A Highly Efficient Dual-Band Transmitarray Antenna Using Cross and Square Rings Elements

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Abstract **─** In this paper, a highly efficient dual-band transmitarray antenna using cross and square rings elements is presented for X and Ku bands. The dual-band transmitarray is designed for downlink/uplink frequencies of Ku band satellite communications. The transmitarray element consists of four metal patches and two dielectric substrates. The metal patch is printed on both sides of the substrate. By optimizing the parameters, the transmitarray element can achieve a transmission phase coverage greater than 360° and work independently in both frequency bands. Then, a method to select the size of the element is proposed, so that all the elements in the array can realize the transmission phase of the two frequencies as much as possible. A 201-elements transmitarray antenna is fabricated and measured and the band ratio of the antenna is 1.13. The measured maximum gain at 11.5 GHz is 22.4 dB, corresponding to the aperture efficiency is 52.7%. The measured maximum gain at 13 GHz is 24.2 dB, corresponding to the aperture efficiency is 62.4%. The 1-dB gain bandwidths are 9.7% (10.8-11.9 GHz) at X band and 9% (12.6-13.8 GHz) at Ku band.

Index Terms **─** Dual-band antenna, highly efficient, transmitarray antenna.

I. INTRODUCTION

TAs the transmitting and receiving device of wireless communication system, antenna directly affects the performance of communication system [1-3]. Compared with parabolic antenna, planar array antenna uses horn antenna to feed, which avoids complex feeding network. It also has the characteristics of multi-frequency band, miniaturization, low profile and high gain. Planar array antenna includes reflectarray antenna (RA) and transmitarray antenna (TA). Compared with the RA [4-6], the feed of the TA and the radiated electric field are not on the same side, which can completely eliminate the influence of feed occlusion on the antenna performance and has a huge advantage in realizing high-gain directional beam. Therefore, the research of transmitarray antenna has received more and more scholars' attention.

Although the research of transmitarray antenna is relatively mature, it still has the disadvantages of narrow bandwidth and low efficiency. Therefore, in order to meet the needs of communication system, it is necessary to develop dual-band transmitarray antenna. In [7], a triple-layer dual-band transmitarray antenna using orthogonal slots was proposed. The band ratio of the antenna was 1.46 and its 1-dB bandwidth was 7.5% and 4.28% at the center frequency of 12GHz and 17.5 GHz, respectively. In [8], a multilayer dual-band (20/30GHz) transmitarray antenna using cross dipole was reported. The aperture efficiency of the TA was 35% and 50%. However, the transmission phase of the TA was less than 360°. [9] presents a dual-band, dual-polarised metallic slot transmitarray antenna. The antenna does not contain dielectric substrate and consists of only three thin metallic layers. Due to the high transmission loss of the TA element, the aperture efficiency of the TA was only 34.0% and 37.2% at 11 GHz and 12.5 GHz, respectively. A dual-band transmitarray antenna using four-layer metallic slots was designed in [10]. The band ratio of the antenna was 1.5 and its aperture efficiency were 52% and 53% at the center frequencies of 12 GHz and 18 GHz, respectively.

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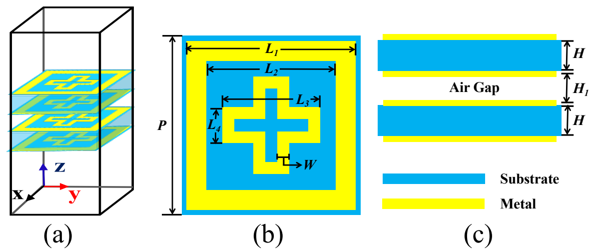


Fig. 1. Geometric model of the dual-band TA element: (a) three-dimensional plot, (b) top view, and (c) lateral view.

Table 1: Design parameters of the dual-band TA element

Parameter	Value
P	9mm
H	1.5mm
H_1	1.5mm
L_1	8.5mm
L_2	Vary
L_3	L_2-1.6mm
L_4	1.8mm
W	0.6mm

The TA element of different frequency bands were placed in the same plane by special arrangement so that the transmitarray antenna could works in both frequency bands. However, this arrangement will be limited by the space, the design flexibility will be greatly reduced, and the coupling between high and low frequency TA elements is large. Other researches on dual-band transmitarray antenna were reported in [11-13].

