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RESEARCH ARTICLE

W-Band Single-Layer Broadband Reflectarray Antenna

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ABSTRACT In this paper, a W-band single-layer reflectarray antenna is proposed with the advantages of broadband and high aperture efficiency. A novel dual rotation-symmetry windmill element is designed in the W-band, which consists two layers of copper patches printed on a Rogers RT5880 substrate. Based on the analysis of the proposed metasurface element, a square reflectarray with 13.85λ_0 (44.2 mm) aperture diameter at 94 GHz center frequency was designed, fabricated and measured. The designed reflectarray antenna shows a 1-dB gain bandwidth of 25.5% (89-113 GHz) in the W-band. Moreover, the measured gain is 31.1 dBi at 94 GHz and the maximum aperture efficiency is 53.4%. The result shows that the proposed design has prospects in wireless communication applications.

INDEX TERMS W-band, broadband, low-profile, reflectarray.

I. INTRODUCTION

As a new generation of high-gain antennas, microstrip reflectarray antennas (RAs) are processed by printed circuit board (PCB) technology, which has the advantages of low-profile, small size, light weight, and easy processing. Moreover, RAs are foldable and easily conformal to different carriers [1], [2]. Compared with the low frequency band, the millimeter wave (30-300 GHz) has large available bandwidth, short wavelength, high resolution, and strong anti-interference ability. According to the theory of electromagnetic waves, electromagnetic wave in W-band (75-110 GHz), especially near 94 GHz, has low attenuation during transmission. Therefore, W-band RAs have important applications in high-resolution imaging systems, high-resolution radar, precision guidance and point to point data transmission [3], [4], [5], [6], [7]. W-band RAs are one of the hot spot areas of high gain antenna research.

Narrowband is an inherent characteristic of RAs. The bandwidth of traditional RAs is generally only about 5%, while the bandwidth of the antenna typically requires at least 10% in modern communication and radar systems. Therefore, expanding the bandwidth of RAs has been an important research topic. After decades of unremitting efforts, various methods have been proposed to expand the bandwidth of RAs. Firstly, some novel resonant elements, multiple shape combinations, or novel change modes of elements can be used to solve the narrowband problem of RAs, such as the fractal elements proposed in [8], the phoenix element proposed in [9] and the double circular ring element proposed in [10]. Apart from those above-mentioned novel methods, five parallel dipole elements [11], elements with attached phase-delay lines [12], [13], [14], [15], or aperture-coupled elements with slots and lines of variable length [16], [17] were also used to solve this problem.

Moreover, adding an air layer between the dielectric substrate and metal patch [18], using multilayer stacked patches [16] and increasing the thickness of the substrate are also common methods to improve the bandwidth of RAs. However, the size of W-band antennas is very small which require high machining accuracy. Using multilayer stacked patches or adding an air layer will not only increase the profile

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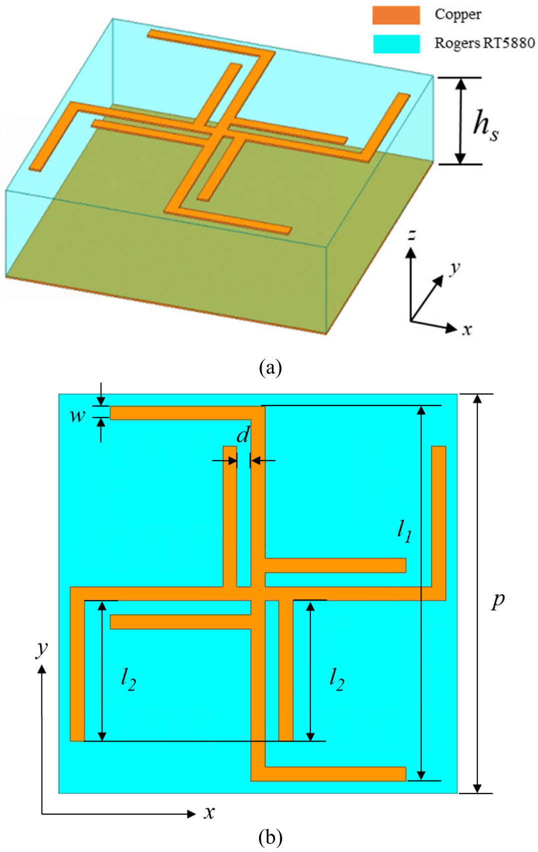

FIGURE 1. The structure of the broadband reflectarray element. (a) Perspective view, (b) Top view.

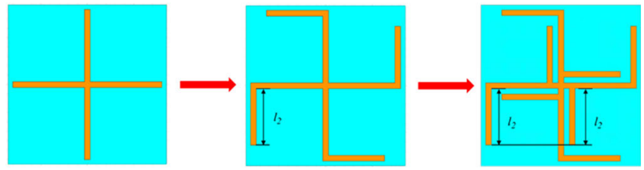

FIGURE 2. Design of the element.

