A Low-Cost Wideband Circularly Polarized Slot Array With Integrated Feeding Network and Reduced Height

Xiaolei Jiang, *Student Member, IEEE*, Zhijun Zhang, *Fellow, IEEE*, Yue Li, *Member, IEEE*, and Zhenghe Feng, *Fellow, IEEE*

***Abstract*—This letter proposes a wideband unidirectional circularly polarized (CP) slot array with a truly planar structure, which integrates the feeding network on a single substrate. The height of the array is reduced by half compared to traditional arrays with a reflector. Four parasitic slots are etched at the edges of the ground plane to improve the gain performance when the height is reduced. The measured results show that the bandwidths (BWs) for impedance, axial ratio (AR), and gain are all more than 23%, and these three bandwidths almost cover the same frequency band. The proposed array has a good unidirectional pattern and can be used in base-station applications.**

***Index Terms*—Circularly polarized, planar array, reduced height, slot antenna, wideband axial ratio.**

I. Introduction

CIRCULARLY polarized (CP) antennas with wideband axia-ratio (AR) bandwidth have become desirable in recent years because they can be used by two or more communication systems. When used in base-station applications, antennas with unidirectional patterns and sufficient gain are required.

With the advancement of printed circuit technology, enormous planar CP antenna arrays have been reported in the literature. Corner-truncated patch arrays are the most common forms due to their simple structure. However, AR bandwidth improvement [1]–[3] in these arrays is limited due to the intrinsic narrow bandwidth of the traditional patch. Modified CP patches [4], [5] can achieve wideband AR bandwidth, but they need either nonplanar feeding method or a stack structure, which makes the antenna complex. Besides patch arrays, other forms such as loops [6] or dipoles [7] can be used for wideband CP arrays. These could be fabricated on a single printed circuit board (PCB). However, an additional PCB is necessary for the feeding network, which is separated from the antenna.

In comparison, slot arrays are favorable for a planar and integrated design. Because of the inherent ground, the feeding network could be printed on the same substrate as the antenna [8], [9]. However, most slot arrays are bidirectional and suffer from low gain and poor front-to-back ratio, which makes them unusable for base stations. To obtain a unidirectional pattern, a metal plate is usually placed at the back as a reflector [10]. However, the reflector may change the performance of the array such as the AR bandwidth and gain performance. To overcome the deficiency, a stack structure is used in [10], which cannot take advantage of the integrated features of a slot array. In addition, neither the effect of the height of the reflector on the antenna performance nor the gain BW have been considered enough in the literature. The height is always set to $\lambda_0/4$ (λ_0 is the wavelength of the center frequency) [7], [11], and there is no discussion about the gain BW [7], [10].

In our previous work [11], a wideband CP slot array was studied. It was fabricated on a single substrate and had unidirectional patterns, and the distance between antenna substrate and reflector was still $\lambda_0/4$. However, there are always some design constraints in the actual scenario, such that the height of the antenna may have to be reduced to make it more compact and meet the application requirements. It is the intent of this letter to show how the height can be reduced from $\lambda_0/4$ to $\lambda_0/8$ while still retaining the key feature of integrated feeding network and the wide bandwidth.

II. Antenna Design

Fig. 1 shows the geometry of the proposed array antenna from the top and side views. The basic structure is based on [11] with an FR4-epoxy substrate ($\varepsilon_r = 4.4$, $\tan\delta = 0.02$). Four ring slot elements are arranged in a rotational symmetric structure and excited by applying a well-known sequentially rotated feeding network [12]. Different from that in [11], four additional narrow slots are etched on the ground plane. They are arranged in a rotational symmetric structure according to the antenna center, which could minimize negative effects on the CP characteristic. These slots play an important role in retaining the antenna performance. They act like four open-ended radiating slots and could compensate gain drop when the antenna height is reduced. Detailed discussion will be given in Section III. With such a structure, the whole array still needs only one PCB, in which all the elements and feeding network are integrated together.

III. Parameter Study

A. Effect of the Antenna Height

We first modeled the structure of the antenna, shown in the inset in Fig. 2, with the use of High Frequency Structure Sim-

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The authors are with the State Key Lab of Microwave and Communications, Tsinghua National Laboratory for Information Science and Technology, Tsinghua University, Beijing 100084, China (e-mail: zjzh@tsinghua.edu.cn).