In this work, an efficient dual-band transmitarray antenna using cross and square rings elements with low frequency separation is presented. In order to meet the requirements of satellite communication, the downlink and uplink frequency of the transmitarray antenna is 11.5/13 GHz, the band ratio of the antenna is 1.13. The chapters of the article are arranged as follows. Section I is the introduction of the transmitarray antenna. Section II is the structure and performance analysis of the TA element. In Section III, a method is proposed to select the element parameters so that all the elements in the array can phase compensate as much as possible in both frequency bands. The simulation and measurement results of the TA are also given in Section III. Finally, Section IV is the conclusion of this paper.

II. DUAL-BAND TA ELEMENT DESIGN

A. The TA element structure

The traditional dual-frequency TA is designed by arranging the element of different frequency bands in the same plane through reasonable space allocation, so that the TA could work independently in both frequency bands [11]. However, this design method is limited by space and only applicable to antennas with large band ratio. The TA element proposed in this paper can use the same structure to work simultaneously in both frequency bands, which can avoid the problem of the arrangement of high and low frequency elements. The band ratio of the TA is only 1.13. The structure of the TA element is shown in Fig. 1. In order to achieve sufficient transmission phase range, the TA element consists of four patches and two dielectric substrates. The patches are printed on either side of the dielectric substrate. Each patch consists of a cross and a square ring. There is an air gap between the two dielectric substrates, the height of which is equal to the thickness of the dielectric substrates. The relative permittivity and loss tangent of the dielectric substrate are 3.5 and 0.0027, respectively.

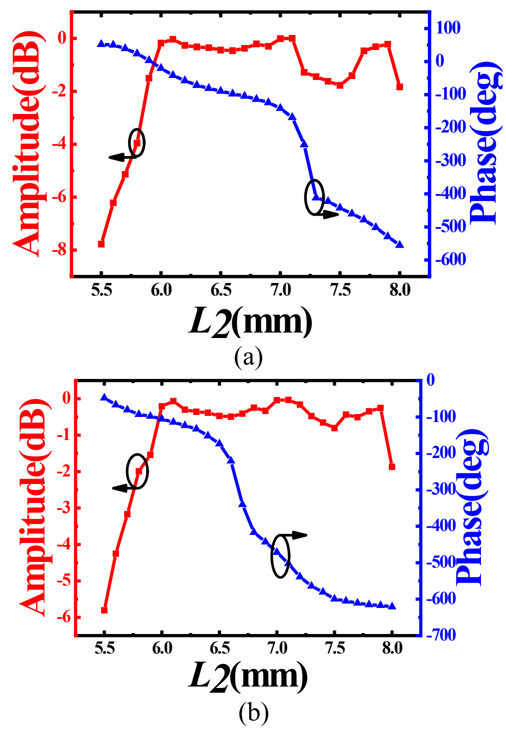


Fig. 2. The transmission amplitude and transmission phase versus L_2: (a) Freq = 11.5 GHz and (b) Freq = 13 GHz.

In this design, high frequency electromagnetic simulation software Ansys HFSS is used to simulate and optimize the TA element. Master and slave boundary is selected to simulate planar periodic structural surfaces. In order to simplify the design and analysis while increasing the polarization stability of the TA element, the designed element adopts symmetrical structure in the X and Y directions. The peripheral size L_1 of the TA element is fixed, which can effectively suppress the phase error caused by coupling effect between the elements. By optimizing the size of the TA element, the transmission phase of the element is greater than 360°. The specific size of the TA element is shown in Table 1. As shown in this table, the period *P* of the TA element is 9 mm (0.346 λ_{lower} at 11.5 GHz and 0.391 λ_{higher}). By using cross and square rings structures, there are eight adjustable parameters of the TA element. By optimizing a variety of adjustable parameters, the phase coverage of TA element can be greater than 360° and has a good oblique incidence performance. The period of the TA element are less than 0.5λ at both low and high frequencies, so the element has the advantage of high efficiency.