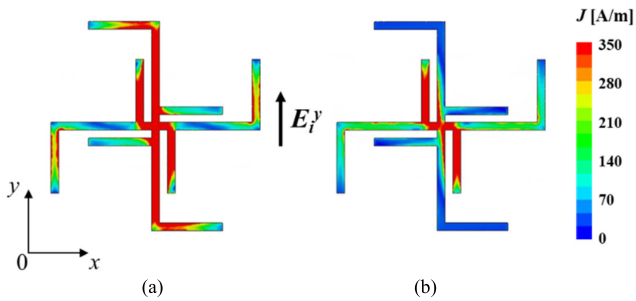

FIGURE 3. Surface current of the broadband reflectarray element with E_i^y at (a) 84 GHz and (b) 104 GHz.

of RAs, but also the risk of errors during assembly, which causes a significant impact on antenna performance during the artificial manufacturing process. In short, using the above two methods will make the W-band RA more expensive and difficult to manufacture. Therefore, a single-layer multiresonant element is used to expand the antenna bandwidth in this study.

In this paper, we propose a W-band broadband RA, which consists of a horn antenna and a low-profile reflectarray. A novel single-layer multiresonant element with two layers of copper patches printed on a Rogers RT5880 substrate is proposed and analyzed. The simulation results show that the element can reach more than 360° smooth phase shift range and has good broadband performance. We further design and fabricate a planar square reflectarray including 676 elements, to verify the capability of our designed element.

The outline of this paper is as follows. Section II introduces the proposed element and its design process. Section III presents the design, manufacture and measurements of the RA. Finally, section IV gives the conclusion and summarization of this work.

II. THE DESIGN OF REFLECTARRAY ELEMENT

The geometric structure of the proposed broadband reflectarray element is shown in Fig. 1. It composed of two copper layers (orange parts) printed on a 0.508 mm Rogers RT5880 substrate (blue part, $\tan\delta = 0.0009$, $\varepsilon_r = 2.2$, $h_s = 0.508$ mm).

Based on the structure of cross I, the radiation patch of the proposed element is a rotation-symmetry windmill structure, as shown in Fig. 2. When the length l_2 of the element changes, the delay phase of the reflected wave changes. However, as a single resonant element, the reflection phase shift range of the rotation-symmetry windmill element is only about 150°, which cannot meet the requirements to form RAs. Therefore, we add a smaller reverse rotation-symmetry windmill structure at the center of the element to provide an additional resonance point in the element, which will change the element to a single-layer multiresonant element.

Elements are closely adjacent to each other in the reflectarray. We define the distance between these elements as element spacing, which is important for the design of RAs. If the element spacing is too large, grid lobes will appear in the antenna pattern. To avoid above problem, the required element spacing $p$can be obtained by the following equation [19]:

$$p \leq \frac{\lambda_0}{1 + \sin\theta} \tag{1}$$

where p is the element spacing, θ is the maximum angle of incidence from the feed, λ_0 is the electromagnetic wave length at the center frequency.

If the element spacing is too small, mutual coupling between elements will be strengthened. Generally, the period of elements is equivalent to half-wavelength or subwavelength [20]. Considering the phase compensation range and the limit in the actual processing of the element, the element spacing here is chosen as 1.7 mm (p=1.7 mm, corresponding to $0.53\lambda_0$, where λ_0 is the electromagnetic wave length at 94 GHz).

To obtain a smooth phase shift curve, it is necessary to adjust the position and intensity of the resonance point. Next,

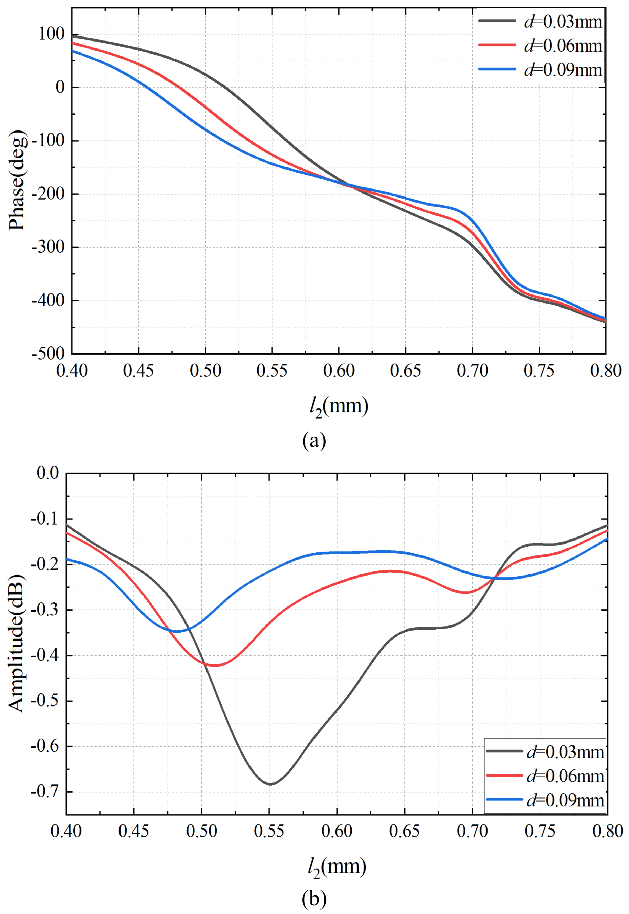

FIGURE 4. Reflection responses of the broadband reflectarray element with different values of parameter d. (a) Phase, (b) Amplitude.

