

# A Reflectarray with Low Profile Based on the Method of Choosing the Certain Phase Constant

Wenting Li, *Member, IEEE*, Wenting Lin, Ruiyang Li, Yejun He, *Senior Member, IEEE*, Yao Gao, Chong Zhang, Steven Gao, *Fellow, IEEE*

**Abstract**—In this letter, a reflectarray antenna with a small focal diameter ratio (F/D) is presented. It is found that when the F/D is extremely small, the phase constant used in calculating the required reflection phase on the reflecting surface significantly affects the radiation pattern. In certain cases, an unsuitable phase constant can even cause the main beam to split. The unit cell is implemented as a stacked patch, and the reflecting surface comprises  $14 \times 14$  elements. The effect of the phase constant on the radiation pattern is analyzed, and two reflectarrays with phase constants of  $90^\circ$  and  $180^\circ$ , both operating at 10 GHz with an F/D of 0.05, are compared. These two reflectarrays are simulated, fabricated, and measured. The measured results show good agreement with the simulations. Within the operating band, the reflectarray with a phase constant of  $90^\circ$  achieves a maximum measured gain of 20.42 dBi, with the first sidelobe level (SLL1) below -10 dB. The radiation pattern of the reflectarray with a phase constant of  $180^\circ$  is totally distorted, resulting in a measured gain of 6.56 dBi at 10 GHz and an SLL1 of -5.8 dB.

**Index Terms**—Low profile, phase constant, reflectarrays.

## I. INTRODUCTION

Compared with traditional phased arrays, reflectarrays typically have a larger profile, which is determined by their feeding mechanism [1]. For elements on the reflecting surface, the incident angle of electromagnetic (EM) waves increases as the profile decreases, which alters the performance of these elements [2]. This constraint limits profile reduction. If the distance between the feed antenna and the reflecting surface is forcibly reduced without special design considerations, the radiation pattern may become distorted, and the gain could decrease.

Researchers have proposed different methods to reduce the profile of reflectarrays. One effective approach is the use of folded reflectarrays. In [3] - [5], the transmitarray is applied as the polarizer in folded reflectarrays, effectively reducing the antenna's physical profile. In [6] and [7], a grid polarizer is used to construct a folded reflectarray. In [8], a folded reflectarray is realized by utilizing a metal grid, which acts as the polarizer. In [9], a spherical polarizer instead of a flat one is employed to build a folded reflectarray. In [10], a circularly polarized selective surface is used as a polarizer to design the folded reflectarray. In [11], a Cassegrain reflectarray with a sub-reflector is proposed. Apart from reducing the profile by applying folded reflectarrays, researchers have also analyzed the performance of reflectarray elements under large electromagnetic wave incident angles. In [12] and [13], the forced linked boundary condition (FLBC) allows for calculating the reflection phase of elements at large incident angles. In [14], a reflectarray with an F/D of 0.117 is designed, where the reflection phase is calculated using a  $7 \times 7$  reflecting surface illuminated by a plane wave.

In this letter, an ultra-low-profile reflectarray is proposed, in which the feed antenna is implemented as a waveguide. Stacked patches are used as the unit cells to build the reflecting surface. When calculating the required reflection phase of the unit cell on the reflecting surface, an adjustable constant is added. The effect of the phase constant on the radiation pattern of the reflectarray is analyzed, and by selecting an appropriate phase constant, a reflectarray with an F/D of 0.05 is realized. The resulting reflectarray exhibits stable radiation patterns.

In this design, as the reflecting surface is square,  $D$  is the length of its sides. To the best of the authors' knowledge, the proposed reflectarray achieves the smallest F/D among all low-profile reflectarrays reported.

## II. DESIGN OF THE LOW-PROFILE REFLECTARRAY

In this section, a low-profile reflectarray operating at 10 GHz is designed. The structure of the elements on the reflecting surface is described, and a detailed analysis of the phase constant's effect on the radiation pattern is provided.

