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A Broadband Low Cross-Polarization U-Slot Patch Antenna Array Based on Differential Feed

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Abstract—In this paper, a single layer 4×4 U-slot patch antenna array based on differential feed was developed to achieve a wide bandwidth and low cross polarization with a simple feed network. A U-slot was cut on a radiation patch to realize a wideband performance, and a microstrip-line fed structure was adopted to make the patch and feed network placed in a single layer. In order to reduce extra cross-polarization level in the H-plane caused by cutting U-slot, differential feed is adopted, which also makes it easily integrated with differential devices (such as differential amplifier) directly without baluns. A single layer U-slot patch array based on differential feed and an array having the same structure but based on normal feed were made and compared with each other. The designed differentially-fed patch array has more than 12% measured impedance bandwidth and stable gain at 18–19 dBi across the operating band from 5.2 to 5.88 GHz. The measured result shows that a better asymmetry of radiation pattern in the E-plane and a lower than -45 dB cross-polarization level in the H-plane can be achieved compared with normally-fed array.

1. INTRODUCTION

Microstrip patch antennas have become the favorite of antenna designers because of their versatility and advantages of planar profile, easy fabrication, compatibility with integrated circuit technology, and conformability with a shaped surface [1]. However, they also suffer from an obvious drawback — narrow bandwidth, which makes their application greatly restricted in wireless communication, high speed data transmission and other fields. Cutting a U-slot or E-slot on the patch, with simple structure and significant improvement in bandwidth, becomes one of the widely used methods to achieve a wideband and high gain performance [2]. An antenna fed by coaxial probe with a U-slot on the patch has been proved to provide impedance bandwidth of 10%–40%, even with nonair substrate [3]. However, this structure fed by coaxial probe makes it difficult to build an array in a single layer. A wideband U-slot patch antenna array based on aperture-coupled is proposed in [4], with a 27% impedance bandwidth. A wideband array whose U-slot patch and microstrip-line feed network were placed in the single layer was firstly proposed in [5], with a 18% impedance bandwidth.

However, a much greater cross-polarization level will be brought *because of U-slot generating new current component* while an improvement can be achieved in impedance bandwidth. In recent years, differentially-fed patch antenna has been particularly studied because of its advantage in low cross-polarization and ease of being integrated with ready-made differential devices [6]. A differentially-fed microstrip antenna integrated with a push-pull power amplifier in complimentary metal oxide semiconductor technology is presented in [7]. A differentially-fed microstrip antenna integrated with an oscillator including a buffer amplifier in Silicon Germanium semiconductor technology is proposed in [8]. A single differentially-fed patch antenna was proposed in [9], with a symmetric co-polarization

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and low cross-polarization across a 34.5% bandwidth. An aperture-coupled patch antenna is designed to provide a differential interface toward monolithically integrated circuits in [10]. Measurements show around 5.5 dBi antenna gain with a cross-polarization below −27 dB. The differential low-noise amplifier provides more than 10 dB gain improvement. Differential feed has also been applied in higher-order mode millimeter-wave patch antenna [11]. In this paper, the combination of these two modes (TM10 and TM30) broadens the impedance bandwidth of the element to 18%. Symmetric radiation patterns in the E-plane and high cross-polarization levels in the H-plane generated by a single patch are eradicated by feeding two mirrored elements differentially. In [12], two differentially-fed Ku-band 2×2 patch antenna arrays using multilayer printed circuit board technology were developed, and an antenna array comprising a compact feed network is achieved by comparing with each other.

This paper presents a single layer 4×4 U-slot patch antenna array based on differential feed. A microstrip-line fed structure was adopted to take the place of traditional coaxially feed, making patch and feed network placed in a single layer. In order to enhance the bandwidth of microstrip antenna, a U-slot was cut on the patch. The application of differential feed effectively eradicates the large cross-polarization generated by U-slot while making it easily integrated with differential devices directly without baluns. The test results show that a wider impedance bandwidth and lower cross-polarization levels can be achieved than normally-fed antenna.

2. WIDEBAND DIFFERENTIALLY-FED U-SLOT PATCH ELEMENT

The single U-slot patch element of the proposed antenna is illustrated in Fig. 1. It is designed at WLAN bands using a Duroid 5880 substrate with a dielectric constant $\varepsilon_r = 2.2$ and thickness $H = 3.175$ mm. The patch, with a U-slot located in the center, has a length L and width W. Two vertical rectangular slots and a horizontal rectangular slot of U-slot have the same width Wd. The lengths of a horizontal rectangular slot and two vertical rectangular slots are Lp and Wp. The width of microstrip feedline is Ws.