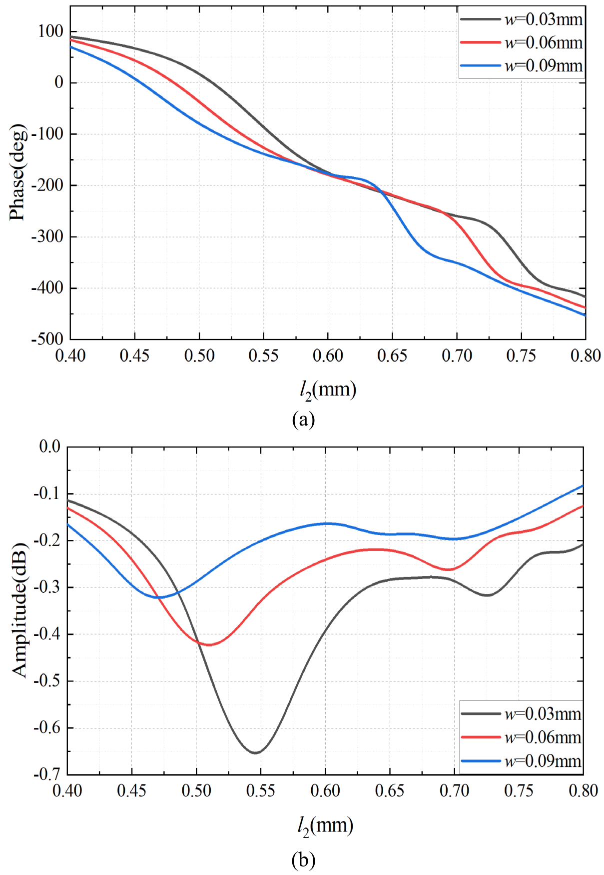

FIGURE 5. Reflection responses of the broadband reflectarray element with different values of parameter w. (a) Phase, (b) Amplitude.

the effect of element structure parameters on phase compensation characteristics is analyzed.

A. EFFECT OF PARAMETER D ON PHASE COMPENSATION CHARACTERISTIC OF EIEMENT

Firstly, the parameter d is an important structure parameter which could affect the coupling between the inner and outer rotation-symmetry windmills. Therefore, the value of parameter d has an important impact on the phase compensation characteristics of the element. The value of the d is set as 0.03, 0.06, and 0.09 mm respectively, when l_2 varies from 0.4 to 0.8mm. Fig. 4 showed the reflection responses of the proposed element with different values of parameter d.

As shown in Fig. 4, the phase shift range can exceed 400° with different parameter d, indicating that the multiresonant element can effectively expand the phase shift range. When d=0.09 mm, the two resonance points of the element is relatively far, and the resonance strength is low. When we reduce the value of parameter d, the two resonance points gradually approach. When d=0.03 mm, the two resonance points is too close, which will lead to the first resonance point almost cover the second and further cause a higher resonance strength and deeper phase shift curve.

B. EFFECT OF PARAMETER W ON PHASE COMPENSATION CHARACTERISTIC OF EIEMENT

Then we analyze the effect of parameter w on the phase compensation characteristic of the element. Taken $w$as 0.03, 0.06 and 0.09 mm respectively, with other parameters unchanged. Simulate and draw the reflection responses of the broadband reflectarray element with different values of parameter $w$when parameter d=0.06 mm.

As shown in Fig. 5, the increase of parameter w leads to the two resonance points of the element shift to left together. Meanwhile, the resonance strength of the element at two resonance points decreases, but the distance between the two resonance points does not change much. When w=0.03 mm, the phase shift curve presents two turning points due to the excessive strength of the two resonance points. When w = 0.09 mm, the curve is relatively smooth at the beginning due to the weak resonance strength at the first resonance point. However, the curve will fluctuate significantly when entering the second resonance point at l_2 =0.65 mm.

