed to obtain good CP performance and then stub length b is tuned to match impedance.

2.2. Square Slot with Two Notches (Case 2)

Another square patch with two notches is shown in Figure 3(a). Two small square notches are added to two opposite edges and RHCP can be achieved. The square slot antenna with two square notches is proposed as shown in Figure 3(b). The two square notches locate at the position just the same as that of stubs in Case 1 and have dimensions of a and c, respectively. All the optimized parameters are tabulated in Table 1.

The slot antenna with two notches obtains the impedance bandwidth ($S_{11} < -10\,\text{dB}$) of 33.1% (2.07–2.89 GHz) and the 3-dB LHCP AR bandwidth of 8.3% (2.30–2.50 GHz). The effects of the notches' lengths a and c on S_{11} and AR are examined as shown in Figure 4. The center of the AR band and S_{11} value are heavily dependent on the lower-left notch's parameter. While the upper-right notch's length c influences the depth of the AR curve and slightly affects the impedance bandwidth. When designing the slot antenna with notches, the upper-right notch is adjusted firstly to lower the AR value and then the lower-left notch is tuned to move the AR center frequency and get wide impedance bandwidth.

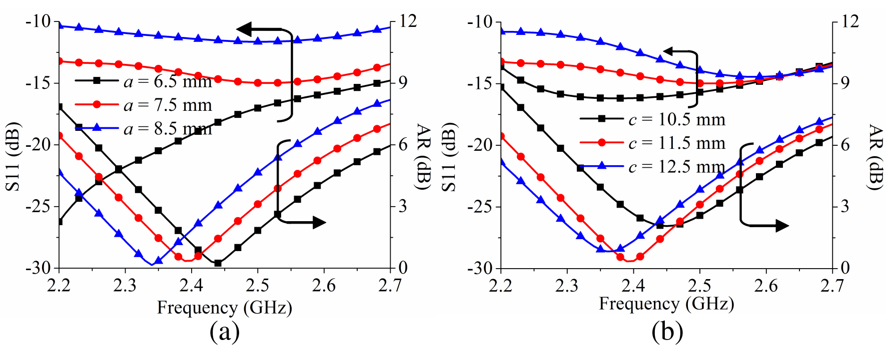


Figure 4. Effects of notches' parameters on S_{11} and AR characteristics. (a) Effect of the length of the lower-left notch a. (b) Effect of the length of the upper-right notch c.

For the conventional patch with stubs shown in Figure 1(a), the lower resonant frequency generates along the stub direction and the higher frequency vertical to the unmodified edges. Phase difference between the two modes is 90° and LHCP is yielded. While for the patch with notches in Figure 3(a), the higher resonant mode generates along the notch direction which has $-90°$ phase difference with the lower mode generating vertical to the unmodified edges and RHCP is yielded. Moreover, the slot antennas radiate the inverse rotated CP wave in corresponding to their complementary patches. Therefore, the slot antennas obtain RHCP and LHCP for Case 1 and Case 2, respectively. The simulated far field radiation pattern characteristics of Case 1 and Case 2 in xz-plane at each center frequency are shown in Figure 5.

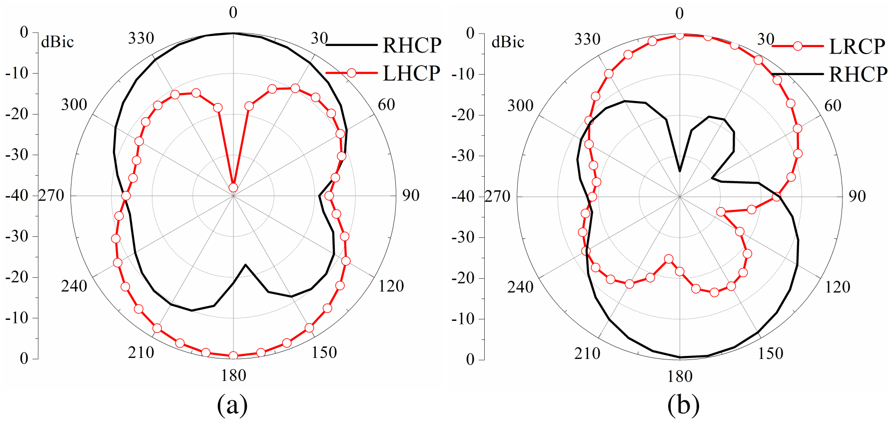


Figure 5. Radiation patterns of xz-plane at center frequency. (a) Case 1 at 2.5 GHz. (b) Case 2 at 2.4 GHz.