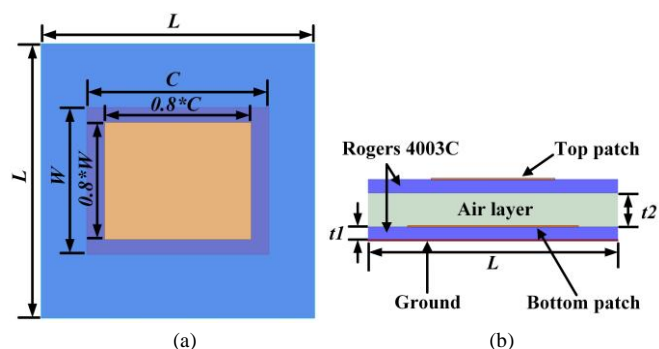


Fig. 1. Geometry of the unit cell. (a) Top view. (b) Front view.

### A. Unit Cell

The unit cell applied in the proposed reflectarray is the stacked patch, as shown in Fig. 1. Each unit cell is composed of two substrates separated by an air layer. The thickness of the air layer is  $t_2$ . Two patches are printed on the top surfaces of the substrates (Rogers 4003C), each with a thickness of  $t_1$ . The Rogers 4003C has a relative permittivity of 3.55 and a loss tangent of 0.0027. The dimensions of the top patch are 0.8 times those of the bottom patch. The size of the element is  $L \times L$ . The dimension of the bottom patch is  $W \times C$ . The reflection phase of the element is controlled by varying  $W$ . As  $W$  changes from 3 mm to 13 mm, the reflection phase varies from  $0^\circ$  to  $-557^\circ$ . The parameter values of the element are shown in Table I.

TABLE I  
PARAMETERS OF THE REFLECTARRAY ELEMENT (UNIT: mm)

Parameter	$L$	$C$	$t_1$	$t_2$
Value	15	10	0.813	2

### B. Phase Calculation

In the traditional reflectarray theory, the required phase of each element on the reflecting surface is given by [15-17]

$$\varphi(x_{mn}, y_{mn}) = -k_0 \sin \theta_b (x_{mn} \cos \phi_b + y_{mn} \sin \phi_b) + k_0 R_{mn} + \varphi_c \quad (1)$$

where  $(x_{mn}, y_{mn})$  is the coordinate of the element and  $R_{mn}$  is the distance between the phase center of the feed and the element.  $k_0$  is the wave number in free space. The direction of the required beam is

$(\theta_b, \phi_b)$ .  $\varphi_c$  is a constant.

Theoretically,  $\varphi_c$  does not affect the radiation patterns of the reflectarray and can take any value. This applies to reflectarrays with a relatively large F/D. Fig. 2 shows the radiation patterns of reflectarrays with different F/D values as  $\varphi_c$  changes. These results are obtained via full-wave simulation. In Fig. 2 (a) and (b), it is evident that when F/D is larger than 0.5, the radiation patterns are almost not affected by  $\varphi_c$ .

However, as the F/D decreases,  $\varphi_c$  begins to affect the radiation patterns of the reflectarray. In Fig. 2 (c), it can be seen that the beamwidth of the main beam changes slightly as  $\varphi_c$  varies. In Fig. 2 (d), when F/D is 0.134, the SLL1 is approximately -20 dB, with  $\varphi_c$  being 270°. However, it increases to -14 dB when  $\varphi_c$  is 90°.

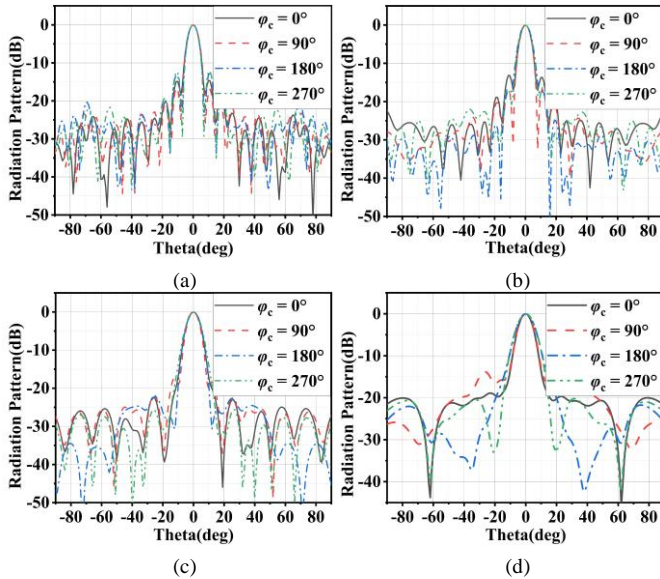


Fig. 2. Radiation patterns with different  $\varphi_c$  values when F/D is (a) 0.85, (b) 0.5, (c) 0.289 and (d) 0.134.