C. EFFECT OF PARAMETER h_s ON PHASE COMPENSATION CHARACTERISTIC OF EIEMENT

Parameter h_s is the thickness of the substrate. Next, we analyze the effect of parameter h_s on the phase compensation

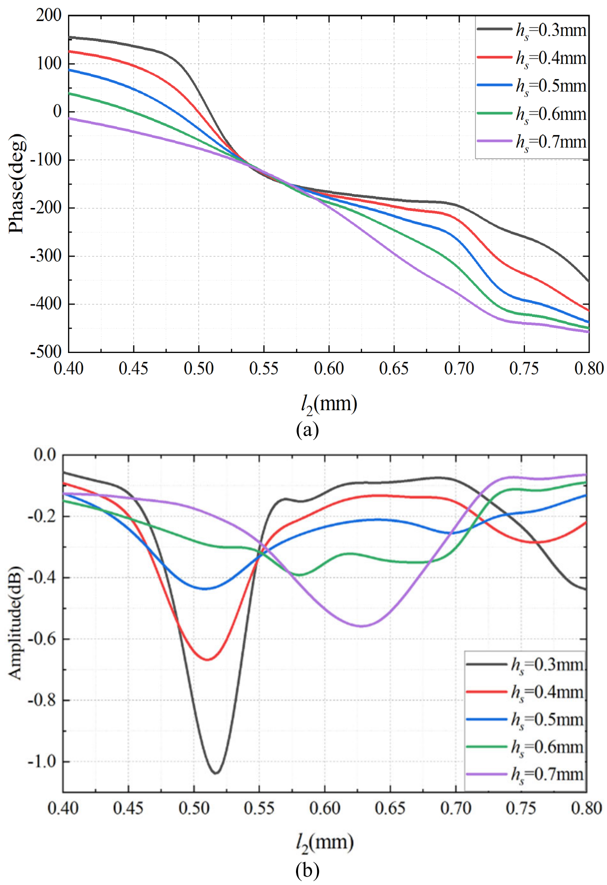

FIGURE 6. Reflection responses of the broadband reflectarray element with different values of parameter h_s. (a) Phase, (b) Amplitude.

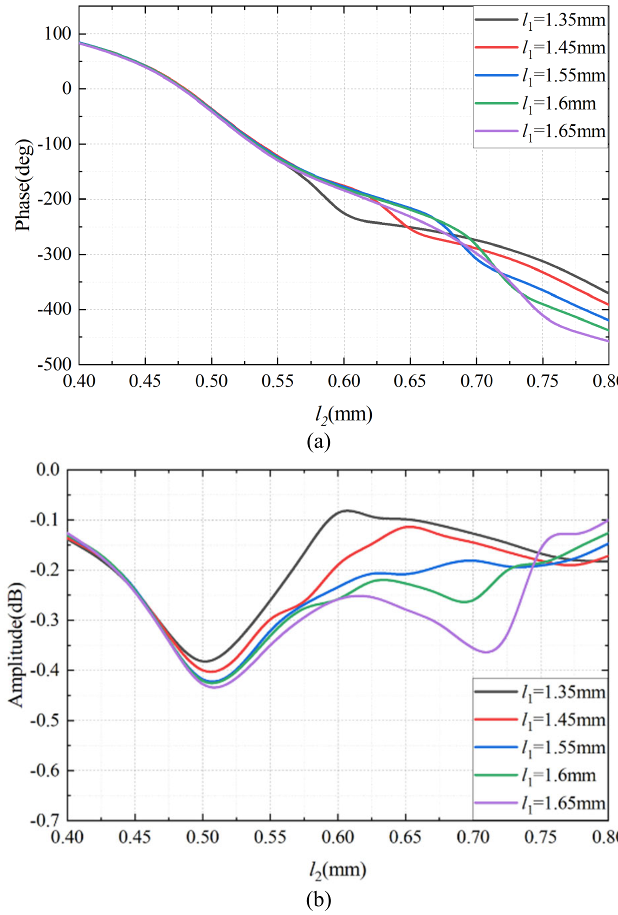

FIGURE 7. Reflection responses of the broadband reflectarray element with different values of parameter l_1. (a) Phase, (b) Amplitude.

characteristic of the element. The parameter h_s is taken as 0.3, 0.4, 0.5, 0.6 and 0.7 mm, respectively. The reflection responses of the broadband reflectarray element with different values of parameter h_s are shows in Fig. 6.

As the thickness of the substrate increases, the resonance strength at two resonance points decreases. Meanwhile, the two points gradually approaches. When taken parameter h_s as 0.6 mm, the two resonance points is gradually starting to merge. When taken parameter h_s as 0.7 mm, the two resonance points is too close so that they completely merge into a single strong resonance point. That's why the thickness of the substrate needs to be focused when designing the multiresonant broadband reflectarray element.

D. EFFECT OF PARAMETER L $_1$ ON PHASE COMPENSATION CHARACTERISTIC OF EIEMENT

Finally, we analyze the effect of parameter l_1 on the phase compensation characteristic of the element. We take l_1 as 1.35, 1.45, 1.55, 1.6 and 1.65mm respectively, with other parameters unchanged. Then simulate and draw the reflection responses of the broadband reflectarray element with different values of parameter l_1.

