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DESIGN AND STUDY OF WIDEBAND SINGLE FEED CIRCULARLY POLARIZED MICROSTRIP ANTENNAS

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Abstract—The performance of single feed truncated corner circularly polarized microstrip antennas with different substrate thickness is studied by simulation and experiment. It is found that the axial ratio bandwidth could be enhanced considerably when a thicker substrate is used, provided that a U-slot and/or L-probe is used to effect impedance matching. One of the configurations attains an axial ratio bandwidth (< 3 dB) of about 14% within the impedance matching band when the substrate thickness is about $0.2\lambda_o$.

1. INTRODUCTION

In the past two and a half decades, many techniques have been developed to broaden the impedance bandwidth of probe feed microstrip patch antennas. In particular, the U-slot patch [1] and the L-probe feeding method [2] enable a single patch single layer microstrip antenna to attain over 30% impedance bandwidth. Both the U-slot and the L-probe introduce a capacitance which compensates for the inductance of the feeding probe, thus allowing for the use of thick substrates. The use of thick and low permittivity substrates is the main reason for achieving wide impedance bandwidth.

Although many papers have been devoted to the U-slot and L-probe patches in the last decade [1–9], the studies were concerned with linear polarization. There has been no systematic study of the application of these techniques to single feed circularly polarized (CP) patch antennas. The objective of this paper is to present such a study for the case of single feed truncated corner patch antenna.

Circular polarization is one of the common polarization schemes used in current wireless communication systems, for example: radar and satellite systems, since it can provide better mobility and weather penetration than linear polarization. The circularly polarized antenna could have many different types and structures, where the basic operation principle is to radiate two orthogonal field components with equal amplitude but in phase quadrature. Many studies on CP microstrip patch antennas have been reported in [10, 11], and the structure of the antenna could be mainly classified into three categories: single-fed [12, 13], dual-fed and sequential array [14–16]. The single-fed type has the simplest structure among the three types; it does not require external circuitry to excite CP. However, this type of antennas has the drawback of narrow axial ratio (AR) bandwidth. Wider AR bandwidth could be achieved in the dual-fed and sequential array structure, but they require more complicated design and may occupy larger space.

It was pointed out in [17] that the AR bandwidth of a rectangular microstrip patch antenna could be increased, by decreasing the Q of the antenna or by using thicker substrate. Similarly, the closed-form expression for the AR bandwidth of a single-fed circularly polarized microstrip antenna is presented in [18], which shows that the AR bandwidth is inversely proportional to the Q of the antenna. However, their studies did not address the problem of how to match the antenna to the feed line in the case of thick substrates. In [19], several probe-fed square ring microstrip antennas with thick substrate are presented. However, the probe feed technique limits the thickness of the substrate, and the largest thickness they could design is $0.07\lambda_o$. They achieved an AR bandwidth of about 5.3% with the $0.07\lambda_o$ thick design.

In this paper, a systematic study of AR bandwidths of single-fed truncated-corner microstrip patch antennas with different thickness is presented. Experimental results are presented for some particular cases to validate the simulation results. Our study shows conclusively that: (1) the axial ratio bandwidth increases with substrate thickness but the antenna is not matched when the thickness exceeds a certain value; (2) the U-slot and/or L-probe techniques are very effective in achieving a matched antenna with AR bandwidth exceeding 10%. One of the configurations attains an AR bandwidth (< 3 dB) of about 14% by utilizing foam or air substrates of about $0.2\lambda_o$.

2. PROBE FED TRUNCATED CORNER MICROSTRIP ANTENNA

In this section, the performance of probe fed truncated corner microstrip antennas is presented. A series of probe fed truncated corner microstrip antenna are designed with different patch height. The return loss and axial ratio bandwidth are compared and discussed. The geometry of the antennas and the results will be separately presented below.

