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Design of X/Ku Dual-Band Dual-Linear Polarization Reflectarray Using Double Parallel Dipole Elements

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Abstract—Two single-layer X/Ku dual-band dual-polarization reflectarray antennas of different sizes with double parallel dipole elements are presented. Elements of the two bands are set to two orthogonal linear polarizations and placed in interlaced grid. The proposed reflectarrays operate in two frequency-bands within X-band centered at 10 GHz and Ku-band centered at 13.58 GHz. The smaller size reflectarray with elements arranged in a 13×13 grid for X-band and in a 12×12 grid for Ku-band is designed and simulated first. Based on the excellent dual-band performance of the small size reflectarray, then a larger size prototype has been designed, manufactured and measured. Measured results demonstrate the maximum gain of 28.54 dB with 50.93% aperture efficiency at 10 GHz and 31.06 dB with 51.34% aperture efficiency at 13.58 GHz, which show desirable dual-band dual-polarization radiation performance.

1. INTRODUCTION

Parabolic reflectors and arrays are playing an important role in high gain applications. However, both of them have obvious disadvantages. For parabolic reflector, the specifically curved surface makes it difficult to manufacture, in particularly at higher frequencies. It also has difficulties in achieving wide angle beam scanning. The array antenna always requires a complex feed network, which cause high transmission loss and low efficiency of antenna. In order to avoid the above mentioned disadvantages, reflectarray antenna emerged with the advantages of high gain, low profile and mass, low cost, flatness and so on. It is usually an antenna that consists of an illuminating feed antenna and a flat reflecting surface with many microstrip elements [1–3].

Dual-band operation has been a subject of intense interest in microstrip reflectarray design. In the past decades, several techniques have been proposed to achieve dual-band performance of the reflectarray, such as elements printed on a single layer [4–6] or two layers [7–9], or using frequency selective surface (FSS)-backed structures [10–12].

A multiresonance curved double cross element is presented in [4] to achieve dual-band dual linear polarization performance and some simulations have been carried out to confirm the negligible mutual effect between the elements of the two bands. In [5], a single layer element consists of a circular patch with slots and two phase delay lines attached to the patch is utilized to develop dual-band reflectarray operating in X- and K-bands. For the case of two closely separated frequencies, a single layer element consisting of a square ring and patch loaded with slots was suggested in [6]. The required phase shifts in two bands are achieved by varying the size of element and good performance of reflectarray was achieved.

For a two-layer structure, ring with gaps was used as the element to develop a dual-band circularly polarized (CP) reflectarray operating in C- and Ka-bands [7]. In another two-layer configuration, thin

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membranes were utilized to achieve X/Ka-dual-band CP performance and high efficiency was achieved at both bands [8]. However, using a two-layer configuration has certain disadvantages such as additional cost, manufacture complexity and increased weight.

Using FSS-backed structure, a circularly polarized reflectarray operating at L- and Ka-band is presented in [10]. The Ka-band reflectarray with a FSS ground-plane (which consists of many concentric dual-loop element) above the L-band array and excellent dual-band performance results were achieved. In [11], a double square ring structure was used as the element for linearly polarized in both the X- and Ka-bands. A single square ring was used for the construction of the FSS ground-plane for Ka-band and a solid ground-plane was defined for the X-band. A dual-band FSS consisting of cross ring elements and square ring elements were proposed in [12]. The FSS is used as a reflective ground-plane in order to reduce the coupling between the elements of the two bands. However, most of the reflectarrays mentioned above operate in two widely separated frequencies. There are few researches on a single-layer, dual-band dual-polarization reflectarray covering two closely separated frequencies [13], which can be used in dual-link satellite communications.

In this paper, two different sizes single-layer dual-band dual-polarization reflectarray antennas operating in X-band centered at 10 GHz and Ku-band centered at 13.58 GHz are presented. Two orthogonal sets of double parallel dipoles, each individually for one band, are used as the cell element. The smaller size reflectarray is composed of 13×13 elements for X-band and 12×12 elements for Ku-band. Simulated results show excellent performances of dual band dual polarization. Then, a larger size reflectarray is designed, manufactured and tested. Only one pyramidal horn antenna is designed as feed of the dual-band reflectarrays for both bands in a fixed position with two orthogonal polarization directions. Measured results show the maximum gain of 28.54 dB at 10 GHz and 31.06 dB at 13.58 GHz and more than 50% efficiency are achieved at both frequency bands.

2. ELEMENT DESIGN AND PHASE CHARACTERISTICS

The proposed reflectarrays are composed of two orthogonal sets of double parallel dipoles elements which configuration and arrangement are illustrated at Fig. 1. The double parallel dipoles for both bands are interlaced on top of a single-layer substrate with the same periodicity of L. The periodicity L is set to 14 mm, which equals 0.47 wavelengths at 10 GHz and 0.63 wavelengths at 13.58 GHz. The substrate is F_4B laminates with relative permittivity of 2.25 and thickness of $h = 1.5$ mm. The length of the short dipole b is proportional to the length of long dipole a with ratio k (i.e., $b = k \times a$). The gap between the two dipoles is d and the widths of the two dipoles are both w.