As shown in Fig.7, the reflection responses of the element almost remain unchanged when l_1 is less than 0.55mm. Parameter l_1 mainly impact the location of the second resonance point. As the value of l_1 increases, the second resonance point gradually shifts toward the right, and the phase shift range of the curve expands. The distance of adjacent elements becomes too close when l_1 reaching the value of 1.65mm, which can result in an intensification of mutual coupling between elements and also an elevation in the slope of the phase shift curve preceding the second resonance point. Therefore, if $p = 1.7$mm and l_1 is selected as 1.6mm or less, it will not cause enhanced mutual coupling between elements.

Based on the above-mentioned effect of structure parameters on the phase compensation characteristic of element, we further use simulation software to optimize structure parameters and then obtain a good phase shift curve. RAs are processed by PCB technology. The process of PCB is limited by the minimum line spacing in actual processing. Besides, the boards used have some fixed standard thicknesses. Considering the actual machining process, we selected the thickness of the substrate as 0.508 mm. The detailed dimensions of the proposed element are shown in Table 1.

Use master-slave boundaries and floquetport excitations to establish and simulate the proposed element by HFSS from ANSYS. Fig. 8(a) shows the simulated results of

TABLE 1. **Reflectarray element geometry parameters.**

Parameter	Value(mm)
p	1.7
w	0.06
d	0.06
l_1	1.6
l_2	0.4~0.705

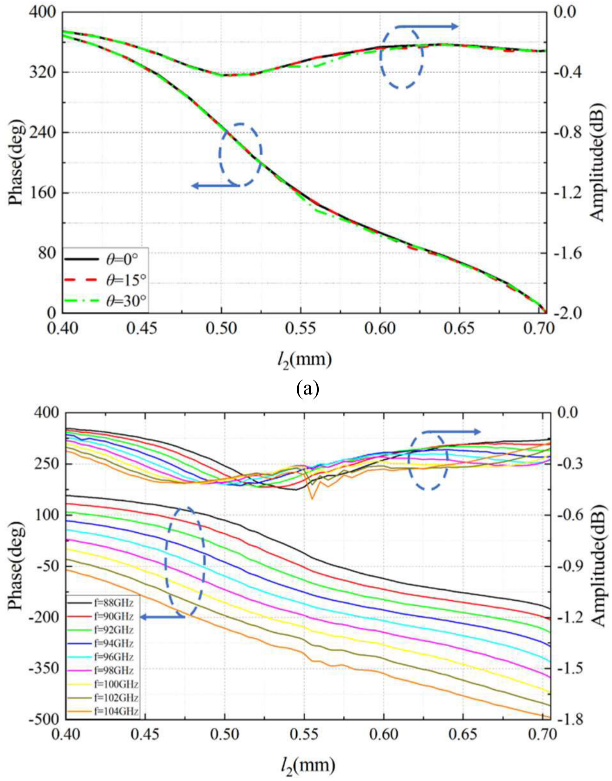

FIGURE 8. **Reflection responses of the broadband reflectarray element with (a) Different incidence angles and (b) Frequencies.**

the broadband reflectarray element. When l_2 varies from 0.400 to 0.705 mm, the reflection amplitude is greater than -0.42 dB at 94 GHz and a phase shift range of 370° is obtained. The phase shift curve is smooth and has good linearity. Fig. 8(b) shows the frequency sweep results varying from 88 to 104 GHz. It can be seen that each reflection phase shift curve is approximately parallel, indicating that the phase compensation characteristic of the proposed element is nearly identical at different frequencies, which means that the element has good broadband performance.

In Table 2, the reflection performance of the proposed element is compared with other reported multiresonant elements. It can be seen that the proposed element with a single layer is less sensitive to parameter changes, which is more suitable for the actual manufacturing of W-band RAs.

TABLE 2. **Comparison of multiresonant elements between reported and proposed RAs.**

	Frequency (GHz)	Phase shift range (°)	Amplitude (dB)	Num. of substrate	Air layer	Max phase sensitivity (°/0.1λ_0)
this work	94	369	>-0.42	1	no	387
[10]	10	423	>-0.75	1	no	540
[21]	28	> 360	--	1	yes	625
[22]	88	375	--	1	no	500
[23]	7.5	> 360	>-0.07	1	no	400
[25]	165	420	>-0.35	1	no	409