In order to avoid the difficulties in design and manufacture of multilayer structure when structuring an antenna array, a microstrip-line fed structure was adopted so that the patch and feed network can be placed in a single layer, resulting in a simple structure. To enhance the bandwidth of antenna, a U-slot near microstrip feedline is introduced. *A new current path is introduced on the shorter patch, making a new resonant point, because of the added U-slot dividing microstrip patch into two parts.* A wider bandwidth can be achieved when these two resonant points are located in close frequency range. The simulated reflection coefficient of single U-slot patch adopted at last is shown in Fig. 2.

The simulated reflection coefficient shows 12.7% impedance bandwidth from 5.2 to 5.89 GHz for the reflection coefficient less than −10 dB. Although the introduction of U-slot can increase the bandwidth, the current component going along the horizontal rectangular slot will become very large in all the bandwidth as shown in Fig. 3. Those currents will affect radiation patterns, especially in the H-plane

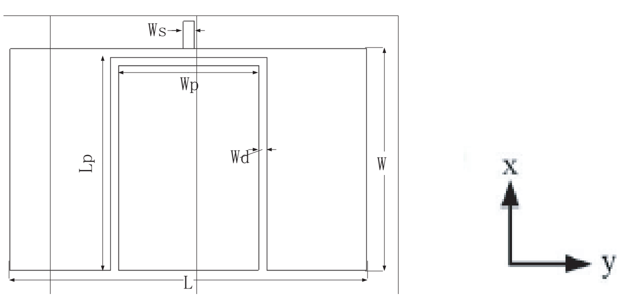


Figure 1. Geometry of the single U-slot patch element.

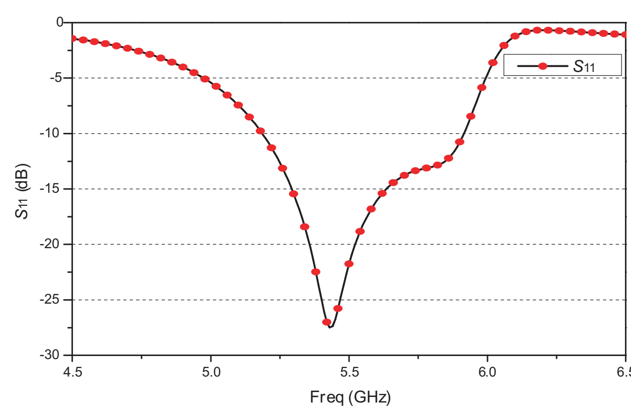
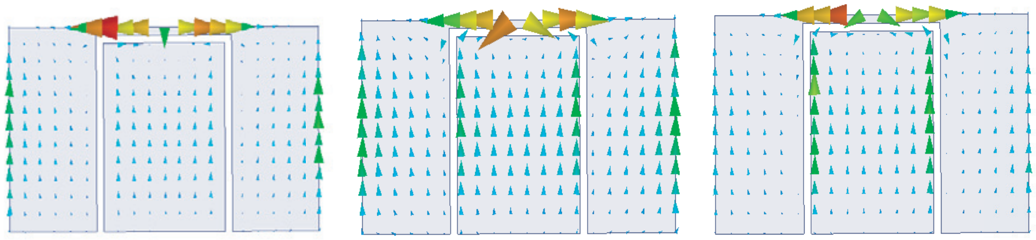


Figure 2. Reflection coefficient of the single U-slot patch.



(a) (b) (c)

Figure 3. Current distribution on U-slot patch at different frequencies.

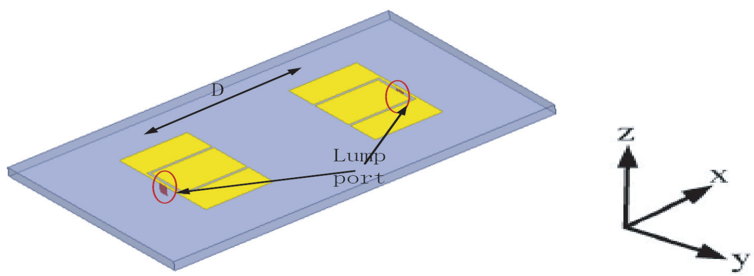
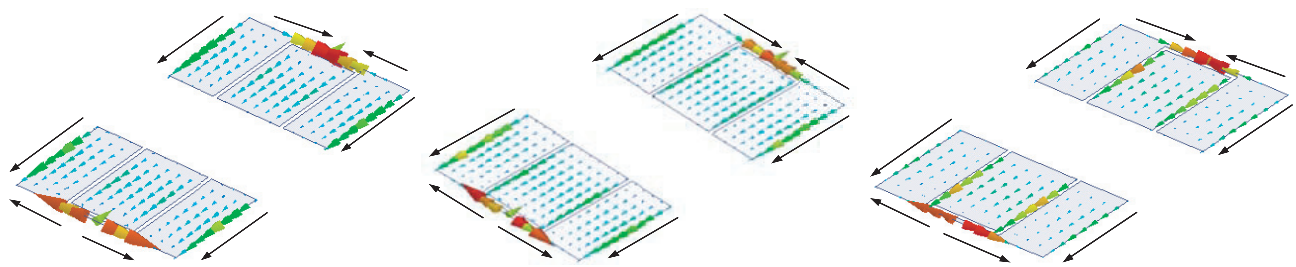


Figure 4. Structure of the differentially-fed U-slot patch antenna.