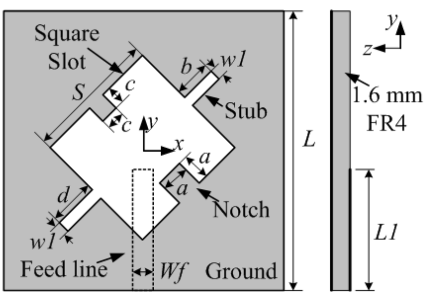


Figure 6. Square slot with two stubs and two notches (Case 3–5).

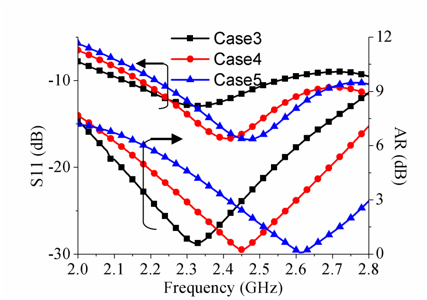


Figure 7. Simulated S_{11} and AR for Case 3 to 5.

2.3. Square Slot with Two Stubs and Two Notches (Case 3–5)

In Case 2, the slot will yield RHCP when the two notches are added to another opposite edges. Since Case 1 and 2 obtains RHCP and LHCP respectively even though the positions of stubs or notches perturbations are the same, the notches are embedded along the orthogonal edges with respect to the stubs to obtain wider bandwidth. The structure of the slot with two stubs and two notches is shown in Figure 6. When two types of perturbations are added to the square slot, more parameters can be controlled to obtain circular polarization with minimum AR. In comparison with Case 1, the higher modes along the notches in Case 3–5 exert higher resonant frequency when the notches are added. Therefore, wider AR bandwidths can be achieved for the slots with two perturbations. In the parameters optimized procedure, we found that the dimensions of the lower-left stub and the lower-right notch have an obvious impact on antenna's CP performance. Additionally, the upper two modifications are tuned to trim the impedance matching. Three cases with different ground sizes are investigated and the dimensions of the three cases are tabulated in Table 1. It is found that when the ground size is reduced, wider AR bandwidths could be obtained which can be seen in Figure 7 and Table 2. This may be explained that less undesired rotations of the surface current vector exist on the ground for slot with smaller ground.

To validate this design strategy, a prototype of Case 5 is built and measured, as shown in Figure 8. The impedance and AR curves of Case 5 are shown in Figure 9. Measured results show that the antenna attains the impedance bandwidth ($S_{11} < -10\,\text{dB}$) of 16.7% (2.31–2.73 GHz) and 3-dB AR bandwidth of 15.5% (2.45–2.86 GHz). The overlapped bandwidth is about 10.8%. Minor discrepancies between the simulated and measured results exist which may be due to the fabrication tolerances. The radiation patterns of this antenna at 2.6 GHz are shown in Figure 10. The radiation pattern is bidirectional and RHCP is obtained on the $+z$-axis with peak gain of 3.2 dBic.

Table 2. Performances of the modified square slot antennas of Case 1 to 6.

Case	Simulation (GHz)		Measurement (GHz)	
	S_{11} BW	AR BW	S_{11} BW	AR BW
1	1.85–3.20 (53.4%)	2.38–2.62 (9.6%)		
2	2.07–2.89 (33.1%)	2.30–2.50 (8.3%)		
3	2.12–2.56 (18.8%)	2.20–2.45 (10.7%)		
4	2.16–3.25 (40.3%)	2.29–2.60 (12.6%)		
5	2.21–2.76 (22.1%)	2.41–2.79 (14.6%)	2.31–2.73 (16.7%)	2.45–2.86 (15.5%)
6	2.34–2.59 (10.1%)	2.37–2.54 (6.9%)	2.33–2.71 (15.1%)	2.38–2.54 (6.5%)

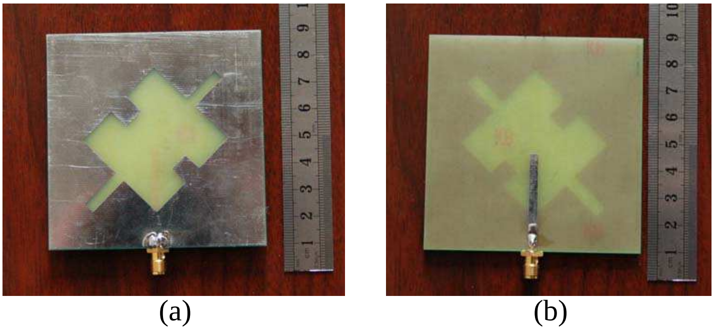


Figure 8. Photographs of the slot antenna prototype in Case 5. (a) Front view. (b) Back view.