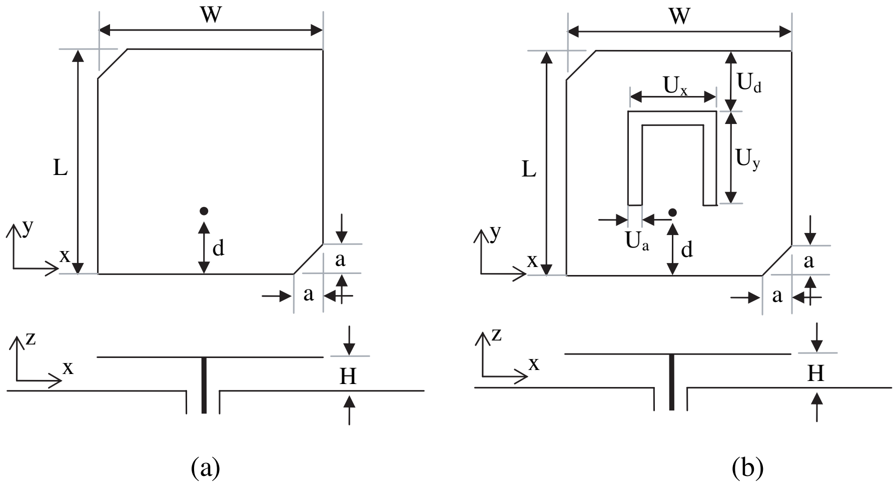

Figure 1. Geometry of the single probe-fed truncated corner microstrip antennas (a) without Uslot and (b) with U-slot. The width (W) and length (L) of the patch are both 28.6 mm. Other dimension parameters are case dependent, please refer to Table 1.

2.1. Geometry

The geometry of the conventional probe fed truncated corner microstrip antenna is shown in Figure 1(a). A pair of opposite corner of a square patch is truncated to excite two orthogonal modes. The square shaped structure of the patch limits the freedom in tuning the impedance matching of this antenna. The input impedance could be tuned by changing the position of the feeding probe (d), while the AR bandwidth could be tuned by changing the length of the truncated corner (a). U-slot is added on the patch when the patch height of conventional probe fed antenna is too high to obtain acceptable matching, and the geometry is shown in Figure 1(b). For simplicity and ease of comparison, all the antennas presented in this paper have patch dimensions of 28.6 mm (W) $\times$ 28.6 mm (L). Air substrate ($\varepsilon_r = 1$) and infinitely large ground plane are used in the simulation; while for the fabricated antenna prototypes, foam ($\varepsilon_r \approx 1$) is used, and the dimensions of the ground plane are 100 mm $\times$ 100 mm. For different substrate thickness (H), the position of the probe (d) and the corner truncation length (a) are tuned to obtain wide AR bandwidth, while maintaining the impedance matching bandwidth to overlap with the AR bandwidth. Moreover, the dimensions and position of the U-slot are tuned to broaden the impedance matching bandwidth of the antenna in thick substrate case. The dimensions of the antennas are tabulated in Table 1, and their respective free space wavelengths (λ_o) are calculated from their center AR frequency.

Table 1. Dimension of the single probe-fed truncated corner microstrip antennas (Unit: mm).

Case	Substrate thickness (H)		Configuration	a	d	U_a	U_d	U_x	U_y
1	1 mm	$0.016\lambda_o$	Probe	3.3	8.2				
2	1.5 mm	$0.024\lambda_o$	Probe	4.5	7.2				
3	2 mm	$0.032\lambda_o$	Probe	4.9	5.5				
4	3 mm	$0.046\lambda_o$	Probe	5.9	5.1				
5	4 mm	$0.06\lambda_o$	Probe	6.9	4.3				
6	4 mm	$0.05\lambda_o$	U-slot, probe	5.7	12.6	1	9.8	12	14
7	6 mm	$0.08\lambda_o$	U-slot, probe	7.7	9.6	1	9.8	12	14
8	7.5 mm	$0.1\lambda_o$	U-slot, probe	8.2	5.6	1	9.8	11	14

It can be seen from Table 1 that the corner truncation length (a) is required to be increased with the substrate thickness (H). Furthermore, the probe distance from the edge of the patch (d) decreases as the substrate thickness (H) increases.

2.2. Results and Discussions

The performance of the antennas is tabulated in Table 2. Simulation results are obtained by commercial software, Zeland IE3D ver. 11 [20]. Experiment verifications are carried out in some particular cases.

The performance of conventional truncated corner antennas (cases 1 to 5) is studied by simulation. It is observed that the AR bandwidth increases when the substrate thickness increases from 1 mm to 4 mm. On the other hand, the impedance matching bandwidth could be maintained in around 4 to 7% for different substrate thickness. However, the AR and RL bandwidth do not overlap when the substrate thickness increases. When the substrate thickness increased, the center frequency of the AR drops, and the center frequency of the RL maintains a relatively stable value. In cases 3 to 5, the RL frequency band does not overlap the AR frequency band, which mean even wider AR bandwidth could be obtained, the antennas are still not suitable in practical applications. Therefore, U-slot is used to broaden the impedance matching bandwidth and to tune the impedance matching frequency band to overlap the AR frequency band.