5.3 G 5.5 G 5.8 G

Figure 5. *Current distributes on U-slot patch which based on differential feed at different frequency.* The dark arrows represent the directions of the horizontal and vertical currents.

(yoz-plane), resulting in a very high cross-polarization level. As for the E-plane (xoz-plane), the impact on radiation patterns of this current component is very restricted. The undesirable cross-polarization level degrades the performance of the antenna. In order to improve the cross-polarization level in the H plane, *a differentially-fed U-slot patch antenna structure is demonstrated in Fig. 4. D is the distance of the two patches, and the other parameters are the same as single patch.* Two lumped ports are used to take the place of microstrip feedline, making simulation more convenient in HFSS.

Due to the differential feed design, shown in Fig. 5, currents going through the horizontal arm of the U-slot on one patch are comparable with their image counterparts in amplitude, but with different direction. This leads to cancelation of the radiation *in the H-plane* and results in much lower cross-polarization compared with the single U-slot element design. This design will make the antenna not only have the advantage of wideband characteristic of the single U-slot element, but also achieve symmetric radiation patterns and much lower cross-polarization levels in the H-plane.

Figure 6 shows the cross-polarization level of a normally-fed U-slot patch and differentially-fed U-slot patch in the H-plane from 5.3 GHz to 5.8 GHz when $D = 50$ mm. Compared with normally-fed U-slot patch, it is obvious that a remarkable improvement is achieved when differentially-fed U-slot patch is adopted. The distance between the two U-slot patches (D) is a noteworthy parameter when a