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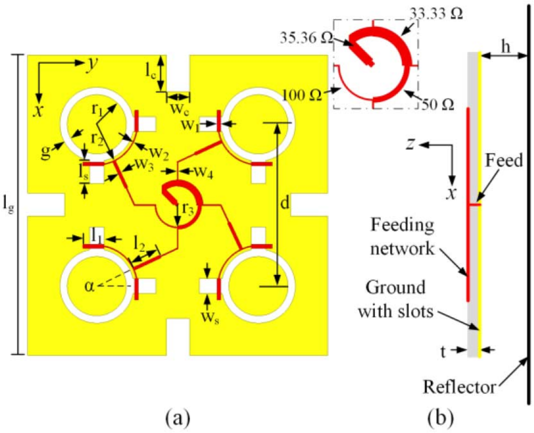

Fig. 1. Geometry of the proposed antenna: (a) top view; (b) side view. Parameters are the same as [11] except: $h = 16$, $l_c = 20$, $w_c = 12.5$, $l_s = 12$, $w_1 = 2$, $w_2 = 0.5$, others are $r_1 = 16$, $r_2 = 22.25$, $r_3 = 12$, $g = 4$, $w_3 = 1.64$, $w_4 = 0.44$, $w_s = 8$, $l_1 = 11.5$, $l_2 = 16$, $d = 87.5$, $t = 1$, $l_g = 162.5$, all in millimeters, $\alpha = 25°$.

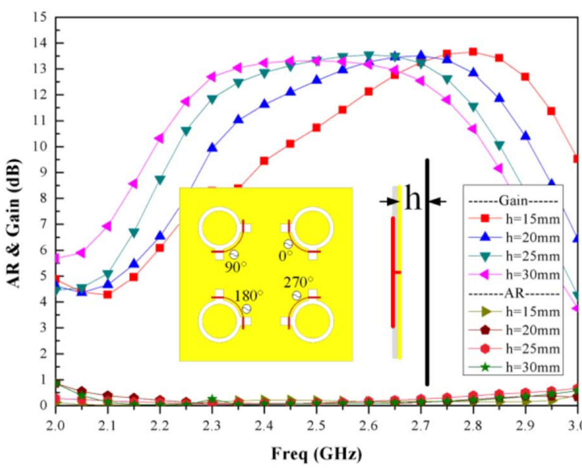

Fig. 2. Effect of the height h on axial ratio and peak realized gain.

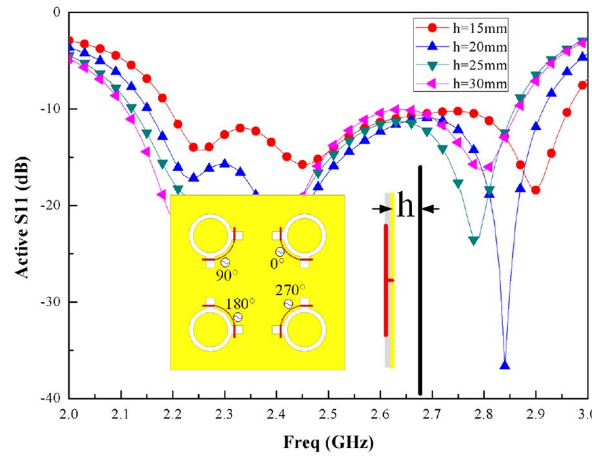

Fig. 3. Effect of the height h on active S_{11}.

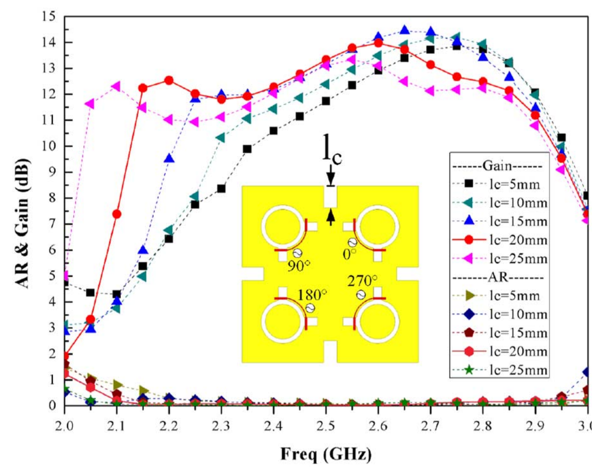

Fig. 4. Effect of the etched slot length l_c on axial ratio and peak realized gain.

ulator (HFSS ver. 14). This model is the initial design of the proposed antenna in Fig. 1; the antenna h is first set to 30 mm, which is about a quarter-wavelength of the center frequency of 2.45 GHz. The four narrow slots are not yet etched on the ground plane, and the sequentially rotated feeding network is left out for simplicity. Four lumped ports are used to excite the antenna; these have the same magnitude, but a progressive phase of 90° for the circular polarization.