Table 2. Performance of the single probe-fed truncated corner microstrip antennas.

Case	Substrate thickness (H)	Configuration	Simulation (GHz)		Measurement (GHz)	
			RL BW	AR BW	RL BW	AR BW
1	1 mm	Probe	4.86-5.06 (4.0%)	4.90-4.94 (0.82%)		
2	1.5 mm	Probe	4.88-5.08 (4.0%)	4.79-4.86 (1.45%)		
3	2 mm	Probe	4.85-5.11 (5.2%)	4.68-4.78 (2.1%)		
4	3 mm	Probe	4.81-5.18 (7.4%)	4.52-4.66 (3.1%)		
5	4 mm	Probe	4.89-5.09 (4.0%)	4.40-4.57 (3.8%)		
6	4 mm	U-slot, probe	3.83-4.18 (8.7%)	3.96-4.05 (2.2%)		
7	6 mm	U-slot, probe	3.73-4.2 (11.9%)	3.96-4.12 (4.0%)	3.66-4.16 (12.8%)	3.91-4.12 (5.23%)
8	7.5 mm	U-slot, probe	3.84-4.08 (6.1%)	3.84-4.09 (6.3%)	3.88-4.08 (5.0%)	3.82-4.05 (5.84%)

Thus, in cases 6 to 8, U-slot is added on the patch to improve the impedance matching bandwidth of the antenna. Similarly, the AR bandwidth increases when a thicker substrate is used. Moreover, in cases 6 and 7, the RL bandwidth could be tuned to overlap the AR bandwidth. In case 8, the RL bandwidth of the antenna is narrower than the AR bandwidth.

In [3], it was demonstrated that the RL bandwidth is in the range of 20–30% when the substrate thickness of a rectangular U-slot microstrip antenna is about $0.08\lambda_o$. Since rectangular patch, instead of square patch is used in [3], it is predicted that the U-slot may function better on rectangular patch than square patch. In [21], a single feed "asymmetric U-slot" microstrip antenna is presented. CP is generated by the unequal arms of the U-slot and not from the truncated corners using in our design. Their substrate thickness is about $0.085\lambda_o$, and it attains an AR bandwidth of about 4% and an RL bandwidth of about 9%. Their results are similar to our case 7 when U-slot is introduced on the truncated corner patch with similar substrate thickness.

On the other hand, adding U-slot could reduce the center frequency of AR. Cases 5 and 6 compare the performance of antenna after added the U-slot. It is found that a narrower AR bandwidth is obtained when the U-slot is added. The reduction in the center AR frequency increases the Q of the antenna, as the patch is electrically smaller than the conventional design as shown in case 5.

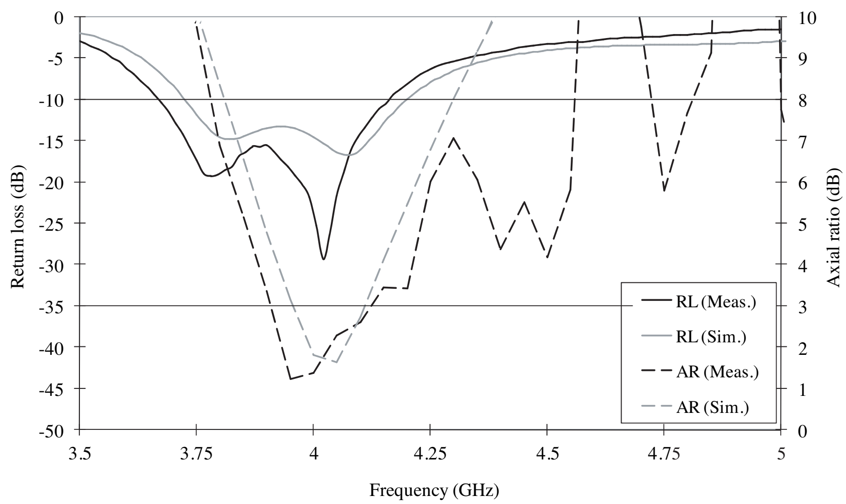

Figure 2. Return loss and axial ratio of case 7.