For analyzing the reflection phase characteristics of the element, simulations are analyzed using HFSS, and master-slave boundaries with Floquet port are used to model periodic structures. Figs. 2–4

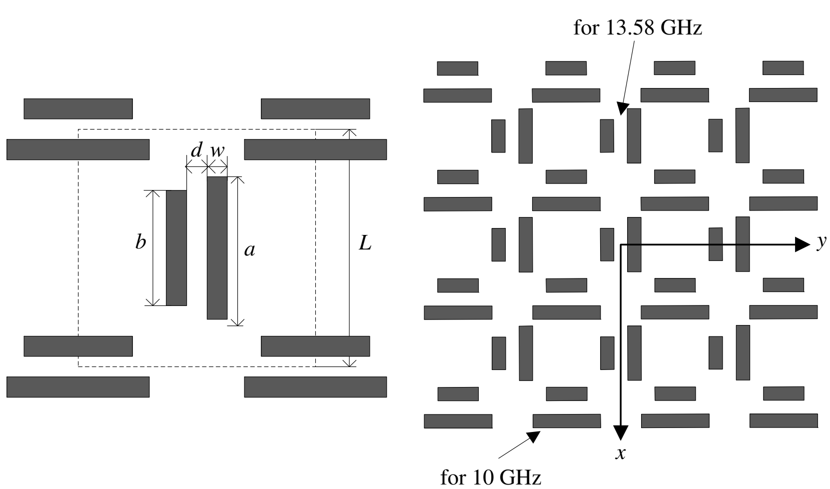
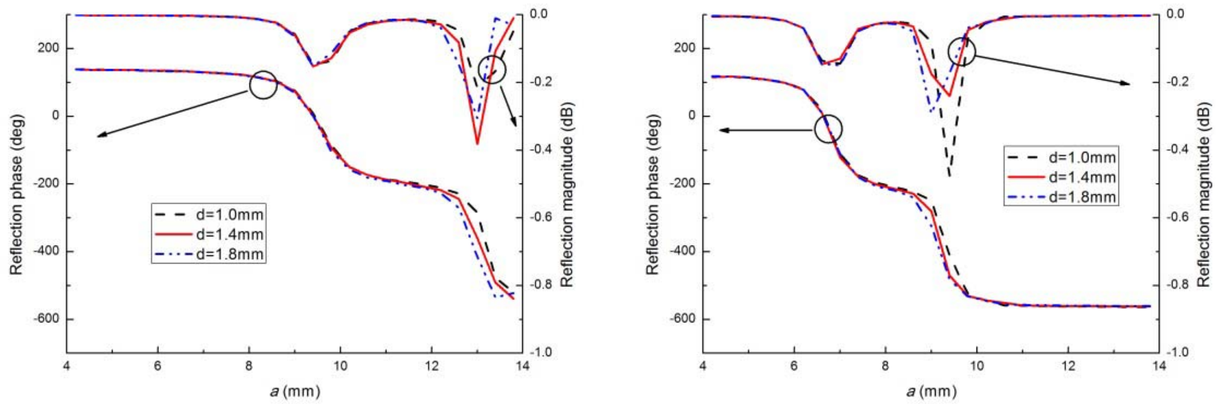
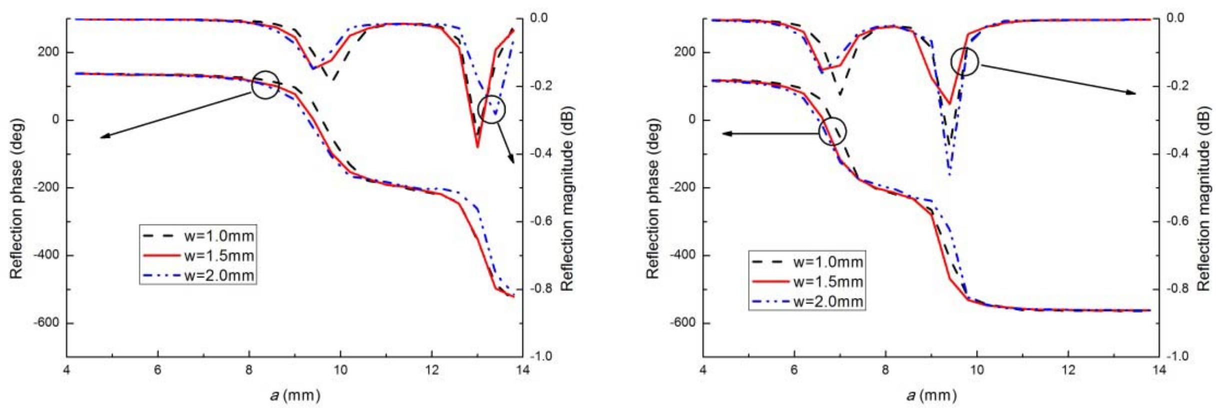


Figure 1. Schematic view of double parallel dipoles elements.