Then, we investigated the effect of h. As shown in Fig. 2, when h decreases from 30 to 15 mm, the axial ratio changes slightly but the 3-dB gain bandwidth shifts to a higher frequency, which means that the gain at lower frequency drops but that at higher frequency rises. For the center frequency of 2.45 GHz, for example, the peak gain drops nearly 3 dB when the height is reduced by half. Worse still, the gain at a frequency lower than 2.45 GHz drops even more.

Fig. 3 shows the effect of h on the impedance bandwidth. Because there are four ports excited simultaneously, the active S_{11} should be used to consider the impedance bandwidth. Here, the normalized impedance of the ports is set to 30 Ω, and the antenna can be matched to 50 Ω by using the feeding network later. The results show that reducing h also shifts the impedance bandwidth to a higher frequency. However, the change is not as significant as that in the gain bandwidth.

B. *Effect of the Etched Slot*

To compensate for the decreases in gain at lower frequency after the height is reduced, four slots are etched at the edge of the ground plane. These slots need no additional space and make the antenna still on a single substrate. As the simulated results show that deterioration on active S_{11} caused by these four slots is acceptable, we just investigate their effect on axial ratio and peak realized gain. Here, the antenna height h is set to 16 mm, which is the suggested value for practical applications.

Fig. 4 shows the axial ratio and peak gain versus the slot length l_c for the slot width w_c of 12.5 mm. The axial ratio still has little effect due to the rotational symmetry and progressive feeding phase of 90°. For the peak gain, however, the improvement is significant. With the increase in l_c, the gain at lower frequency can be pulled up to a certain level before the height is reduced and to even higher levels at some frequencies. In addition, the gain at higher frequency does not change much when l_c increases to 20 mm. This means that such structure can expand the gain bandwidth compared to that in Fig. 2: The reduced height is responsible for higher frequency, whereas the etched slot accounts for the lower frequency. For the slot width w_c, results show that it has little effect on both AR and gain, thus for concision, we do not show the details.

We can treat these slots as four open-ended parasitic slots. When the length l_c is approximately a quarter-wavelength of a

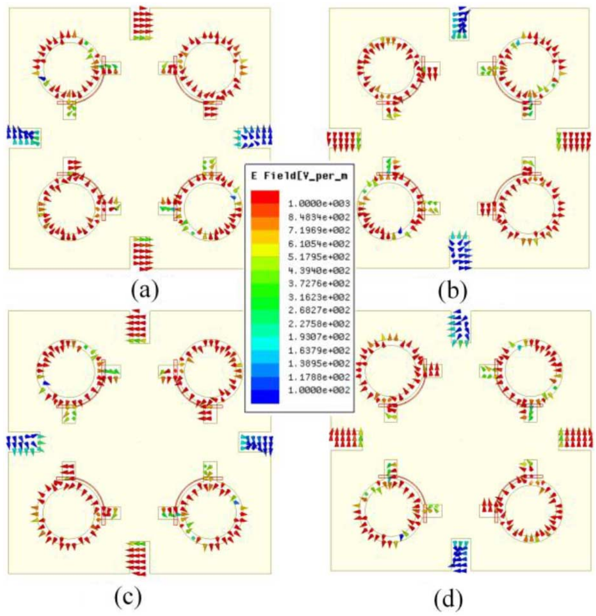

Fig. 5. Field distribution on etched slots in a period at 2.25 GHz. (a) $t = 0$. (b) $t = T/4$. (c) $t = T/2$. (d) $t = 3T/4$.

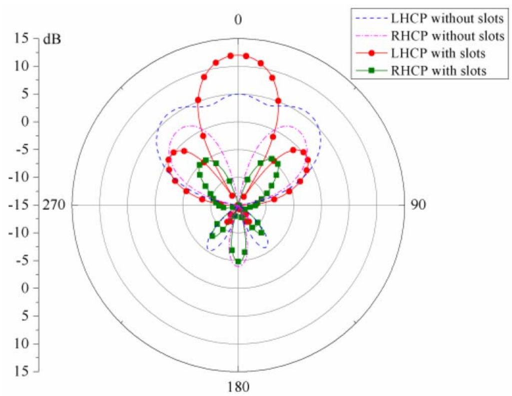

Fig. 6. xz-plane patterns at 2.25 GHz.

certain frequency, the slots can be excited to compensate for the gain at this frequency. To further explain the CP compensation, Fig. 5 depicts the electrical field (E) distribution over a certain period at a lower frequency of 2.25 GHz. As shown in Fig. 5(a), E reaches maximum in the top and bottom slots, whereas the minimum E is achieved in the left and right slots. The total E of these four slots point right at $t = 0$. After a quarter of the period, as shown in Fig. 5(b), the maximum and minimum E become interchanged between the top/bottom and the left/right slots, thus making the total E rotate 90° clockwise. Fig. 5(c) and (d) further shows the clockwise rotation of the total E with the time varying. Therefore, the four slots as a whole form the left-hand circularly polarized (LHCP) radiation.