To demonstrate the effects of  $\varphi_c$  when F/D is extremely small, the radiation patterns of the reflectarray with the F/D of 0.05 are shown in Fig. 3. With such a small F/D, the radiation patterns are significantly influenced by  $\varphi_c$ . The radiation patterns keep stable when  $\varphi_c$  is 0°, 90°, and 270°. However, the main beam of the reflectarray splits completely when  $\varphi_c$  is 180°. In this case, the directivity decreases by approximately 13 dB, and the SLL1 deteriorates dramatically.

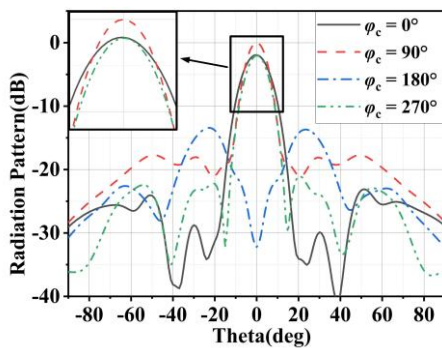


Fig. 3. Radiation patterns with different  $\varphi_c$  values when F/D is 0.05.

This phenomenon can be attributed to two main factors. First, when F/D is very small, the incident angle for each element on the reflecting surface varies substantially. Fig. 4 shows the incident angles on the reflecting surface for different F/D values. In Fig. 4 (a), most incident

angles range from 15° to 20°, with the largest angle being 30°. The largest incident angles are 45° and 60°, respectively, in Fig. 4 (b) and (c). In Fig. 4 (d), with the F/D being 0.134, most incident angles range from 50° to 70°, with the maximum angle being 75°. For certain elements, it is evident that smaller F/D values correspond to larger incident angles. When the incident angle becomes sufficiently large, the reflection phase of the element varies with changes in the incident angle [18]. Although the FLBC proposed in [12] provides a method to analyze the reflection phase of elements with arbitrary incident angles, it gives the reflection phase only when the incident angle is less than 60°.

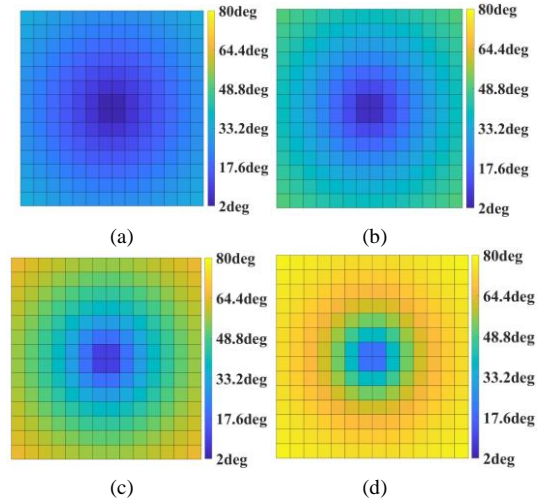


Fig. 4. The incident angles for the element on the reflecting surface when F/D is (a) 0.85, (b) 0.5, (c) 0.289 and (d) 0.134.

The second reason is that when F/D is very small, the incident angles of adjacent elements differ significantly, causing partial disruption of the periodic boundary conditions of the element on the reflecting surface. Fig. 5 shows the directivity and SLL1 for different  $\varphi_c$  values when F/D is 0.05. As  $\varphi_c$  increases from 0° to 270°, SLL1 initially increases and then decreases. The highest SLL1 reaches -9.55 dB, which occurs when  $\varphi_c$  is 180°. The highest directivity is 21.35 dBi, which is achieved when  $\varphi_c$  is 90°, and the lowest directivity, 7.93 dBi, is observed when  $\varphi_c$  is 180°. These results indicate that  $\varphi_c$  affects the radiation patterns, directivity, and SLL1 of the reflectarray when F/D is very small.

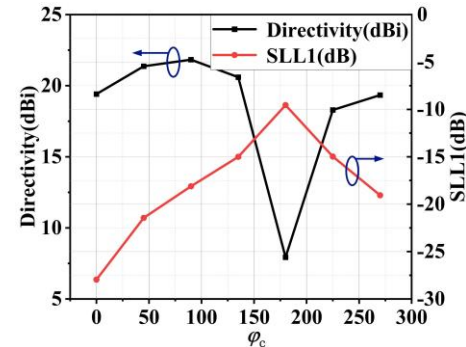


Fig. 5. Directivity and SLL1 with different values of  $\varphi_c$  when F/D is 0.05.