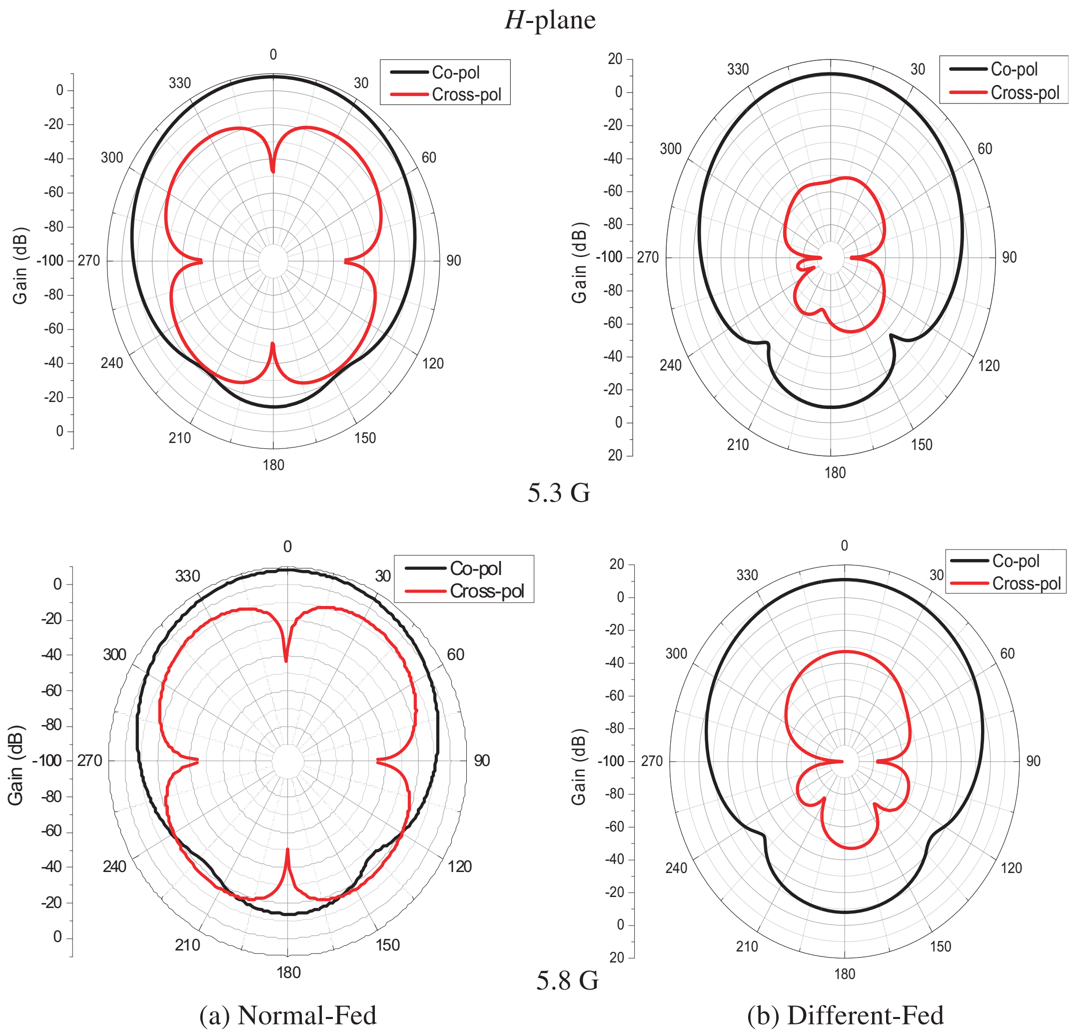


Figure 6. Radiation patterns of (a) normally-fed U-slot patch and (b) differentially-fed U-slot patch in the H-plane.

differentially-fed U-slot patch is adopted. Fig. 7 shows the change of radiation patterns in the E-plane and the H-plane with D at different frequencies. Because the differentially-fed U-slot patch is a two-element array, radiation patterns in the E-plane will change with D. But the cross-polarization level keeps relatively stable in the E- and H-planes across the band when D is changing. It can be assumed that the improvement of the cross-polarization level brought by differential feed is rarely affected by the change of D.

3. DESIGN OF WIDEBAND DIFFERENTIALLY-FED U-SLOT PATCH ANTENNA ARRAY

In practical application, *due to the finite gain of a single U-slot patch antenna, antenna array is widely applied to obtain a higher gain.* A novel low cross-polarization level U-slot patch antenna array based on differential feed is proposed in this section. In order to avoid the complex structure of microstrip feed network when differential feed is applied in every two U-slot patch elements, a new design of feed network is illustrated. In this design, an antenna array will be divided into two symmetrical sub-arrays while differential feed is only applied in two sub-arrays, with every single element in two sub-arrays being connected together by parallel feeding.