To investigate the compensation ability, a comparison of the patterns at 2.25 GHz with and without etched slots was done, as shown in Fig. 6. Due to the rotational symmetry, the patterns at the xz- and yz-planes have the same shape. Thus, for simplicity, we only show the results at xz-plane. These indicate that 7 dB compensation is achieved in the LHCP pattern and that cross-polarization level [right-hand circularly polarized (RHCP)] is also improved.

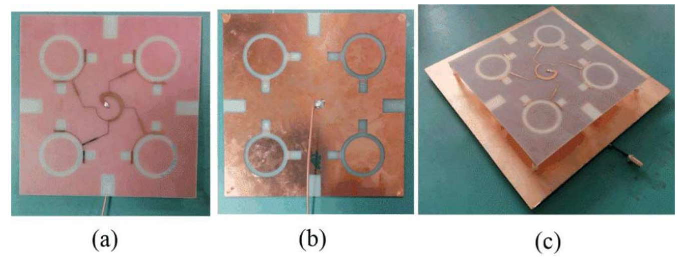

Fig. 7. Photographs of the fabricated antenna: (a) front view of the substrate; (b) back view of the substrate; (c) with reflector.

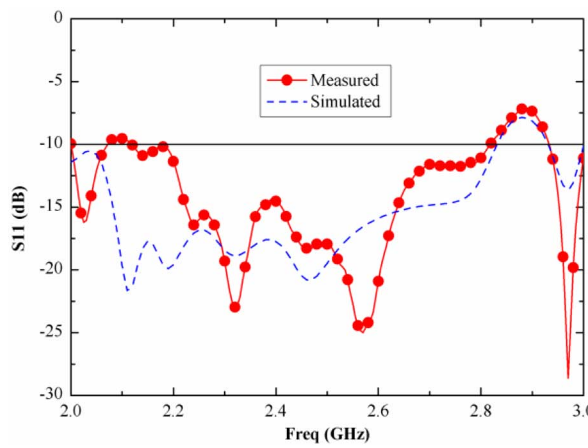

Fig. 8. Simulated and measured S_{11}.

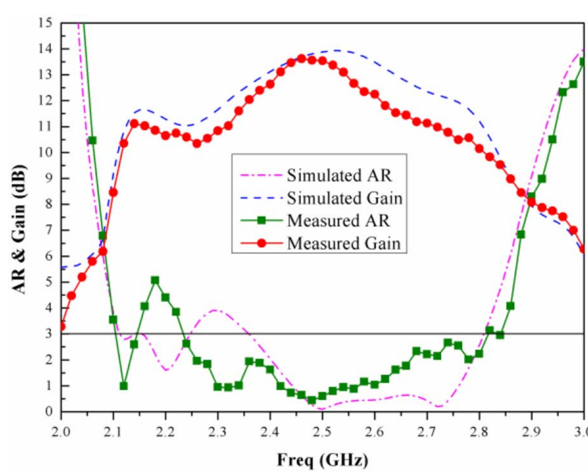

Fig. 9. Simulated and measured axial ratio and antenna gain.

IV. Measured Results

To verify the design of the proposed antenna, a prototype with the parameters listed in Table I is fabricated, as shown in Fig. 7. The prototype consists of a 2×2 array with an element space d of 87.5 mm and an overall size of $205 \times 205 \times 16$ mm^3. The height of the antenna is only about a one-eighth wavelength of the center frequency of 2.5 GHz. A semi-flexible coaxial cable is used to excite the array at the center.

Fig. 8 shows the comparison of the simulated and measured S_{11}. The measured impedance bandwidth ranges from 2.12 to 2.82 GHz (28.4%), whereas the simulated result starts below 2 GHz. The disparity mainly occurs at lower frequency and may be caused by the semi-flexible coaxial cable. Nonetheless, it does not have any serious impact on the practical use of the antenna.