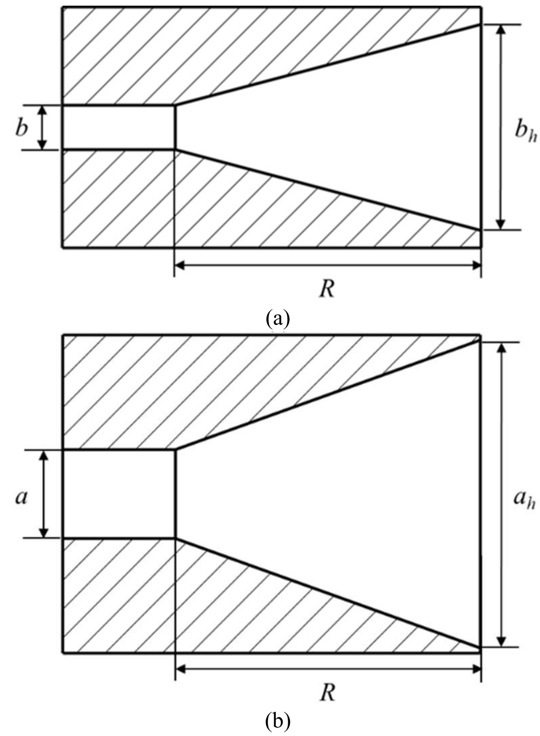

FIGURE 9. **E- and H-plane patterns of the feed (a) E- plane; (b) H-plane.**

III. THE DESIGN AND REALIZATION OF RA

A novel reflectarray has been designed based on our proposed reflectarray element. The reflectors of RAs are planar. Each element on the planar reflectarray needs to provide a suitable reflection phase for compensating the spatial phase delay to simulate the characteristics of a parabolic reflector and form a high gain beam. The required compensation phase ϕ_i at each element across the RA in xy-plane can be obtained by the following equation:

$$\phi_i = k(R_i - \overrightarrow{r_i} \times \widehat{r_0}) + \phi_0 \tag{2}$$

where ϕ_0 is the relative phase, $\hat{r}_0$ is the unit vector in the main beam direction, k is the wavenumber, $\vec{r}_i$ is the position vector

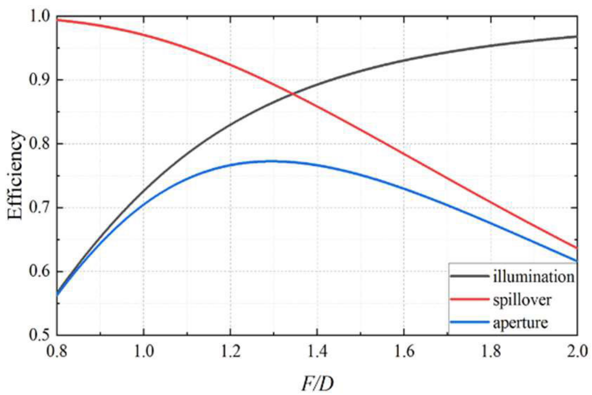

FIGURE 10. The efficiencies versus F/D.

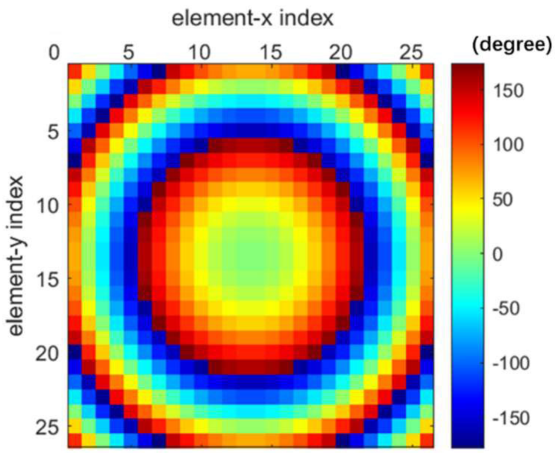

FIGURE 11. The required compensation phase distributions of the reflectarray aperture.

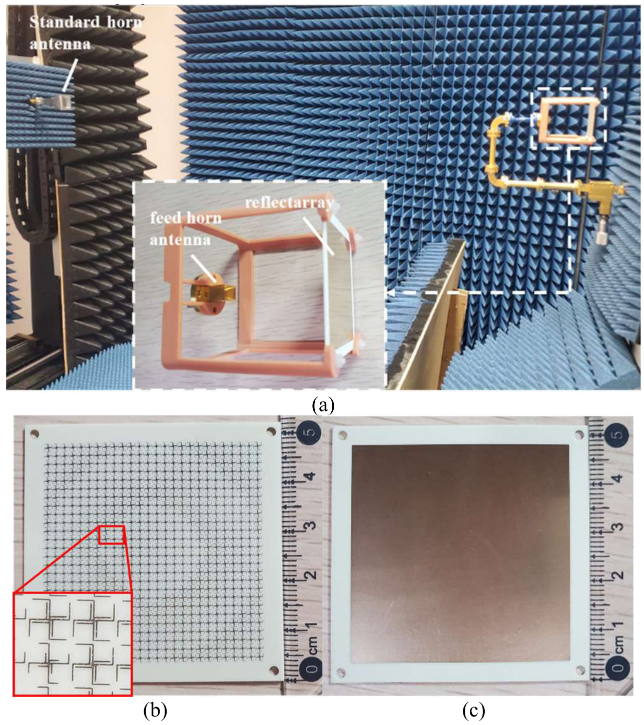

FIGURE 12. Fabrication and measurement setup. (a) Test environment. (b)Top layer of the reflectarray prototype. (c) Bottom layer of the reflectarray prototype.