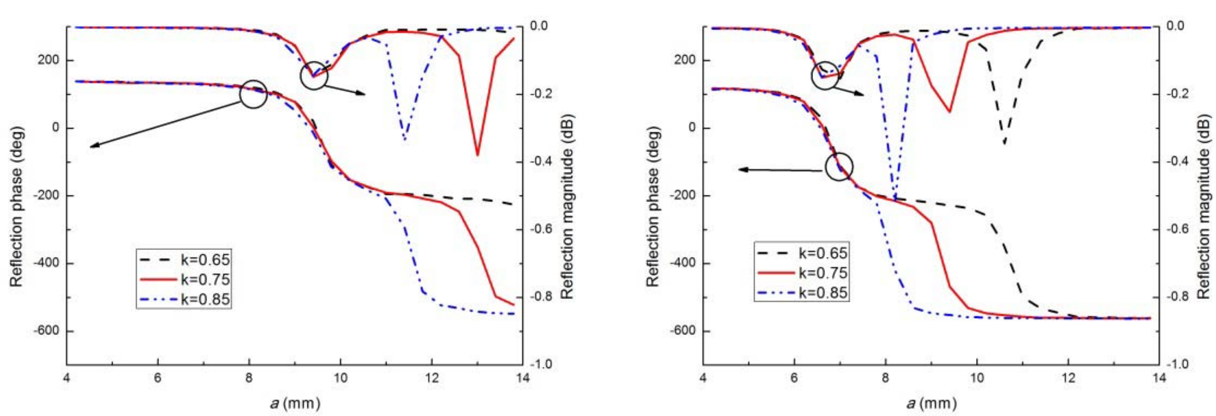
(a) (b)

Figure 2. Reflection phase and magnitude against a for different values of d. ($w = 1.5\,\text{mm}$, $k = 0.75$). (a) 10 GHz. (b) 13.58 GHz.



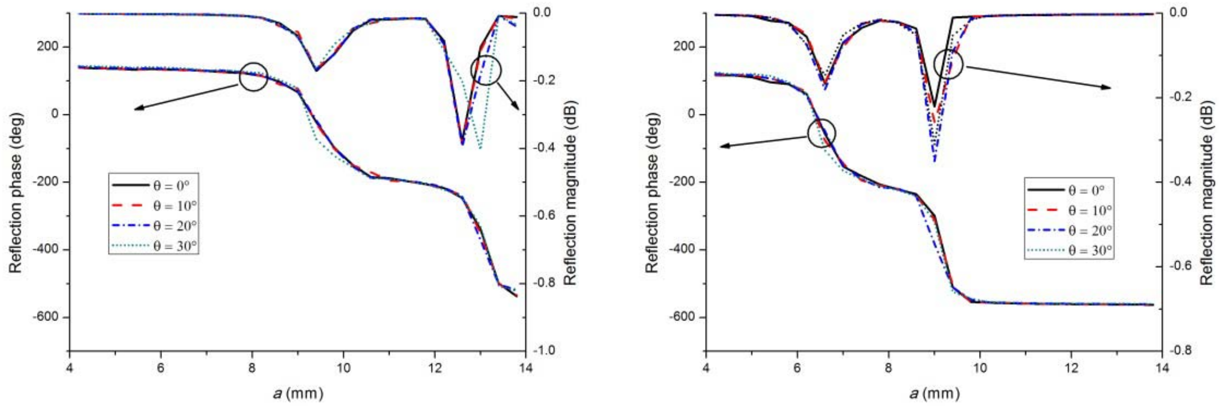
(a) (b)

Figure 3. Reflection phase and magnitude against a for different values of w. ($d = 1.4\,\text{mm}$, $k = 0.75$). (a) 10 GHz. (b) 13.58 GHz.



(a) (b)

Figure 4. Reflection phase and magnitude against a for different values of k. ($d = 1.4\,\text{mm}$, $w = 1.5\,\text{mm}$). (a) 10 GHz. (b) 13.58 GHz.



(a) (b)

Figure 5. Reflection phase and magnitude at different oblique incidence angles. (a) 10 GHz. (b) 13.58 GHz.

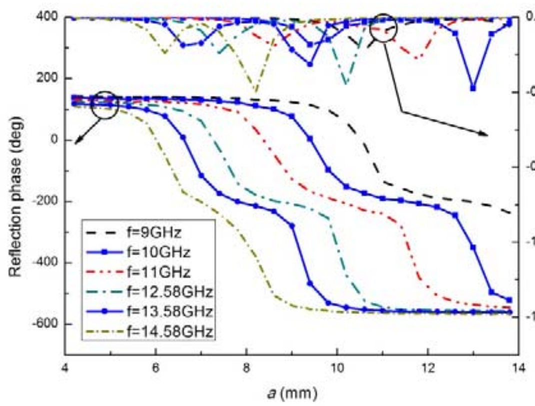


Figure 6. Reflection phase and magnitude against a at X- and Ku-band for different frequencies.