The elements in the central zone of the reflecting surface are analyzed, as these elements receive more EM energy from the feed antenna compared with those outside the central zone. In this zone, there are 12 elements, which are classified into types A and B, as shown in Fig. 6. Type A elements are surrounded by type B elements.

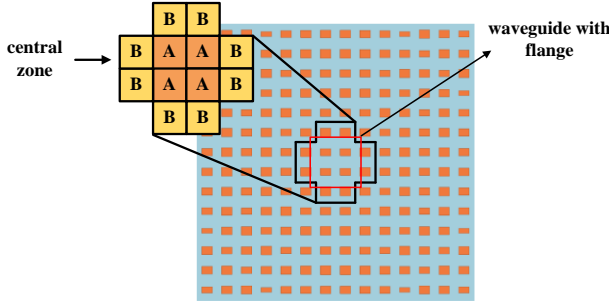


Fig. 6. The positions of type A and B elements.

Table II gives the dimensions of type A and B elements, as well as the directivity of the reflectarray for different  $\varphi_c$  values when  $F/D$  is 0.05.  $W_A$  is the  $W$  of type A elements while  $W_B$  is the  $W$  of type B elements. Table II shows when  $\varphi_c$  is  $90^\circ$ , the directivity is the highest. When  $\varphi_c$  is  $180^\circ$ , the radiation pattern is completely distorted, and the directivity decreases to 7.93 dBi. When  $\varphi_c$  is  $0^\circ$  and  $270^\circ$ , the directivity drops by approximately 2 dB compared to that when  $\varphi_c$  is  $90^\circ$ . Therefore, in the design of reflectarrays with small  $F/D$ ,  $\varphi_c$  being  $180^\circ$  should be avoided.

TABLE II  
PARAMETERS COMPARISON OF THE CENTRAL ZONE ELEMENT WITH  
DIFFERENT  $\varphi_c$

$\varphi_c$ (deg)	$W_A$ (mm)	$W_B$ (mm)	Directivity (dBi)
0	7.4	6.1	19.41
90	6.8	8.2	21.35
180	4.9	7.6	7.93
270	7.9	7.1	19.34

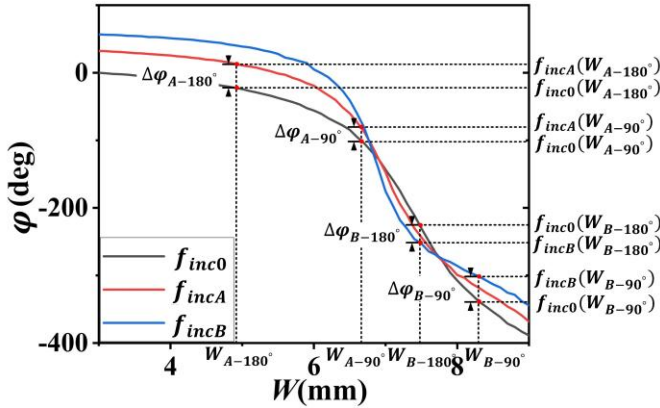


Fig. 7. The positions of type A and B elements on the phase shift curve with different incident angles, with  $\varphi_c$  being  $90^\circ$  and  $180^\circ$ .

To explain the effect of  $\varphi_c$  on the radiation pattern, type A and B elements are analyzed, as they are located in the central zone and receive more EM energy from the feed antenna compared to elements outside this zone. The positions of type A and B elements are shown in Fig. 6. The positions of type A and B elements on the phase shift curve with different incident angles are shown in Fig. 7. The reflection phase curve of the element is different under different incident angles.  $f_{inc0}$  is the reflection phase curve when the incident angle is  $0^\circ$ .  $f_{incA}$  and  $f_{incB}$  are the reflection phase curves with the incident angles for type A and B elements, respectively. In this design,  $incA$  and  $incB$  are  $55^\circ$  and  $72.5^\circ$ , respectively. When calculating the required reflection phase on the reflecting surface, the incident angle of the element is assumed to be  $0^\circ$ . The required phase difference  $\Delta\varphi$

between type A and B elements is given by

$$\Delta\varphi = f_{inc0}(W_{A-\varphi_c}) - f_{inc0}(W_{B-\varphi_c}), \quad (2)$$

where  $f_{inc0}(W_{A-\varphi_c})$  is the reflection phase corresponding to  $W_{A-\varphi_c}$  for type A elements with an incident angle of  $0^\circ$  and  $f_{inc0}(W_{B-\varphi_c})$  is the reflection phase for type B elements.