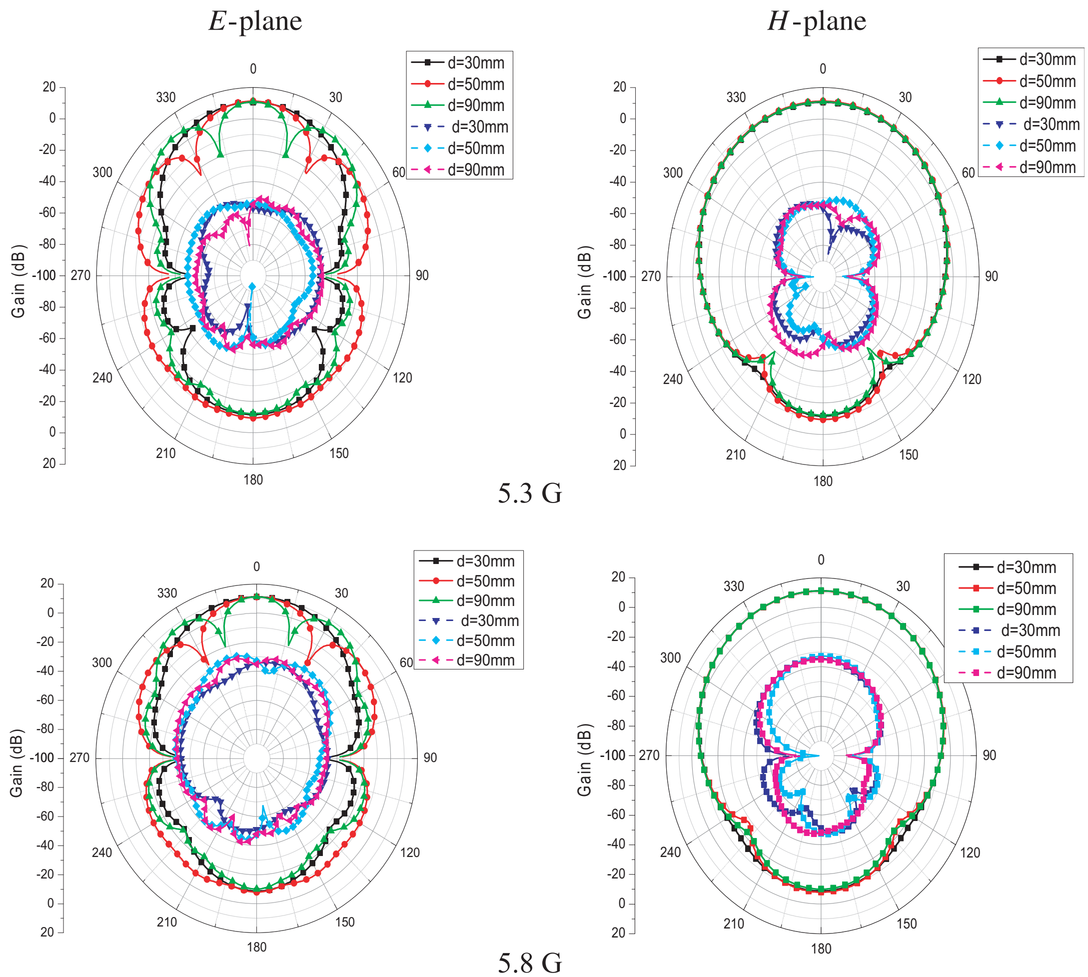


Figure 7. The change of radiation patterns with D at different frequencies.

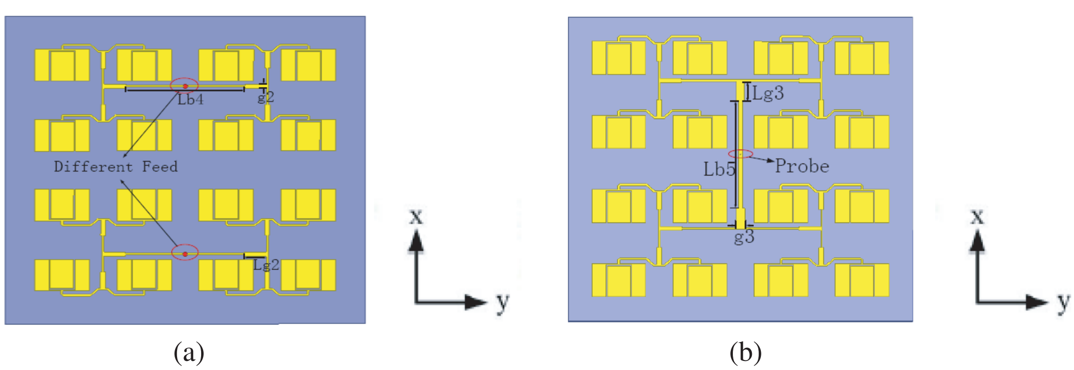


Figure 8. Two different kinds of 4×4 U-slot patch antenna arrays.

The influence of D on the cross-polarization level, when differentially-fed U-slot patch is introduced, has been proved rather limited in the previous section. Currents going through the horizontal arm of the U-slot on every single patch in one subarray are comparable with their image counterparts in amplitude, but with different directions. This will lead to cancelation of the radiation in the far field in the H-plane and results in much lower cross-polarization while D is different.

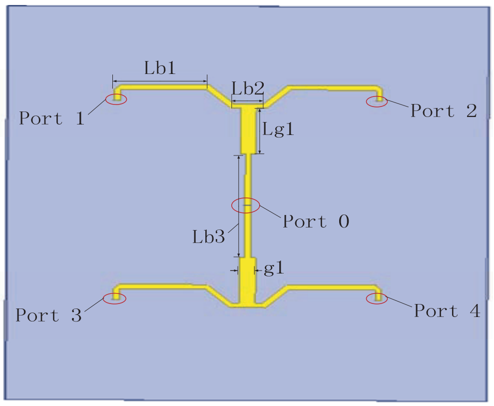


Figure 9. Structure of the quartering power divider in the two array.

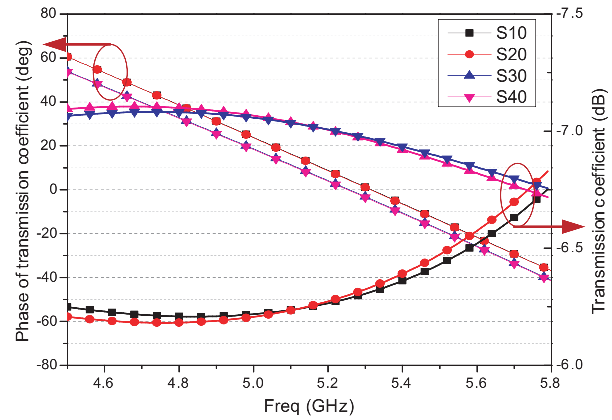


Figure 10. Amplitudes and phases of different ports.