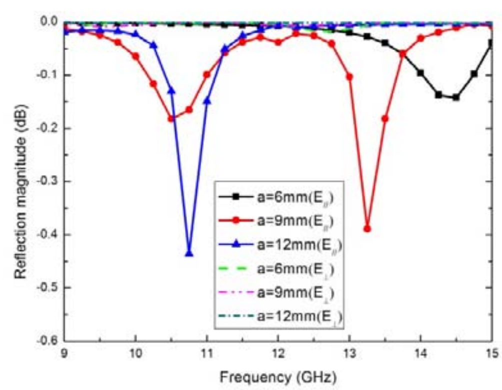


Figure 7. Reflection magnitude against frequency for both polarization.

show the influence of element parameters on reflection phase and magnitude curves at the two bands. It can be concluded that the best values of these parameters to have desired reflection phase and magnitude curves at the two bands are as follows: $d = 1.4\,\mathrm{mm}$, $w = 1.5\,\mathrm{mm}$, $k = 0.75$. The reflection phase and magnitude at different oblique incidence angles are depicted in Fig. 5. It can be concluded that incidence angles have little influence on reflection phase and magnitude. Fig. 6 shows the phase and magnitude response of the element for different frequencies at X- and Ku-band. It can be concluded that by varying the length of long dipole a from 4.2 to 13.8 mm, 650° reflection phase range at 10 GHz and 680° reflection phase range at 13.58 GHz are obtained, which are much more than the minimum required range of 360°.

Figure 7 shows the reflection magnitude against frequency for both polarizations. $E_{//}$ represents the polarization of the incident wave parallel to the length direction of the double parallel dipoles, and $E_{\perp}$ represents the polarization of the incident wave perpendicular to the double parallel dipoles. It can be concluded that the reflection magnitude are better than 0.45 dB for different values of a, regardless of which case ($E_{//}$ or $E_{\perp}$). Fig. 8 shows the coupling of the double parallel dipoles between the two orthogonal directions at 10 GHz. The polarization of the incident wave is set perpendicular to the length direction of the double parallel dipoles. The reflection phase is calculated with respect to the length of the double parallel dipoles. It can be concluded that the reflection phase hardly changes when the

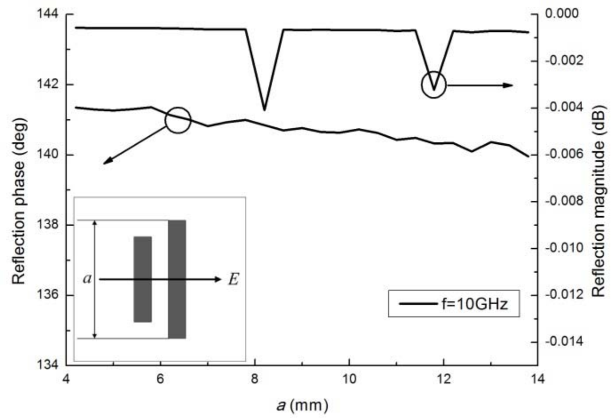


Figure 8. Reflection phase and magnitude against a at 10 GHz when the polarization of the incident wave is set perpendicular to the length direction.

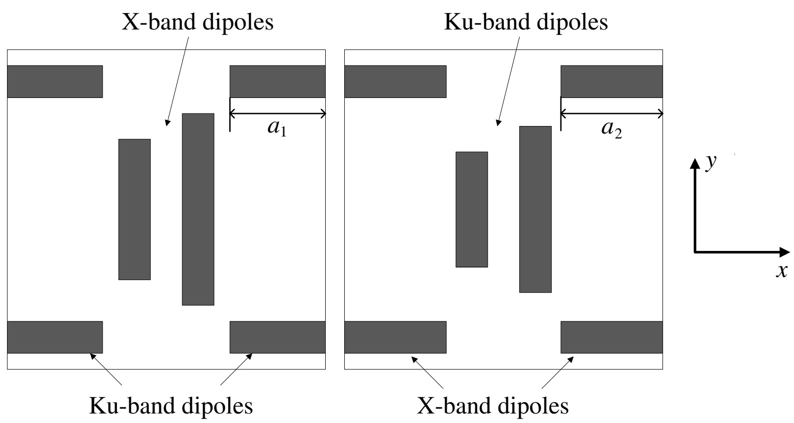
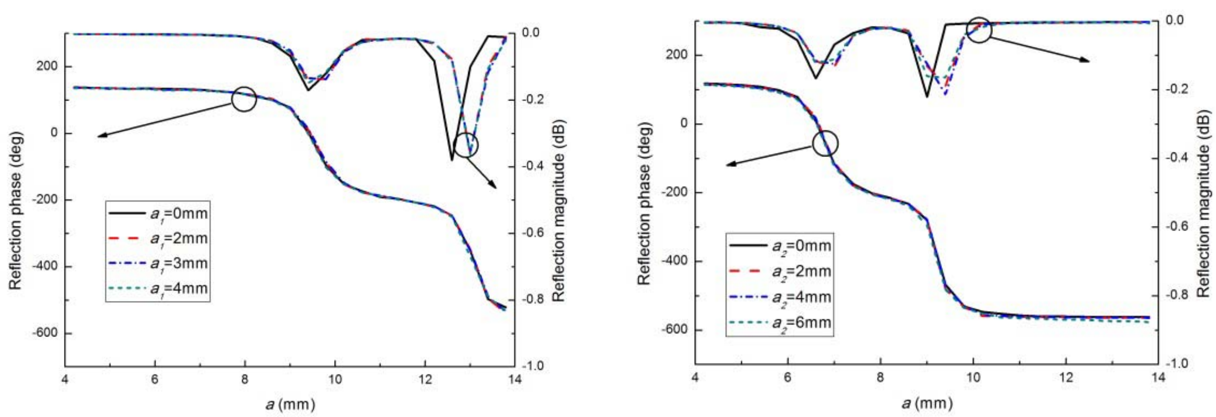