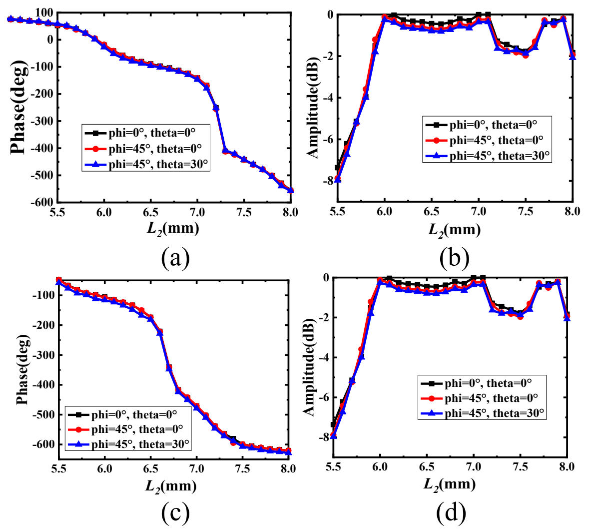


Fig. 3. Transmission coefficient versus L2 at different oblique incidence angles: (a) transmission phase at 11.5 GHz, (b) transmission amplitude at 11.5 GHz, (c) transmission phase at 13 GHz, and (d) transmission amplitude at 13 GHz.

B. Transmission characteristic of the TA element

The transmission amplitude and transmission phase versus L_2 of the designed TA element in both frequency bands is shown in Fig. 2. As shown in this figure, the transmission phase of the TA element is greater than 360° in both frequency bands. At low frequency, when L_2 is greater than 6mm, the transmission amplitude of the element is always greater than -2dB. At high frequency, when L_2 is greater than 6mm and less than 7.9 mm, the transmission amplitude of the element is greater than -1 dB. This indicates that the TA element can be used in the design of dual-band transmitarray antenna. Since the area of the transmitarray is larger than a few wavelengths, most of the TA elements in the array are illuminated by oblique incident waves, the effect of oblique incidence should also be considered. φ is the angle between the incident wave and the *X*-axis, θ is the angle between the incident wave and the *Z*-axis. Figure 3 shows the transmission coefficient of the TA element at different incident angles. As can be seen from the figure, there is little difference between the transmission phase and transmission amplitude of oblique incident waves (φ from 0° to 45° and θ from 0° to 30°) and normal incident wave. Therefore, all the TA elements in the transmitarray can be phase compensated using the transmission phase curve in Fig. 2.

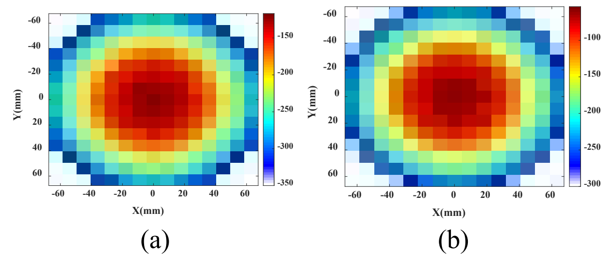


Fig. 4. Transmission phase distribution: (a) Freq = 11.5 GHz; (b) Freq = 13 GHz.

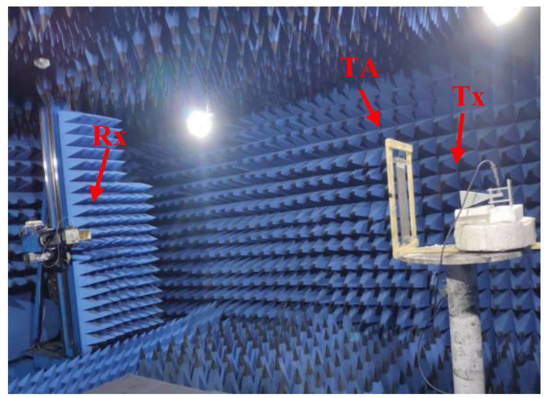


Fig. 5. Fabricated prototype under measurement in the anechoic chamber.

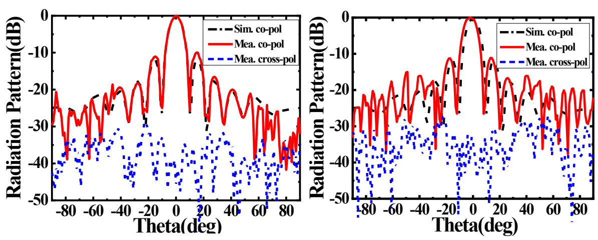
III. DUAL-BAND TRANSMITARRAY ANTENNA DESIGN AND MEASUREMENT

A. Design of dual-band transmitarray antenna

When the TA is in the transmission mode, the electromagnetic wave radiated by the feed horn irradiates to each TA element of the TA along different paths, and the difference of transmission path length leads to a certain wavelength difference between the feed horn and each TA element. Therefore, it is necessary to make corresponding phase compensation for each element in the TA, so as to realize the far-field in-phase superposition in the direction of the main beam. According to the transmitarray theory, the phase compensation value of each TA element can be calculated. In the obtained phase value, firstly select the TA element size that can meet the required transmission phase at both high and low frequencies. If it cannot be realized at the same time, the error coefficient of the TA element needs to be calculated according to equation (1):