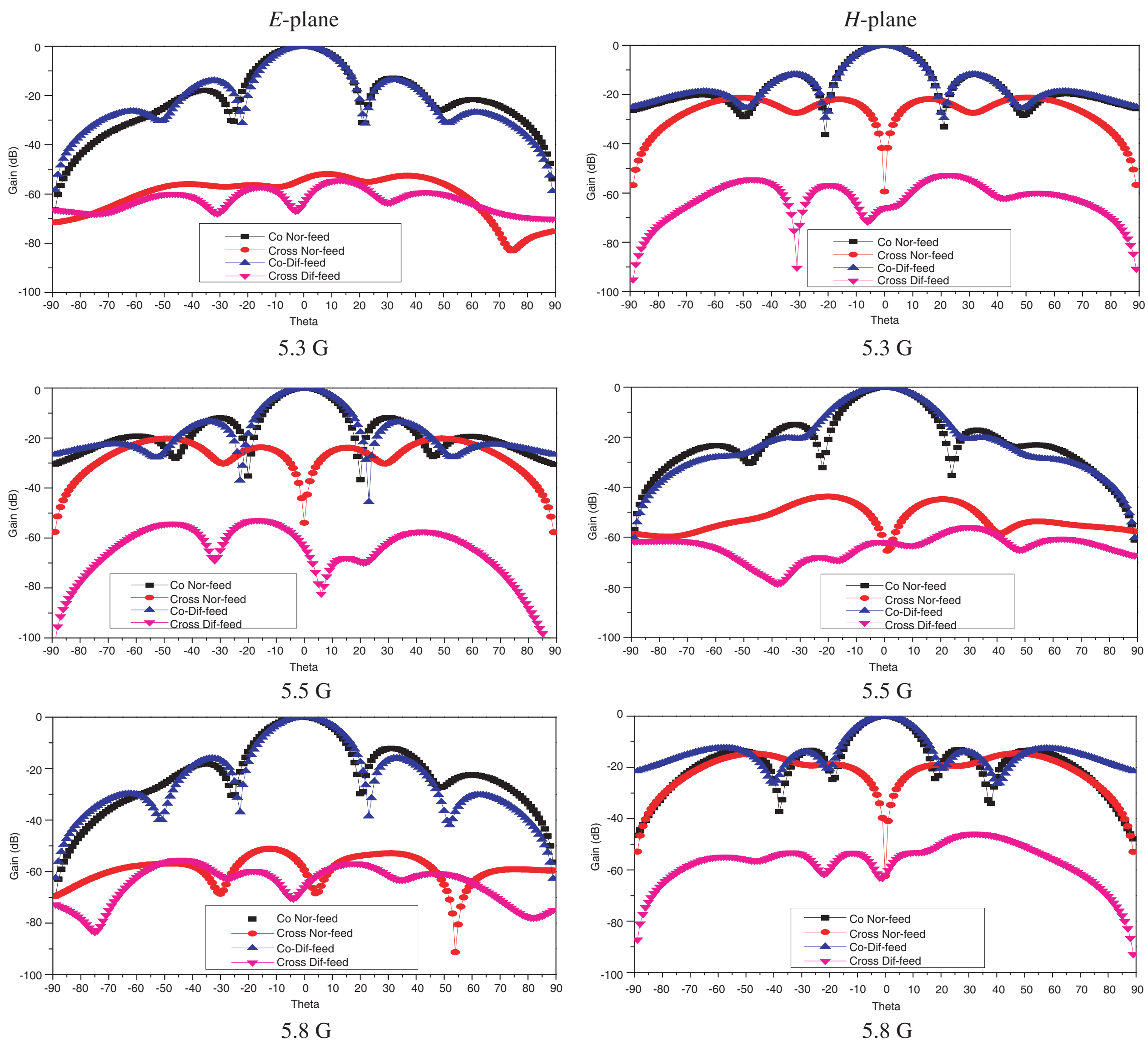


Figure 11. The simulated radiation patterns of two kinds of antenna arrays.

Table 1. Final parameters for the antenna array (all dimensions in mm).