We measured the prototype in our anechoic chamber, and Fig. 9 shows the measured and simulated axial ratios and an-

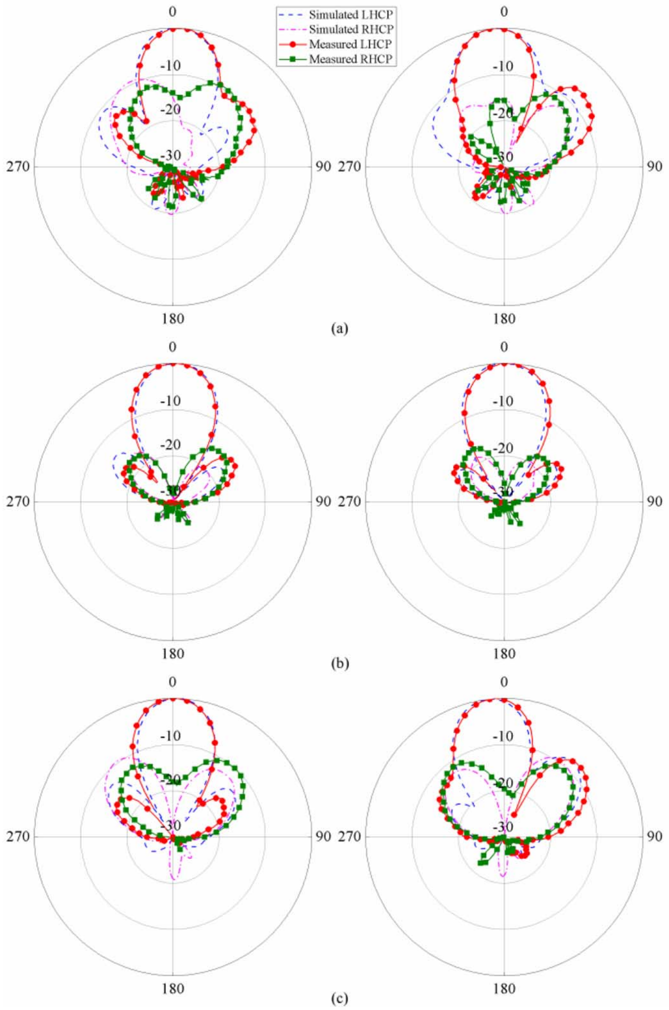

Fig. 10. Simulated and measured patterns at *(left)* xz- and *(right)* yz-planes: (a) 2.25 GHz; (b) 2.45 GHz; (c) 2.65 GHz.

tenna gains. The simulated AR and gain are obtained with the sequentially rotated feeding network. Due to the deterioration of the output phase relation and the mismatched characteristic impedance away from the center frequency, the ARs at lower and higher frequencies are worse before the application of the feeding network. In addition, we could find the AR curve protrusive around 2.3 GHz, which is caused by the characteristics of the feeding network. This phenomenon is also exhibited in cases applying a sequentially rotated feeding network [7], [12]. However, the measured and simulated ARs have reasonable agreement, with only a small shift at lower frequency. The final measured 3-dB AR bandwidth is about 23.6% (2.24–2.84 GHz). In terms of gain performance, as discussed in Section III, there is an obvious improvement between 2.15 and 2.35 GHz. Similar trends in the measured and simulated results are also observed. The measured 3-dB gain bandwidth ranges from 2.14 to 2.78 GHz (26.0%).

Fig. 10 shows the measured and simulated patterns at three frequencies, representing a lower, a center, and a higher frequency. The front-to-back ratios at these three frequencies are all above 20 dB, indicating the practicability of the proposed array. Fig. 10(b) shows that the spinning radiation patterns in the xz- and yz-planes are symmetric at the center frequency. This is a reasonable result because the structure of the array is rotational symmetric and the parameters of the design are optimized at this frequency. However, asymmetric and tilt patterns can be seen at a lower or higher frequency, due to the deterioration of the output phase relation of the feeding network, as previously mentioned.

V. Conclusion

In this letter, we propose a 2×2 CP array that is wideband and unidirectional. The measured results show that the proposed array achieves an impedance BW of 28.4%, a 3-dB AR BW of 23.6%, and a 3-dB gain BW of 26%. The array integrates the feeding network on the same substrate as the element antennas, thus making it easy and low-cost to manufacture. A reflector is placed at the back at a distance of $0.13\lambda_{2.4\ GHz}$, which is only an eighth of the wavelength. Four parasitic narrow slots are etched on the ground plane to expand the gain bandwidth. There is good agreement between the measured and simulated results. The high front-to-back ratio of the antenna makes it applicable for base stations.

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