Figure 9. The unit cell used for analyzing the coupling between the elements of the two bands. (a) The effect of Ku-band dipoles on X-band dipoles. (b) The effect of X-band dipoles on Ku-band dipoles.



(a) (b)

Figure 10. Effect of coupling on the reflection phase. (a) The effect of Ku-band dipoles on X-band dipoles. (b) The effect of X-band dipoles on Ku-band dipoles.

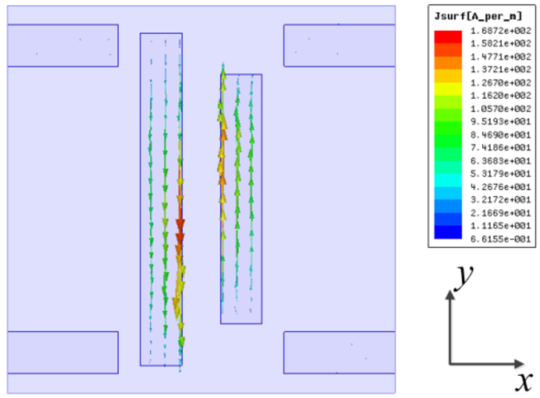
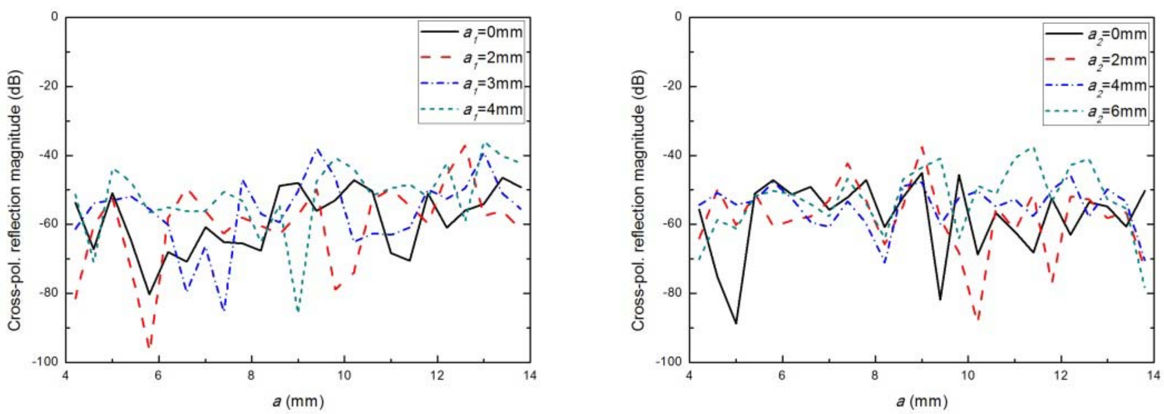


Figure 11. Current distribution on the element surface at 10 GHz.



(a) (b)

Figure 12. Cross-polarized reflection magnitude of the dipoles. (a) 10 GHz. (b) 13.58 GHz.

polarization of the incident wave perpendicular to the length direction of the double parallel dipoles. Similar results can be also achieved at 13.58 GHz, which mean low coupling levels for the double parallel dipoles between the two orthogonal directions.