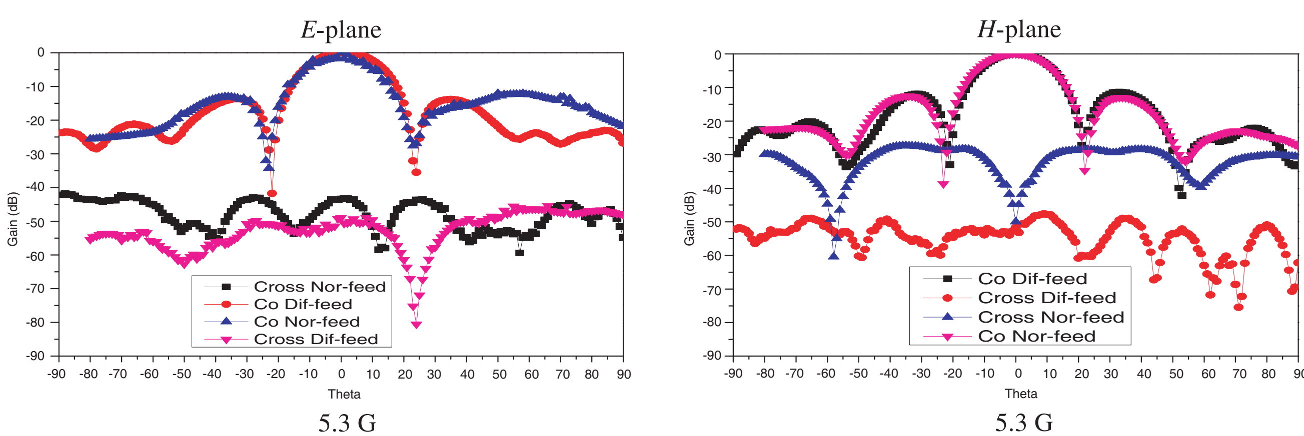
$Lb1$	$Lb2$	$Lb3$	$Lb4$	$Lb5$	$Lg1$	$Lg2$	$Lg3$	$g1$	$g2$	$g3$	L	W	Lp	Wp	Ws	Wd
12.6	4.2	18.8	52.2	52.2	8.2	9.5	9.5	2.2	2	3.2	24	16	15.4	10.2	0.8	0.6

A 4×4 U-slot patch antenna array based on differential feed is proposed and compared with traditional 4×4 patch array in this section, shown in Fig. 8. In order to avoid producing relatively large sidelobe, the distance between two single U-slot patches should not be too large. However, enough space is also needed to make feed network convenient to distribute on the substrate. So the quartering power divider based on tortuous T-junction, as shown in Fig. 9, is widely used in the feed network of an antenna array to solve this problem. The elements of the two arrays are identical with the distance of 36 mm (0.66λ) between two single U-slot patches in the E- and H-planes, and the parameters of feed network are shown in Table 1. In fact, the four ports of quartering power divider does not have the same amplitude and phase, shown in Fig. 10, because the tortuous T-junctions are not completely symmetrical. This will make radiation pattern of antenna arrays, which use normal feeding asymmetry, even produce larger sidelobe. However, in differentially-fed arrays, the asymmetry of radiation pattern in the E-plane caused by the bias of phase in different ports can also be improved effectively due to differential feed making currents going through elements centrosymmetrically.

As shown in Fig. 11, an obvious improvement in the cross-polarization level, especially in the H-plane, and a better asymmetry of radiation pattern in the E-plane can be achieved compared with normally-fed array. To compare the performances of these two antenna arrays, the two prototypes were fabricated and shown in Fig. 12. The specific parameters of these two arrays are shown in Table 1. In Fact, a Balun is demanded to measure the differentially-fed antenna array. So a wideband balun,

(a) (b) (c)

Figure 12. Photos of the fabricated antenna prototype: (a) normally-fed antenna array, (b) differentially-fed antenna array, (c) balun used for testing.