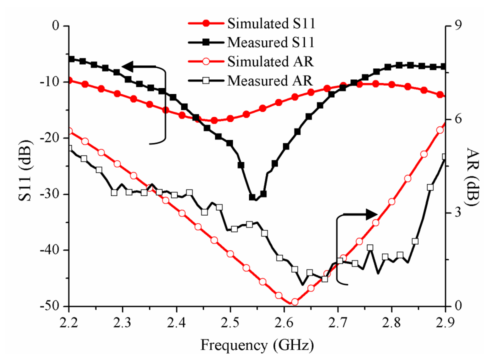


Figure 9. Measured S_{11} and AR for Case 5.

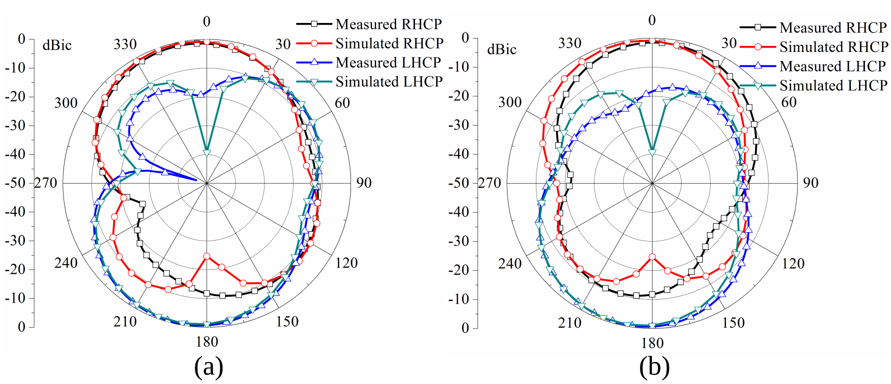


Figure 10. Simulated and measured radiation patterns at 2.6 GHz for Case 5. (a) xz-plane. (b) yz-plane.

2.4. Modified Square Slot Antenna with Reflecting Conducting Plate (Case 6)

Though wide AR bandwidths are obtained in the former modified slot antenna designs, slot antenna has the inherent disadvantage of bidirectional radiation patterns. When the slot antenna is placed above another object, the antenna performances including impedance and polarization would be degraded due to back radiation interference, which cannot meet with the requirements of some wireless communication applications such as radio frequency identification (RFID) readers and GPS devices. A simple way to solve this problem is placing a conducting reflector below the slot antenna by a distance of about one quarter wavelength [14].

In Case 6, we design a modified square slot antenna with a reflecting conducting plate for the applications operating around 2.45 GHz. Figure 11 shows the geometry of the modified slot antenna with a reflector. The conducting plate is placed at the rear of the slot with the height H, which is about one quarter wavelength of the operating frequency. To simplify the design procedure, the two pairs of stubs and notches are set to be both square and the opposite stubs or notches are of the same dimension which is different from the designs of Case 3 to 5. The antenna is firstly designed with a dimension of $W \times W$ and then an impedance transformer is added to the feed line. One edge of the substrate is lengthened to be L and the ground is lengthened with a width of W_1 which has little influence on the CP performance. All the optimized parameters are tabulated in Table 3.

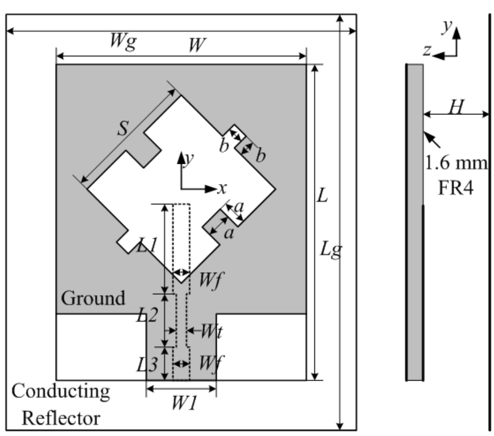
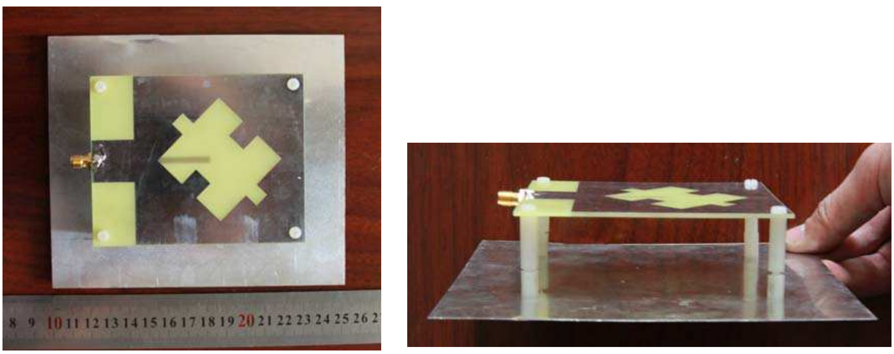


Figure 11. Modified square slot antenna with a reflecting conducting plate (Case 6).