Antenna prototypes of cases 7 and 8 are fabricated and measured. The RL and AR of case 7 are shown in Figure 2, and the radiation pattern of case 7 at 4 GHz is shown in Figure 3. Also, the RL and AR of case 8 are shown in Figure 4, and the radiation pattern of case 8 at 3.95 GHz is shown in Figure 5. Minor discrepancies between the simulated and measured results existed, and this could be due to the fabrication tolerances. For case 8, the antenna attains an AR bandwidth of about 6%, with a substrate thickness of about $0.1\lambda_o$. However, the overlapped bandwidth is about 4.3%. In order to investigate how the AR bandwidth performs when a thicker substrate

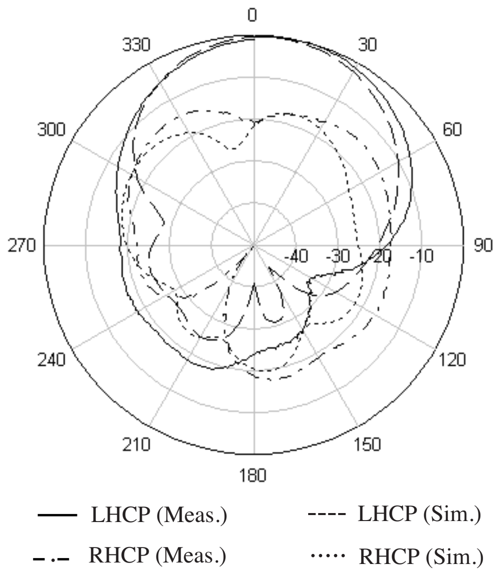

Figure 3. Radiation pattern at 4 GHz of case 7.

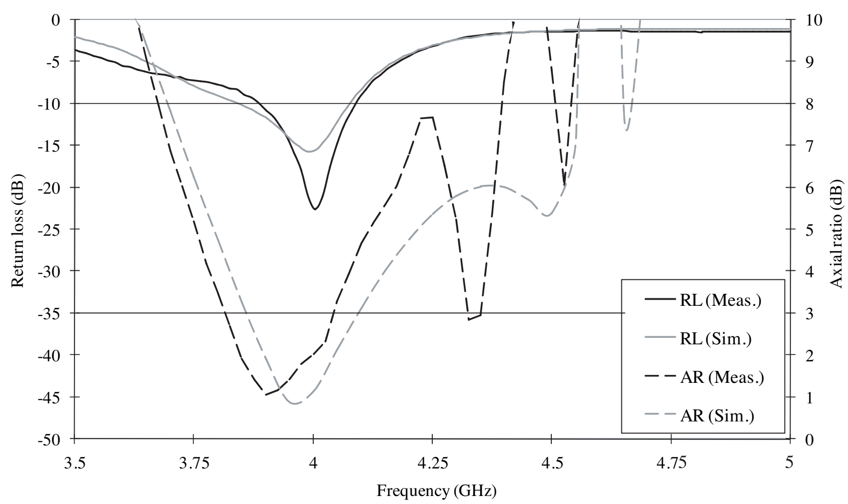

Figure 4. Return loss and axial ratio of case 8.

is used, the L-probe bandwidth enhancement technique is applied to further improve the RL bandwidth, and it will be covered in the next section.

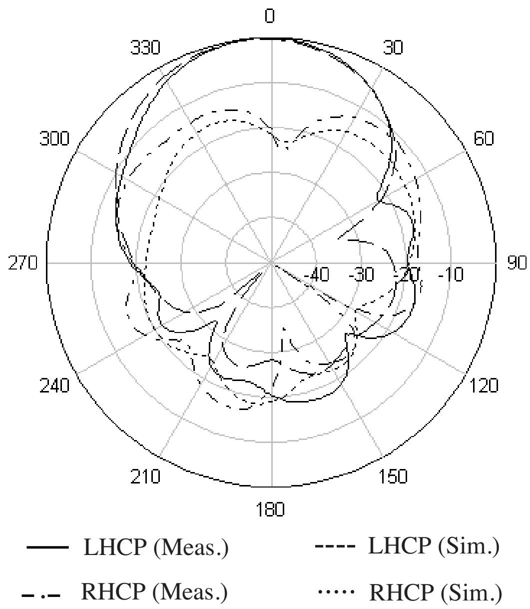

Figure 5. Radiation pattern at 3.95 GHz of case 8.

3. L-PROBE FED TRUNCATED CORNER MICROSTRIP ANTENNA

In the previous section, it has been shown that u-slot could be used to enhance the impedance matching bandwidth of single probe-fed truncated corner microstrip antenna with thick substrate. When the substrate thickness is $0.1\lambda_o$, an overlapped RL and AR bandwidth of about 4.3% is obtained. In this section, another microstrip antenna bandwidth enhancement technique, L-shaped probe, is incorporated. The overlapped bandwidth between RL and AR is presented when the substrate thickness is increased.