However, the practical phase difference  $\Delta\varphi'$  between type A and B elements is given by

$$\Delta\varphi' = f_{incA}(W_{A-\varphi_c}) - f_{incB}(W_{B-\varphi_c}), \quad (3)$$

where  $incA$  and  $incB$  are the incident angles for type A and B elements. Since  $\Delta\varphi$  and  $\Delta\varphi'$  are different, the difference between  $\Delta\varphi$  and  $\Delta\varphi'$  is represented by  $\Delta\varepsilon$ , which is given by

$$\Delta\varepsilon = \Delta\varphi' - \Delta\varphi = \Delta\varphi_{A-\varphi_c} - \Delta\varphi_{B-\varphi_c}, \quad (4)$$

where

$$\begin{cases} \Delta\varphi_{A-\varphi_c} = f_{incA}(W_{A-\varphi_c}) - f_{inc0}(W_{A-\varphi_c}) \\ \Delta\varphi_{B-\varphi_c} = f_{incB}(W_{B-\varphi_c}) - f_{inc0}(W_{B-\varphi_c}) \end{cases} \quad (5)$$

$\Delta\varepsilon$  is determined by  $\Delta\varphi_{A-\varphi_c}$  and  $\Delta\varphi_{B-\varphi_c}$ .  $\Delta\varphi_{A-\varphi_c}$  and  $\Delta\varphi_{B-\varphi_c}$  are related to  $\varphi_c$ . Therefore,  $\Delta\varepsilon$  is also related to  $\varphi_c$ .

Different  $\varphi_c$  values lead to different  $\Delta\varepsilon$  values. The larger  $\Delta\varepsilon$  is, the greater the error between the practical phase difference and the calculated phase difference. Therefore,  $\Delta\varepsilon$  should be as small as possible.

The absolute value of  $\Delta\varepsilon$  is given by

$$|\Delta\varepsilon| = \begin{cases} |\Delta\varphi_{A-\varphi_c} - \Delta\varphi_{B-\varphi_c}|, & \Delta\varphi_{A-\varphi_c} \cdot \Delta\varphi_{B-\varphi_c} > 0 \\ |\Delta\varphi_{A-\varphi_c} + \Delta\varphi_{B-\varphi_c}|, & \Delta\varphi_{A-\varphi_c} \cdot \Delta\varphi_{B-\varphi_c} < 0 \end{cases} \quad (6)$$

From Fig. 7, it can be seen that

$$\begin{cases} \Delta\varphi_{A-90^\circ} = f_{incA}(W_{A-90^\circ}) - f_{inc0}(W_{A-90^\circ}) > 0 \\ \Delta\varphi_{B-90^\circ} = f_{incB}(W_{B-90^\circ}) - f_{inc0}(W_{B-90^\circ}) > 0 \\ \Delta\varphi_{A-180^\circ} = f_{incA}(W_{A-180^\circ}) - f_{inc0}(W_{A-180^\circ}) > 0 \\ \Delta\varphi_{B-180^\circ} = f_{incB}(W_{B-180^\circ}) - f_{inc0}(W_{B-180^\circ}) < 0 \end{cases} \quad (7)$$

Therefore, when  $\varphi_c$  are  $90^\circ$  and  $180^\circ$ ,  $|\Delta\varepsilon|$  is given by

$$\begin{cases} |\Delta\varepsilon(\varphi_c = 90^\circ)| = |\Delta\varphi_{A-90^\circ} - \Delta\varphi_{B-90^\circ}| \\ |\Delta\varepsilon(\varphi_c = 180^\circ)| = |\Delta\varphi_{A-180^\circ} + \Delta\varphi_{B-180^\circ}| \end{cases} \quad (8)$$