TABLE 3. Geometry parameters of the proposed feed.

Parameter	Value(mm)
a	2.54
b	1.27
R	8.762
a_h	8.8
b_h	5.9

of the ith element, and R_i is the distance between the phase center and the ith element.

In this study, the planar square reflectarray contains 676 elements, and the diameter D is 44.2 mm. A horn antenna with a gain of 17 dBi at 94 GHz is selected as the feed. Fig.9 shows the patterns of E- and H-plane of the feed horn, and the detailed parameters of our proposed feed are shown in Table 3. According to reflectarray theory, the value of aperture efficiency η_a is largely depended on illumination efficiency η_i and spillover efficiency η_s, and both are related to the position of the feed horn. Therefore, the focus to diameter ratio (F/D) is a vital parameter for the performance of RAs.

Increased value of F/D will lead to the increase of illumination efficiency η_i and the decrease of spillover efficiency η_s. As shown in the Fig. 10, we found that the optimum F/D is 1.295 ($F = 57.239$ mm). After determining the position of phase center, as shown in Fig. 11, the required compensation phases at each element across the RA in xy-plane can be obtained by equation (2).

As shown in Fig. 12, we further simulated, fabricated, and measured the complete reflectarray. The fabrication process used in our proposed reflectarray is PCB technology, with a fabrication tolerance of -0.006~0mm and a minimum line space of 0.06mm. Under the condition of manufacturing error of -0.006mm, the average phase compensation error of the element is 8.14°, the gain error at the center frequency of 94GHz is -0.179GHz, and the average gain error throughout the entire frequency band is -0.116GHz, as shown in Fig.14. Using a far-field measurement system to measure the gain performance of the proposed RA. The frequency resolution of this system is 1 GHz. Both the feed horn of RA and the receive horn are firstly connected and fixed to the frequency multiplier by the metal waveguide. The feed horn of RA is connected to the transmit port of vector network analyzer. Meanwhile, the receive horn is connected to the receive port of vector network analyzer.

To observe the performance in the broadband, as shown in Fig. 13, we compare the measured and simulated radiation patterns at 89, 94, and 104 GHz, consistency between