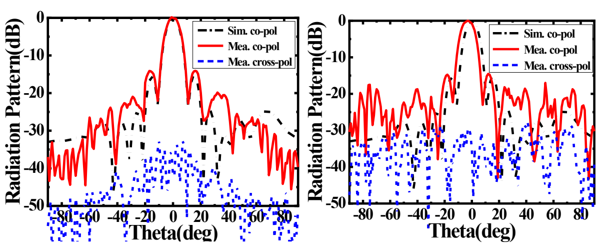
$$e(m,n)=\sum_{i=l,h}\left|\Phi^{desired}(f_i)(m,n)-\Phi^{achieved}(f_i)(m,n)\right|. \quad (1)$$

In this equation, (m,n) is the position of the TA element; $\phi_{desired}$ (f_h) and $\phi_{desired}$ (f_l) are the transmission phases of high frequency and low frequency that can desired specific beam pointing; $\phi_{achieved}$ (f_h) and $\phi_{achieved}$ (f_l) are the transmission phases of high frequency and low frequency that the TA element can achieved through parameter scanning. The error coefficient of each TA element is calculated by equation (1), and the element size with the minimum error coefficient is selected to obtain the optimal element. Finally, the dual-band transmitarray antenna can obtain independent radiation pattern at both frequencies.



(a) (b)

Fig. 6. The simulated and measured normalized radiation patterns at 11.5GHz: (a) E-plane and (b) H-plane.



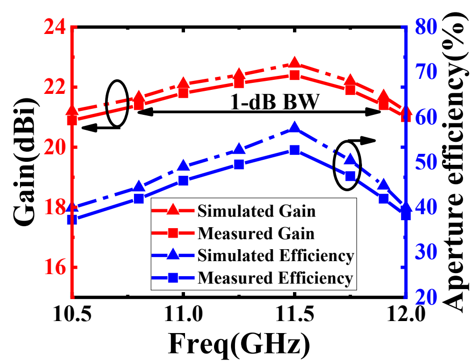
(a) (b)

Fig. 7. The simulated and measured normalized radiation patterns at 13GHz: (a) E-plane and (b) H-plane.

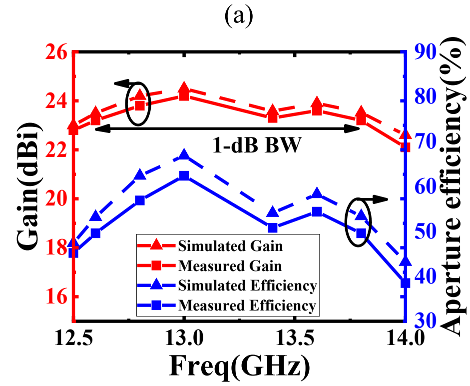
In the design of transmitarray antenna, the number of TA elements also needs to be considered. The aperture efficiency of the array is calculated as follows:

$$\varepsilon_{ap} = \frac{G}{D_{max}}, \qquad D_{max} = \frac{4\pi A}{\lambda}. \tag{2}$$