3.1. Geometry

The geometry of the L-probe fed truncated corner microstrip antenna with U-slot and without U-slot are shown in Figure 6(a) and Figure 6(b) respectively. Similar to the previous section, air substrate ($\varepsilon_r = 1$) is used in the simulation and foam ($\varepsilon_r \approx 1$) is used to support the patch in the experiment. The ground plane dimension of cases 9 and 10 is still 100 mm × 100 mm. For cases 11 and 12, a larger ground plane dimension of 150 mm × 150 mm is used. For ease of comparison,

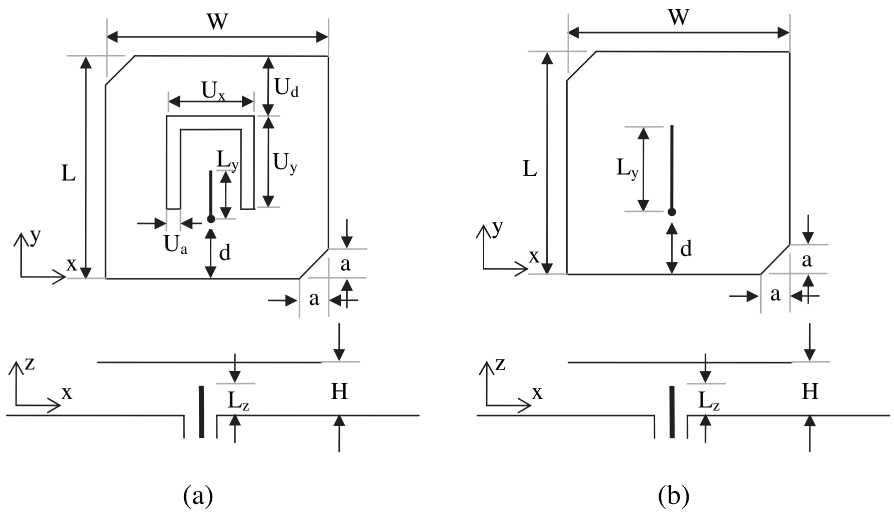

Figure 6. Geometry of the truncated corner microstrip antenna (a) L-probe fed with U-slot and (b) L-probe fed. The width (W) and length (L) of the patch are both 28.6 mm. Other dimension parameters are case dependent, please refer to Table 3.

Table 3. Dimension of L-probe fed truncated corner microstrip antennas (unit: mm).

Case	Substrate thickness (H)		Configuration	a	d	L_y	L_z	U_a	U_d	U_x	U_y
9	7.5 mm	$0.1\lambda_o$	L-probe, U-slot	8.5	0.3	12	6	1	9.3	11	10
10	7.5 mm	$0.1\lambda_o$	L-probe	10	3.3	10	6				
11	11 mm	$0.15\lambda_o$	L-probe	12.5	0	10.5	7.5				
12	15 mm	$0.2\lambda_o$	L-probe	14	3	7.5	10.5				

all the antennas have a patch dimension (W × L) of 28.6 mm×28.6 mm. For different substrate thickness (H), the dimension and position of the L-probe and the corner truncation length (a) are tuned to obtain wide AR bandwidth, while maintaining an overlap impedance matching bandwidth. The dimensions of the antennas are tabulated in Table 3, and their respective free space wavelengths (λ_o) are calculated from their center AR frequency.

3.2. Results and Discussions

In this section, both simulation and measurement results of the four cases are presented and their performance is also summarized in Table 4.

Table 4. Performance of L-probe fed truncated corner microstrip antennas.

Case	Substrate thickness (H)	Configuration	Simulation (GHz)		Measurement (GHz)	
			RL BW	AR BW	RL BW	AR BW
9	7.5 mm	L-probe, U-slot	3.30-4.38 (28.1%)	3.95-4.18 (5.7%)	3.28-4.28 (26.5%)	3.93-4.2 (6.6%)
10	7.5 mm	L-probe	3.54-5.29 (40%)	4.13-4.44 (7.2%)	3.47-5.05 (37%)	4.04-4.36 (7.6%)
11	11 mm	L-probe	3.53-4.63 (27%)	4.01-4.39 (9.05%)	3.29-4.67 (34.7%)	3.93-4.4 (11.3%)
12	15 mm	L-probe	3.82-4.65 (19.6%)	3.89-4.48 (14.1%)	3.62-4.67 (25.3%)	4.15-4.9 (16.6%)