When  $\varphi_c$  is  $90^\circ$ ,  $|\Delta\varphi_{A-90^\circ}|$  and  $|\Delta\varphi_{B-90^\circ}|$  counteract each other, which potentially makes  $|\Delta\varepsilon(\varphi_c = 90^\circ)|$  smaller. When  $\varphi_c$  is  $180^\circ$ ,  $|\Delta\varphi_{A-180^\circ}|$  is added by  $|\Delta\varphi_{B-180^\circ}|$ , which potentially increases  $|\Delta\varepsilon(\varphi_c = 180^\circ)|$ . Therefore, when  $\varphi_c$  is  $90^\circ$ , the practical phase difference is closer to the calculated phase difference, resulting in a better radiation pattern performance than that when  $\varphi_c$  is  $180^\circ$ . Therefore, in the design of low profile reflectarray, the chosen  $\varphi_c$  is supposed to make the  $|\Delta\varepsilon|$  as small as possible.

### C. Reflectarray Design

The proposed reflectarray consists of a waveguide acting as the

feed antenna and a reflecting surface that contains 196 elements. The size of the reflecting surface is 210 mm × 210 mm. The distance from the feed antenna to the reflecting surface is 10.5 mm. The reflectarray is fed by a BJ120 waveguide. The radiation patterns and the normalized energy distribution are shown in Fig. 8.

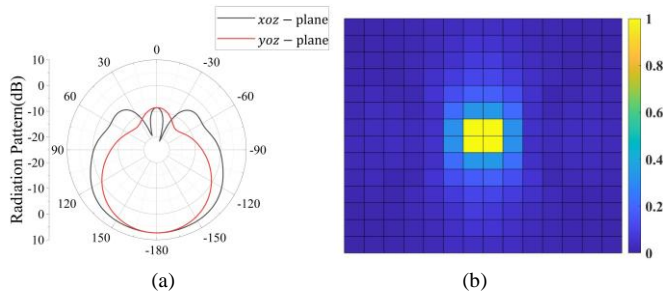


Fig. 8. (a) Radiation patterns of the feed antenna and the (b) normalized energy distribution on the reflecting surface.

### III. PROTOTYPE DEVELOPMENT AND SIMULATED AND MEASURED RESULTS

The proposed reflectarray with  $\varphi_c$  being  $90^\circ$  is simulated, fabricated, and measured. Both the simulated and measured results are shown in this section. To better illustrate the effect of the phase constant on the reflectarray, a second reflectarray with  $\varphi_c$  being  $180^\circ$  is also simulated and measured. The photographs of the reflectarrays with  $\varphi_c$  being  $90^\circ$  and  $180^\circ$  are shown in Fig. 9.

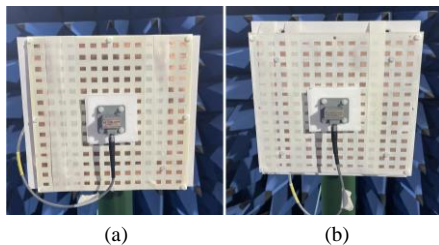


Fig. 9. Photographs of the low-profile reflectarray antenna with  $\varphi_c$  being (a)  $90^\circ$  and (b)  $180^\circ$ .

#### A. Radiation Patterns

The radiation patterns of the reflectarray with  $\varphi_c$  being  $90^\circ$  and  $180^\circ$  at 10 GHz in the operating band are shown in Fig. 10. The measured results are in good agreement with the simulated results. From 9.5 GHz to 10.3 GHz, the radiation patterns of the reflectarray with  $\varphi_c$  being  $90^\circ$  remain stable and undistorted. The simulated SLL1 is below -14 dB, while the measured SLL1 is below -10 dB. At 10 GHz, the simulated SLL1 is -15.7 dB, while the measured SLL1 is -14.5 dB. From 9.9 GHz to 10.1 GHz, the radiation patterns of the reflectarray with  $\varphi_c$  being  $180^\circ$  are totally distorted. At 10 GHz, the simulated SLL1 is -2.5 dB, while the measured SLL1 is below -5.8 dB.