G is the measured gain, D_{max} is the maximum directivity, A is the area of the transmitarray, and λ is the wavelength in free-space. Therefore, the larger the number of elements, the greater the gain of the array, but the aperture efficiency of the array may be reduced. In this paper, a 201-element TA using the proposed TA element is proposed. The original array consisted of 15×15 cells, the corresponding aperture area is 135×135mm^2. In order to improve the aperture efficiency of the transmitarray antenna, six TA elements were deleted in each of the four corners. The final aperture area of the transmitarray is 16281mm^2. When the distance between the horn antenna and the transmitarray is optimal, all elements in the array are irradiated uniformly by the horn antenna, changing the distance will result the decrease of the gain. The value of focal diameter ratio is generally 0.8-1.5, and the distance between the horn antenna and transmitarray is obtained through optimization. Through simulation and optimization, the distance between the horn antenna and transmitarray is 165mm(6.35λ_{lower}). The corresponding focal diameter ratio is 1.22. In the whole design of the transmitarray antenna, the focal diameter ratio is determined first, and then the appropriate feed horn is selected. When the focal diameter ratio is too large, the beam width of the feed horn needs to be narrower and the beam concentration degree should be higher, so as to ensure that most of the energy of the feed horn can be accepted by the transmitarray. Instead, a wide - beam feed antenna needs to be selected. The feed antenna is a wideband pyramidal horn antenna. The aperture size of the horn size is 84 mm*60 mm. The working frequency range of the horn antenna is 6-18GHz. The operating frequency of the horn is 14.8dB at 11.5GHz and 15.6dB at 13GHz. By the calculation of the above theory, the phase distribution of the transmitarray at different frequencies is shown in Fig. 4. The corresponding dimension of the TA element can be obtained through the transmission phase curve in Fig. 2. By the calculation of equation (1), the dimensions of all TA elements can be obtained.



(a)



(b)

Fig. 8. The measured and simulated gain and aperture efficiency versus frequency: (a) X-band and (b) Ku-band.

B. Experimental results

The fabricated transmitarray antenna was measured in a microwave anechoic chamber, as shown in Fig. 5. TA is the transmitarray under test, Tx is the transmitting horn and Rx is the receiving horn. The normalized radiation patterns of the transmitarray antenna at 11.5 GHz are shown in Fig. 6. The normalized radiation patterns of the transmitarray antenna at 13 GHz are shown in Fig. 7. The measured gain is 0.38 dB lower than the simulation gain at 11.5 GHz. The measured gain is 0.3 dB lower than the simulation gain at 13 GHz. The differences between the measurement results and the simulation results are mainly due to the following points: first, the TA elements size are not as accurate as it should be in the manufacturing process; second, there are intrinsic noises in the anechoic chamber; third, the phase center of the horn antenna is unstable. The measured co-pol boresight beams in the designed two bands are not pointed to the desired boresight is mainly caused by the instability of the dielectric substrate during experiment.

In Fig. 6, the cross-polarization of the E-plane and H-plane radiation patterns at 11.5 GHz are 28 dBi and 27 dBi, respectively. The sidelobe level of the E-plane and H-plane radiation patterns at 11.5 GHz are 10 dB and 11 dB, respectively. In Fig. 7, the cross-polarization of the E-plane and H-plane radiation patterns at 13 GHz are 32 dBi and 29 dBi, respectively. The sidelobe level of the E-plane and H-plane radiation patterns at 13 GHz are 14.1 dB and 14.5 dB, respectively. This indicates that the designed transmitarray antenna has good radiation performance. The measured and simulated gain and aperture efficiency versus frequency are shown in Fig. 8. The 1-dB gain bandwidths are 9.7% (10.8-11.9 GHz) at X band and 9% (12.6-13.8GHz) at Ku band. The measured aperture efficiencies in 11.5 GHz and 13 GHz are 52.7% and 62.4%, respectively. Table 2 compares the performance index of the designed TA with other TAs. It can be seen from the table that the designed TA has the characteristics of high efficiency and low band ratio.

Table 2: Comparison of the proposed TA with other TAs

Ref.	Freq. (GHz)	Gain (dB)	Aperture Efficiency (%)	Band Ratio	Total Element Number
[9]	11/12.5	23.74/24.45	38/34.6	1.13	196
[12]	12.5/14.25	31/31.8	45/41.3	1.14	-
[13]	20/30	24.6/27.2	36.0/29.0	1.50	1156
This work	11.5/13	22.4/24.2	52.7/62.4	1.13	201

IV. CONCLUSION

In this paper, a new transmitarray element was proposed for the design of dual-band transmitarray antenna. The transmitarray element structure includes four-layer cross and square rings. The simulation results show that the transmitarray element can reach 360°phase coverage in both frequency bands and has good oblique incidence performance. To verify the validity of the transmitarray element. A 201-element transmitarray antenna using the proposed element was fabricated and measured. The measurement results have shown that the transmitarray antenna has good radiation performance. At 11.5 GHz, the measured gain and aperture efficiency were 22.4 dB and 52.7%, respectively. At 13GHz, the measured gain and aperture efficiency were 24.2 dB and 62.4%, respectively. The 1-dB bandwidth in X band and Ku band were 9.7% and 9%, respectively.

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