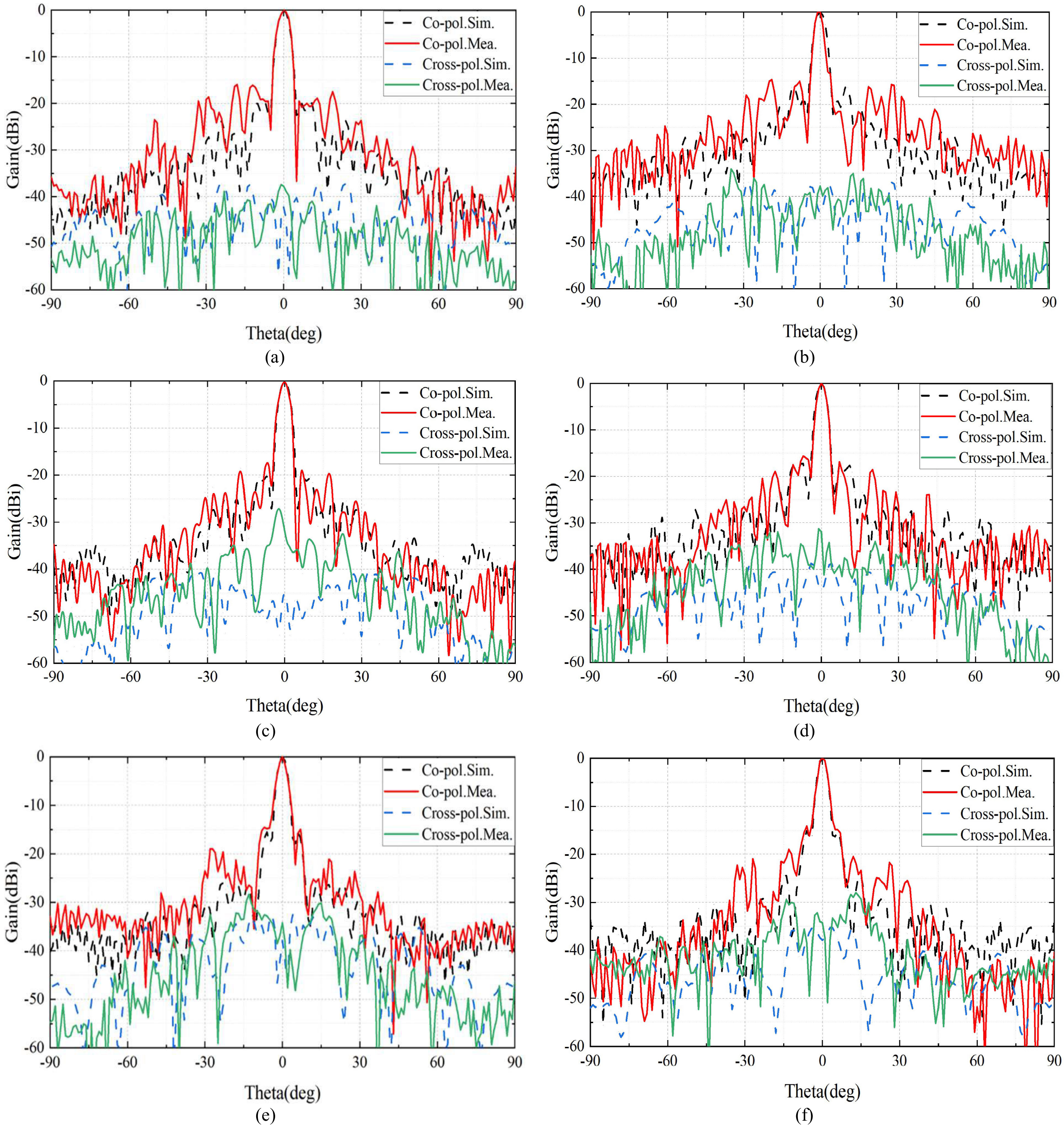

FIGURE 13. Measured radiation patterns and comparison with the simulated result. (a) E-plane and (b) H-plane at 89 GHz; (c) E-plane and (d) H-plane at 94 GHz; (e) E-plane and (f) H-plane at 104 GHz.

simulation and measurement results is good. At the center frequency of 94 GHz, the measured level of the cross-polarization is smaller than -31.9 dB, the measured level of the side-lobe is smaller than -17.3 dB in the E-plane and -15.6 dB in the H-plane. The maximum side-lobe is -14.1 dB. There are discrepancies between simulated and measured results, which are largely caused by the larger size of the connecting flange compared with feed horn. It will further result in more severe feed blocking. Besides, the obstruction of metal waveguides are also important reasons.

We use the comparative method to measure the antenna gain and further calculate the aperture efficiency. The antenna gain and aperture efficiency of the proposed RA were shown in Fig. 14. The maximum efficiency of reflectarray antenna is 53.4% and the 1-dB gain bandwidth is 25.5%, which indicating a good performance in W-band. Besides the feed blocking, there are slight discrepancy in performance between fabricated and simulated reflectarray, which cause the small differences in gain and aperture efficiency of our proposed RA.

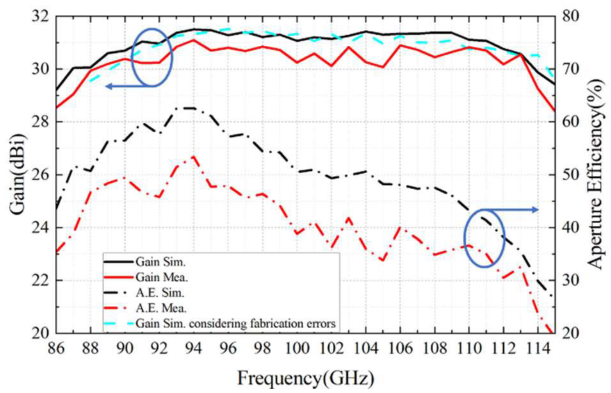

FIGURE 14. Simulated and measured gain and corresponding aperture efficiency within frequency band of 86 GHz-115 GHz.

TABLE 4. Comparison between this work and other W-band or higher band reflectarray antennas.

	Center Frequency (GHz)	process	Gain (dBi)	F/D	Air layer	Aperture Size (λ_0)	AE (%)	1-dB gain BW (%)
this work	94	PCB	31.1	1.295	N	13.78(rectangular)	53.4	25.5
[22]	88	PCB	28.4	0.67	N	17.6(circular)	22.6	6.81
[24]	90	PCB	28.5	0.94	Y	12(circular)	55.3	28.8
[25]	165	PCB	33.2	0.85	N	23.76(circular)	32.5	24.2
[26]	220	3D Printed	27.4	2.75	--	20.53(rectangular)	27.6	20.7
[27]	100	3D Printed	28	0.844	--	21.3(circular)	50.1	15

Finally, Table 4 shows the comparative results between our proposed antenna and recently published reflectarray antennas. Compared with other published antennas, our proposed antenna achieves a wider bandwidth and higher aperture efficiency under higher gain conditions.

IV. CONCLUSION

In this paper, a low-profile W-band broadband RA is proposed, which adopts a single-layer broadband multiresonant reflectarray element. A planar array is designed and measured to analyze the performance of our proposed RA, which has a 44.2 mm-diameter square aperture containing 676 elements. Our measured results shows that the proposed RA can achieve the measured peak gain of 31.1 dB, the maximum aperture efficiency of 53.4% and the 1-dB bandwidth of 25.5% (89-113 GHz). Due to its low-profile, high gain, broadband, and high aperture efficiency, this antenna has great prospects for modern research area of wireless communication systems.

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