The mutual coupling between the dipoles of two bands is also investigated. To evaluate the effect of the dipoles at one band on the dipoles at the other band, the unit cells shown in Fig. 9 are used to analyze the mutual coupling. The coupling between the elements of the two bands is shown in Fig. 10. It can be concluded that Ku-band dipoles have little effect on the reflection phase and magnitude of X-band and vice versa, which indicate low mutual coupling levels for the dipoles between the two bands. Fig. 11 shows the electric current vector on the surface of dipoles element (cf. Fig. 9) when the element is excited by a y-polarized plane wave. It can be seen that most of the current is y-directed and there is almost no x-directed current which is responsible for cross-polarization. Similar results can be also achieved at 13.58 GHz. Fig. 12 shows the cross-polarized reflection magnitude of the dipoles. It can be seen that the cross-polarized reflection magnitude is much smaller than the co-polarized reflection magnitude in Fig. 10, which indicates a substantial reduction in antenna cross-polarization level. It can be concluded from Figs. 10–12 that low mutual coupling levels and cross-polarization level for the dipoles are achieved. The very low mutual coupling levels between the two bands indicate that the coupling has little effect on the performance of the reflectarray, such as cross-polarization, efficiency and gain.

3. REFLECTARRAY DESIGN AND PERFORMANCE

With the double parallel dipoles mentioned in Section 2, two different sizes single-layer dual-band dual-polarization prime focus reflectarray antennas are designed. The double parallel dipoles for both bands are interlaced on top of substrate with the same periodicity of $L = 14$ mm. By varying a from 8.4 mm to 12.3 mm for X-band and 5.8 mm to 8.25 mm for Ku-band, required phase shift can be satisfied at the two bands. The smaller size reflectarray with elements arranged in a 13×13 grid for X-band (centered at 10 GHz) and in a 12×12 grid for Ku-band (centered at 13.58 GHz) is printed on a 1.5-mm F_4B substrate ($\varepsilon_r = 2.25$). The geometry of the small reflectarray is shown in Fig. 13. The X-band of the reflectarray is designed to work in the y-polarization and the Ku-band is designed to work in x-polarization.

The focal distances F (distance between the reflectarray and the feed) of the two bands are set to the same value of 134.4 mm. Fig. 14 shows the simulated radiation patterns of the small reflectarray at 10 GHz and 13.58 GHz. As shown in Fig. 14, the side lobe levels are −16.3 dB in E-plane and −18 dB in H-plane with regard to the peak gain at 10 GHz. The side lobe levels at 13.58 GHz are −17.4 dB in E-plane and −17.1 dB in H-plane with regard to the peak gain. The simulated results show a excellent performance of dual band dual polarization radiation performance.

Based on the good performance of the small size reflectarray, a larger size reflectarray with elements arranged in a 25×25 grid for X-band (centered at 10 GHz) and in a 24×24 grid for Ku-band (centered at 13.58 GHz) is designed, manufactured and tested. Fig. 15 shows a prototype of the reflectarray. The larger size reflectarray is octagon with aperture size D of 350 mm. The focal distances of the large

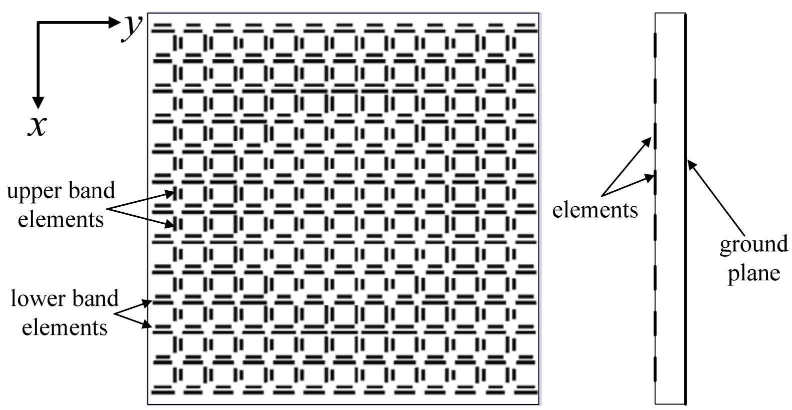


Figure 13. The geometry of the small reflectarray.

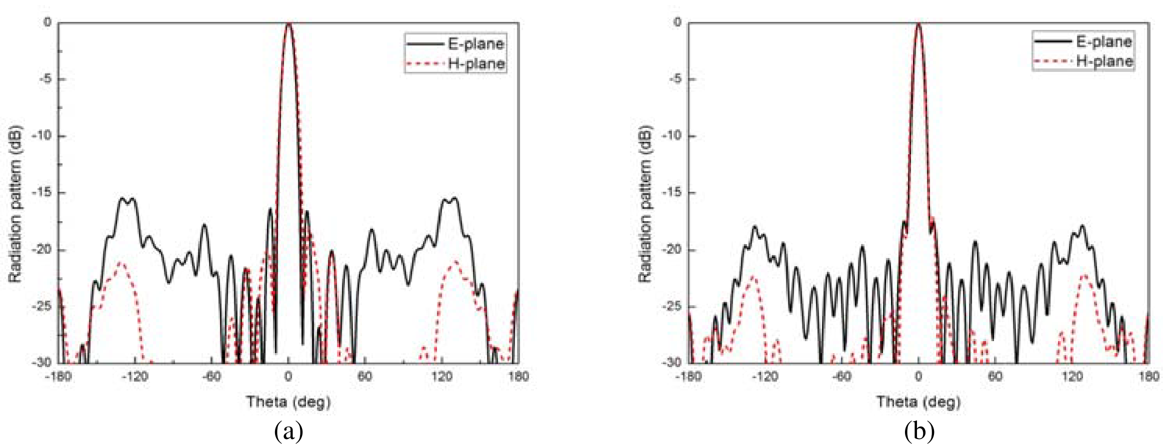


Figure 14. Simulated radiation patterns of the small reflectarray. (a) 10 GHz. (b) 13.58 GHz.