The return loss and axial ratio of case 9 are shown in Figure 7, and the radiation pattern at 4.05 GHz is shown in Figure 8. Good agreement is obtained between the simulation and measurement results. In both cases 8 and 9, U-slot is added on the patch, and their substrate thickness is 7.5 mm ($0.1\lambda_o$). The difference between cases 8 and 9 is that in case 9 an L-shaped probe is used, while in case 8 a vertical probe is used. It can be seen that by exciting a U-slot patch with L-probe could increase the RL bandwidth from 6.1% to 28.1%, while a similar AR bandwidth of about 6% could be obtained in both cases. Since the AR bandwidth depends on the Q of the antenna, and could not be enhanced by utilizing impedance bandwidth enhancement technique, such as using U-slot and L-probe. U-slot and L-probe are used in this paper to enhance the impedance matching bandwidth of the antenna, which is wide enough to cover the AR bandwidth, and enhance the usable AR bandwidth of the antenna.

Furthermore, the performance of the antenna with the same thickness but without U-slot is studied in case 10. The performances of the antenna are shown in Figure 9 and Figure 10. Similarly, good agreement could be obtained between the measurement and simulation results. It is found that wider AR and RL bandwidth could be obtained in this case than in case 9, when U-slot is removed. The reason for the reduction in AR bandwidth in case 9 is similar to the phenomenon as discussed in the previous section. It is because lower center AR

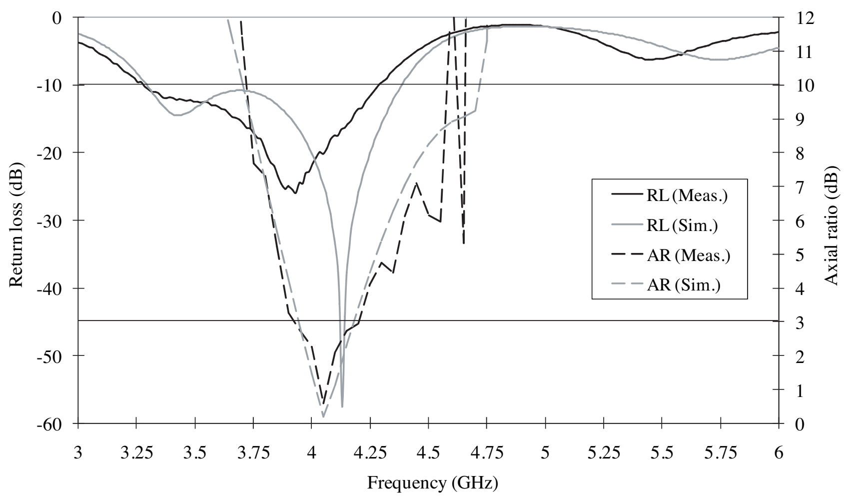

Figure 7. Return loss and axial ratio of case 9.

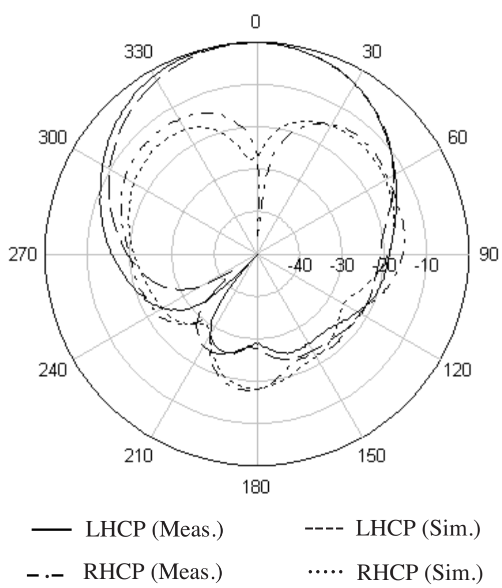

Figure 8. Radiation pattern at 4.05 GHz of case 9.

frequency is obtained in case 9, which means the patch is electrically smaller than case 10. This would make the Q of the antenna larger, and results in a relatively narrower AR bandwidth.