Table 3. Dimension of the modified slot antenna of Case 6. (Unit: mm).

W_g	L_g	W	L	S	a	b	L_1	L_2	L_3	W_f	Wt	W_1	H
130	150	80	100	41	9.5	7	29.5	17.5	9	3.2	1	20	30

Antenna prototype of Case 6 is fabricated as shown in Figure 12. The simulated and measured S_{11} and AR of Case 6 are depicted in Figure 13. The measured results are well matched with simulations and show an impedance bandwidth ($S_{11} < -10\,\text{dB}$) of 15.1% (2.33–2.71 GHz) and a 3-dB AR bandwidth of 6.5% (2.38–2.54 GHz). The measured AR has a minimum value of 1.37 dB at 2.48 GHz. The



(a) (b)

Figure 12. Photograph of the proposed antenna in Case 6. (a) Top view. (b) Side view.

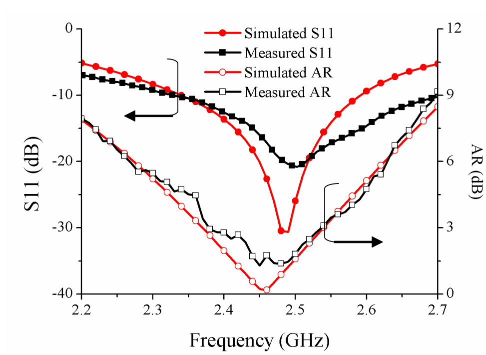


Figure 13. Simulated and measured S_{11} and AR for Case 6.

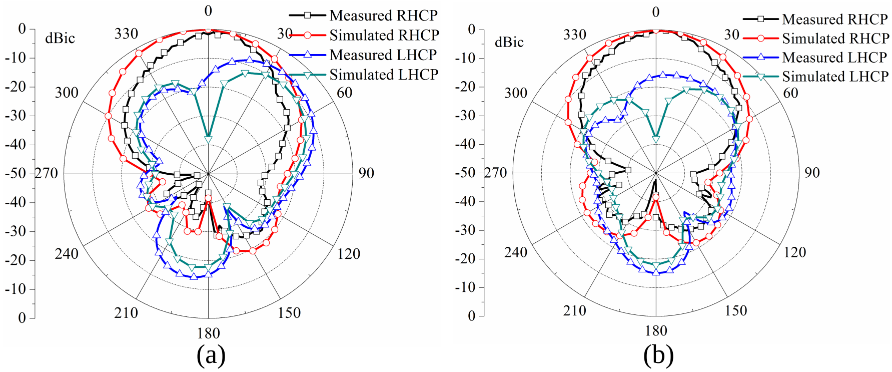


Figure 14. Simulated and measured radiation patterns at 2.45 GHz of Case 6. (a) xz-plane. (b) yz-plane.

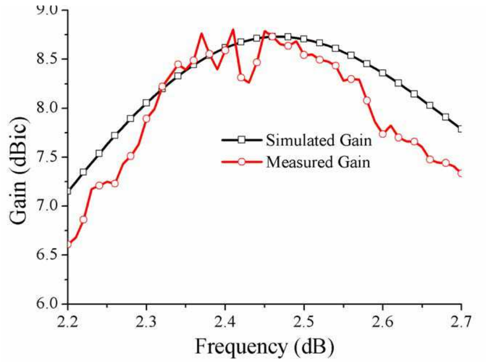


Figure 15. Simulated and measured gain of Case 6.

radiation patterns of Case 6 at 2.45 GHz are shown in Figure 14. Unidirectional radiation characteristic is observed and the front-to back ratio is more than 15 dB in this case. Furthermore, the measured gain in Figure 15 is over 8 dBic within the operating band.

3. CONCLUSION

The perturbation technologies of stubs and notches are introduced to square slot antennas in this paper. Simulations show that low AR value can be achieved when the dimensions of the stubs or notches are properly tuned. In order to further enhance the AR bandwidth, slot antennas with two pairs of stubs and notches are also presented. Results show that a 3-dB AR bandwidth of about 15.5% could be obtained with the combination perturbation of stubs and notches. The proposed modified square slot antenna with conducting reflector achieves excellent CP characteristics and high gain of more than 8 dBic within the wide AR bandwidth of 6.5%. The perturbation technologies we proposed for slot antennas are proved to be an effective way to obtain good broadband CP performance and the antenna structure is simple and easy to fabricate.

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