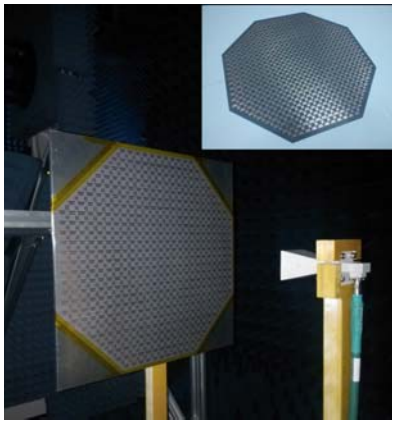


Figure 15. Prototypes of the large reflectarray.

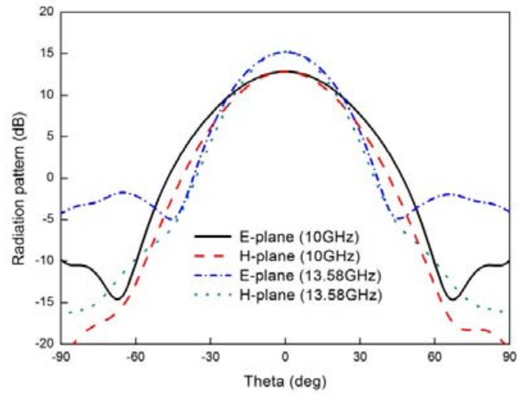


Figure 16. Simulated radiation patterns of the feed horn.

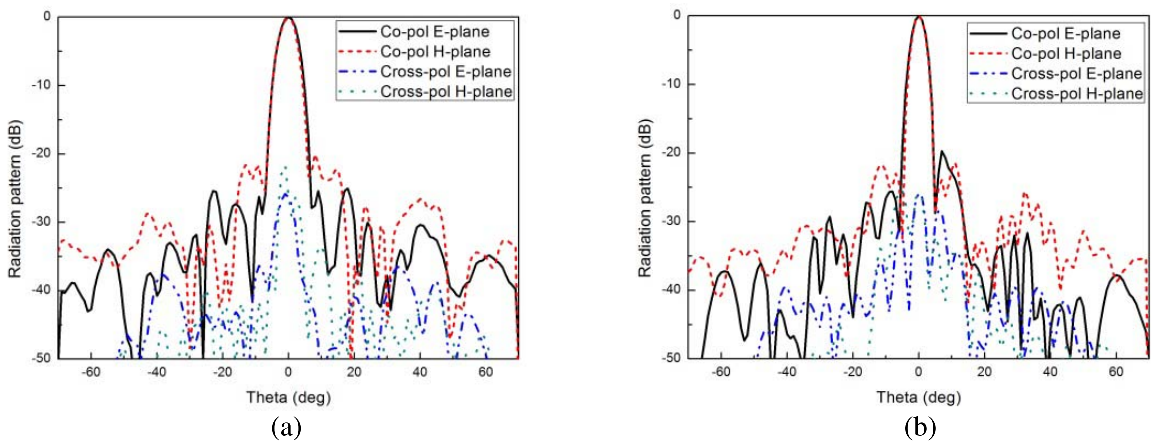
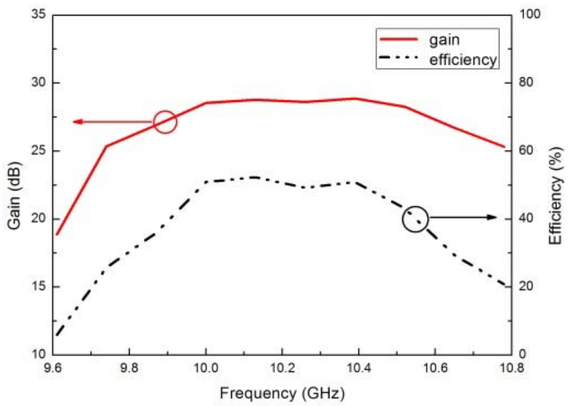