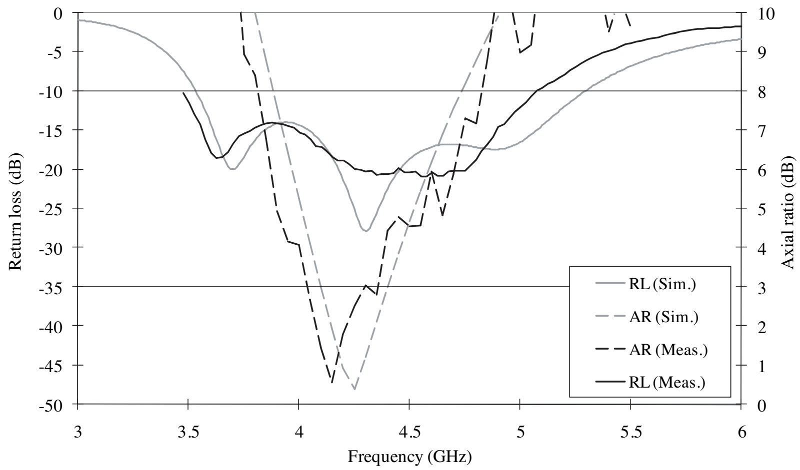

Figure 9. Return loss and axial ratio of case 10.

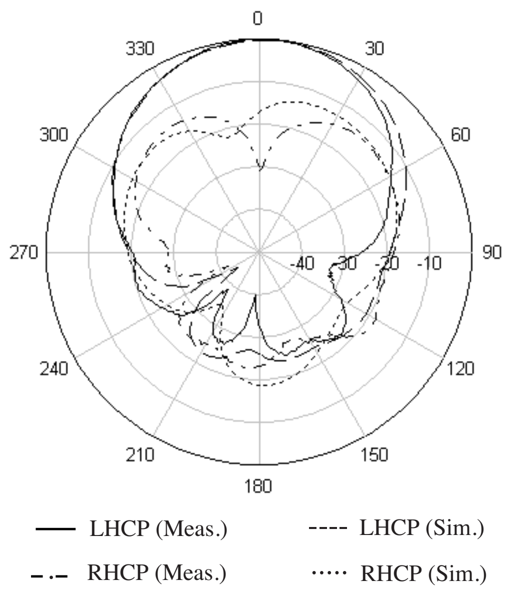

Figure 10. Radiation pattern at 4.15 GHz of case 10.

Since the L-probe fed truncated corner microstrip antenna could obtain a wide RL and AR bandwidth when the substrate thickness is $0.1\lambda_o$, two more cases with thicker substrate are studied. In case 11, the substrate thickness is about $0.15\lambda_o$, and its performance is shown

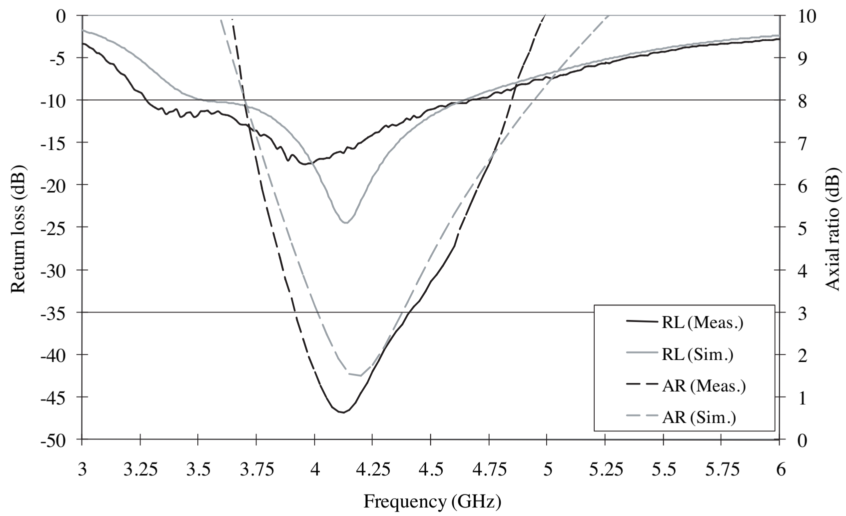

Figure 11. Return loss and axial ratio of case 11.

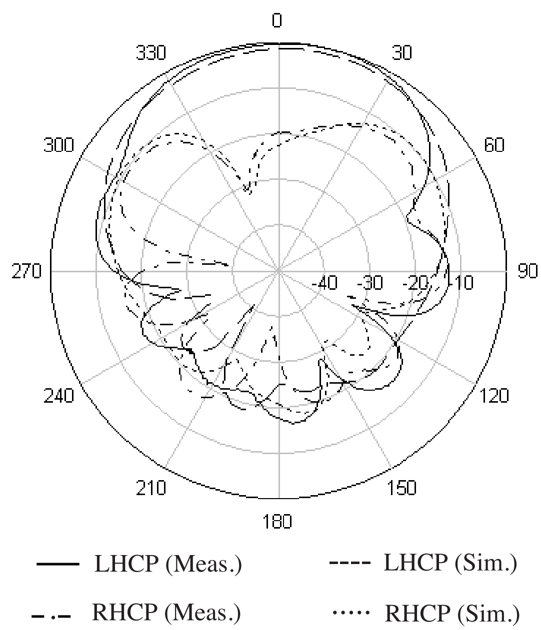

Figure 12. Radiation pattern at 4.15 GHz of case 11.