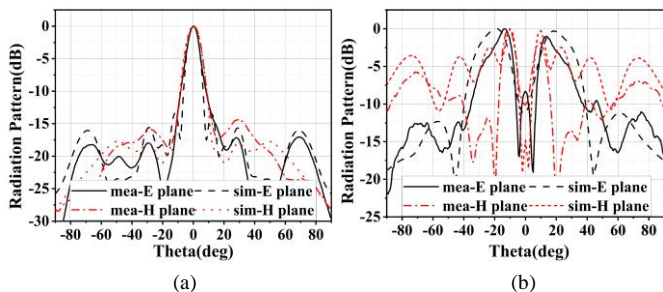


Fig. 10. The measured and simulated radiation patterns of the reflectarray at 10

GHz with  $\varphi_c$  being (a)  $90^\circ$  and (b)  $180^\circ$ .

#### B. Gain and Aperture Efficiency (AE)

Fig. 11 shows the gain and aperture efficiency of the reflectarray with  $\varphi_c$  being  $90^\circ$  and  $180^\circ$ . The measured results shift slightly to higher frequencies, mainly due to manufacturing and assembly errors. When  $\varphi_c$  is  $90^\circ$ , the simulated gain ranges from 15 to 19.42 dBi as the frequency varies from 9.5 GHz to 10.3 GHz, peaking at 9.9 GHz, with the AE being 14.5%. The measured gain ranges from 12.3 to 20.42 dBi in the working band, with the maximum measured gain occurring at 10.1 GHz and the AE being 17.55%. When  $\varphi_c$  is  $180^\circ$ , the simulated gain ranges from -0.48 to 12.8 dBi, peaking at 10.5 GHz, with the AE being 2.81%. The measured gain ranges from 3.91 to 15.26 dBi in the operating band. When  $\varphi_c$  is  $90^\circ$ , the radiation performance of the reflectarray is dramatically better.

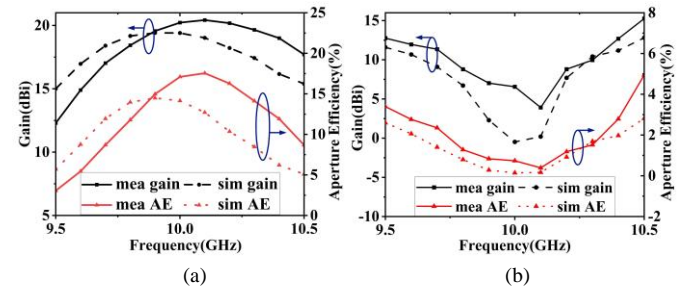


Fig. 11. The measured and simulated gain and aperture efficiency of the reflectarray with  $\varphi_c$  being (a)  $90^\circ$  and (b)  $180^\circ$ .

Some reported low-profile reflectarrays and the reflectarray proposed in this letter are compared in Table III. As some of these low-profile reflectarrays are folded reflectarrays, the ratio of the practical height from the feed to the reflecting surface to the dimension of the reflecting surface (H/D) is also compared. The proposed reflectarray in this paper achieves the smallest F/D.

TABLE III  
COMPARISON OF DIFFERENT LOW-PROFILE REFLECTARRAYS

Ref.	Working frequency (GHz)	F/D	H/D	Maximum Gain (dBi)	Maximum AE (%)	Bandwidth (%)
[3]	20/30	0.8	0.4	28.8/32.6	20.5/21.9	8.3/9(3-dB)
[5]	11/17	0.7	0.35	21.3/23.8	26.4/20	14/8(3-dB)
[6]	11-15	0.74	0.37	20.5-20.88	11.5-19.46	30(1-dB)
[8]	10	0.69	0.345	28.5	45	22(3-dB)
[9]	17	0.82	0.41	28.1	54.1	17(3-dB)
[11]	94.5	0.2	0.2	31.86	31.4	2.3(1-dB)
[12]	12	0.2	0.2	27.8	33.3	/
This work	10	0.05	0.05	20.42	17.55	7.73(3-dB)

### IV. CONCLUSION

A reflectarray with a low F/D is proposed in this letter. The performance of the reflectarray is significantly influenced by the phase constant when F/D is small. Therefore, phase constants that lead to radiation pattern deterioration should be avoided. The effect of the phase constant on the radiation pattern of the reflectarray is analyzed. Two reflectarrays with  $\varphi_c$  being  $90^\circ$  and  $180^\circ$  are simulated, fabricated, measured and compared. The comparison results indicate that different  $\varphi_c$  values affect the radiation pattern of the reflectarray with a small F/D. The maximum measured gain of the reflectarray with  $\varphi_c$  being  $90^\circ$  is 20.42 dBi, and the maximum AE is 17.55%.

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