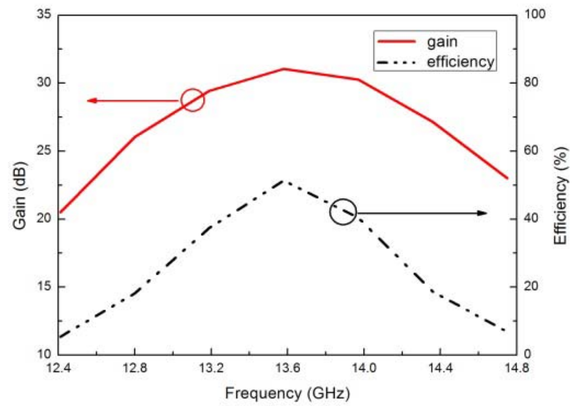
Figure 17. Measured radiation patterns of the large reflectarray. (a) 10 GHz. (b) 13.58 GHz.

reflectarray at the two bands are set to the same value of 268.8 mm. The F/D ratio is 0.768 at X-band and 0.8 at Ku-band. Only one broadband pyramidal horn antenna is designed as feed of the reflectarray for both bands in a fixed position with two orthogonal polarization directions. The simulated radiation patterns of the feed pyramidal horn antenna at 10 GHz and 13.58 GHz are shown in Fig. 16.

The measured radiation patterns of the large reflectarray for 10 GHz and 13.58 GHz are shown in Fig. 17. The measured peak gain is 28.54 dB at 10 GHz with the sidelobe levels of −25 dB in E-plane and −22 dB in H-plane. The maximum cross-polarization levels is −26 dB in E-plane and −22 dB in H-plane. At 13.58 GHz, the measured peak gain is 31.06 dB with the sidelobe levels of −20 dB in E-plane and −22 dB in H-plane. The maximum cross-polarization levels is −26 dB in E-plane and −25.5 dB in H-plane. The measured aperture efficiency ε is calculated using $\varepsilon = G_m/D_{\text{ideal}}$, $D_{\text{ideal}} = 4\pi A/\lambda_0^2$ where G_m is the measured gain, D_{ideal} is the ideal directivity, A is the aperture area of the reflectarray. After calculating, the D_{ideal} is 31.47 dB at 10 GHz and 33.95 dB at 13.58 GHz. The NSI planar near-field system is used to measure the performances of the fabricated prototype. The measured directivity of the reflectarray is 30.12 dB at 10 GHz and 32.7 dB at 13.58 GHz. After calibrated by the standard gain horn, the measured gain of the reflectarray is 28.54 dB at 10 GHz and 31.06 dB at 13.58 GHz. According to the formulas above, the efficiency of 50.93% at 10 GHz and 51.34% at 13.58 GHz are achieved. Measured gain and efficiency of the large reflectarray versus frequency for X- and Ku-band are shown in Fig. 18. It



(a)



(b)

Figure 18. Measured gain and efficiency of the large reflectarray versus frequency. (a) X-band. (b) Ku-band.

Table 1. Comparison of the proposed reflectarray performance with previous works.

Reference	This work	[7]	[12]	[13]	[14]	[15]
Frequency (GHz)	10 13.58	7.3 31.75	8 14	12 14	10.4	12/13 14/15.5
Gain (dB)	28.54 31.06	28.2 40.3	18.3 22.1	32.4 32.7	17.1	23.24/22 25.38/26
Efficiency (%)	50.93 51.34	46 38	29.3 27.7	60 60	-	25/16 30/28
1-dB gain BW (%)	5.5 2.9	7.1 6.3	-	24 19	-	-
3-dB gain BW (%)	10 10.7	-	-	-	-	2.5/2.5 3.45/4.16
Sidelobe level (dB)	< -22 < -20	< -17.3 < -18.7	< -14 < -13	< -19 < -23	-	12.47/15.7 16.8/20
Cross-pol level (dB)	< -22 < -25.5	< -21 < -29	-	< -25 < -26.5	-	$< -30/ < -30$ $< -30/ < -30$
Number of layers	1	2	1	1	1	1
Polarization	Linear	Circular	Linear	Linear	Linear	Linear
Loss (dB) (element)	< 0.4 < 0.3	-	< 0.7 < 0.6	-	< 0.3	-

can be concluded that the 1-dB gain bandwidth of 5.5% for X-band and 2.9% for Ku-band are achieved. The narrow bandwidth performance of the reflectarray could be improved by increasing the thickness of the substrate or inserting an air layer between the substrate and the ground plane. The aperture efficiency of the reflectarray is 50.93% at 10 GHz and 51.34% at 13.58 GHz, which shows high efficiency in both bands.

Table 1 lists the performance of the proposed reflectarray and some previous published works. It can be concluded that the proposed reflectarray has the advantages of high efficiency and low sidelobe level compared to the designs in [7, 12, 14, 15].

4. CONCLUSION

Two different sizes X/Ku dual-band dual-polarization prime focus reflectarray antennas with a single-layer substrate are designed in this paper. The proposed reflectarrays operate in two closely separated frequency bands at two orthogonal polarization directions. Double parallel dipoles are used as the reflectarray elements for both bands and placed in interlaced grid. Based on the good performance of the smaller size reflectarray, a larger size reflectarray is fabricated and measured. The measured results show a good radiation performance with high efficiency in both bands.

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