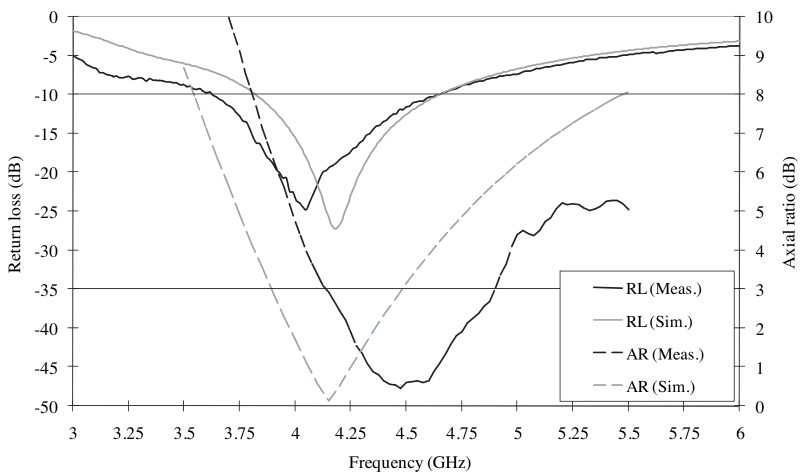

Figure 13. Return loss and axial ratio of case 12.

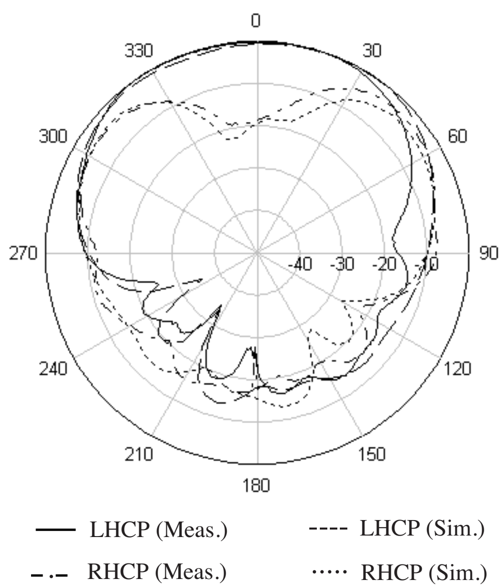

Figure 14. Radiation pattern at 4.3 GHz of case 12.

in Figure 11 and Figure 12. In case 12, the substrate thickness is about $0.2\lambda_o$, and its performance is shown in Figure 13 and Figure 14. It can be observed that the RL bandwidth decreases and the AR bandwidth increases when the substrate thickness increases (cases 10 to 12). This proves that the AR bandwidth is directly proportional to the thickness of the substrate or the Q of the antenna, while the RL bandwidth of the antenna will be limited by the input impedance matching of the antenna. When the substrate thickness is about $0.2\lambda_o$, a usable AR bandwidth of about 14% is obtained in simulation and about 12% is obtained in measurement.

This paper provides a useful guideline in designing wideband single fed truncated corner microstrip antenna. The AR bandwidth could be broadened by increasing the thickness of the substrate. U-slot could be used to broaden the RL bandwidth of the probe-fed truncated corner antenna when the substrate thickness is below $0.1\lambda_o$. Such thicknesses would be too thin for L-probe. On the other hand, L-probe could be used to broaden the RL bandwidth of the antenna when the substrate thickness is around or more than $0.1\lambda_o$. The proposed antennas are also suitable for sequential array design. By using sequential rotation technique, even wider AR bandwidth could be obtained [4–6].

4. CONCLUSION

Single feed truncated corner microstrip antennas with different thicknesses have been designed and studied. Simulation and experimental studies are performed, which show that the axial ratio bandwidth of the antenna is directly proportional to the thickness of the substrate. U-slot and L-probe techniques are used to overcome the impedance mismatching of conventional probe fed microstrip antenna when the thickness of the substrate is increased. When the thickness of the substrate is about $0.2\lambda_o$, an AR bandwidth of about 12% could be obtained within the impedance bandwidth. The thick substrate designs described in this paper retain the advantages of simplicity and small size, but they could achieve wider axial ratio bandwidths than some dual-fed or even sequentially rotated array CP designs.

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