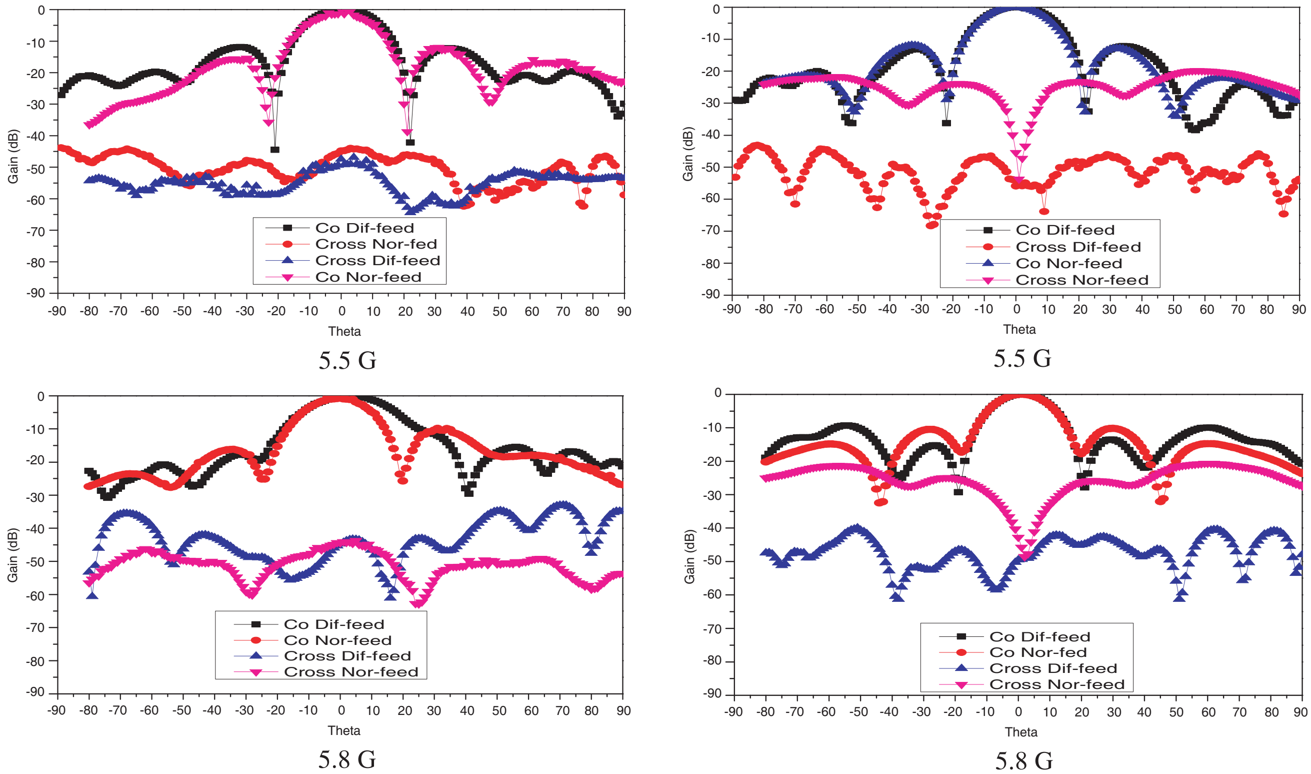


Figure 13. The measured radiation patterns of two kinds of antenna arrays.

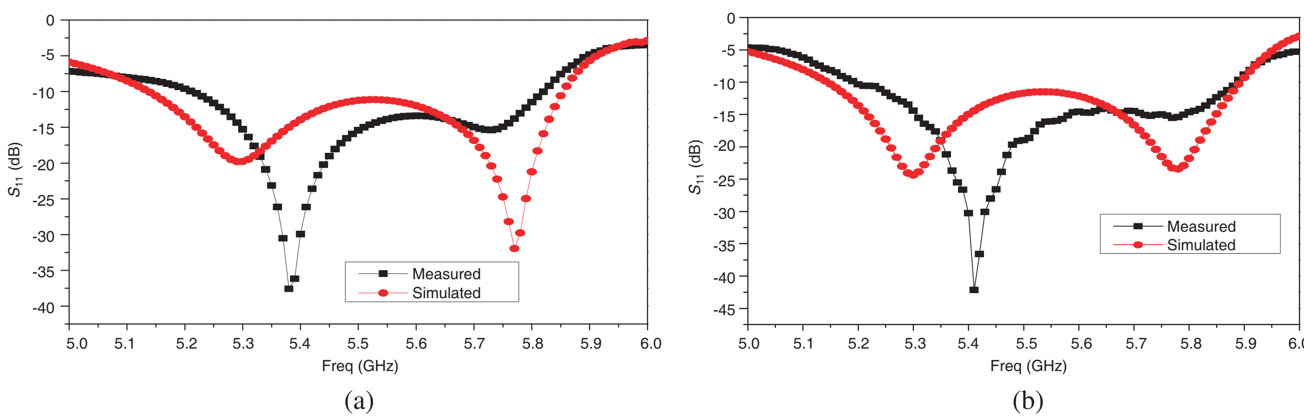


Figure 14. The measured and simulated S_{11} of (a) normally-fed array and (b) differentially-fed array.

proposed in [13], from 3.6 to 10.7 GHz with a good balanced performance within 0.5 dB magnitude imbalance and less than 6° phase imbalance was used in the testing process. The test results of radiation patterns of normally-fed and differentially-fed U-slot patch antenna arrays in the H-plane are compared in Fig. 13. The measured patterns only show results from −90° to 90° due to limitation of the facility. The measured and simulated S_{11} of normally-fed and differentially-fed arrays are shown in Fig. 14. The slight differences between simulated and measured results are due to facility sensitivity, test error and some minor alignment problems. Nevertheless, they still fit each other quite well.

4. CONCLUSION

In this paper, a single layer 4×4 U-slot patch antenna array based on differential feeds is proposed to achieve wideband performance and low cross-polarization levels. The 4×4 array based on differential feeds is measured by a wideband balun which includes the whole bandwidth of the array and compared with an array having the same structure but based on normal feed. The designed array has more than 12.4% (reflection coefficient lower 10 dB) measured impedance bandwidth with stable 18–19 dBi gain across the band. A better asymmetry of radiation pattern in the E-plane and a lower than -45 dB cross-polarization levels in the H-plane can be achieved compared with normally-fed array, which make the array have a better performance in radiation pattern. Furthermore, this work is based on a single layer and differentially-fed design, which makes it simple and easily integrated with different devices directly without baluns.

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