# A High-Efficient Wideband Transmitarray Antenna with Vias


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***Abstract*** **─** This paper presents a high-efficient wideband transmitarray antenna with vias. The transmitarray element consists of two layers of Jerusalem cross patches and four metal vias. Two Jerusalem cross patches are printed on both sides of the substrate and are connected by four symmetrical metal vias. The metal vias can improve the coupling strength between the two patches. By adjusting the size of the patch and the position of the metal vias, the transmission phase of the element is greater than 360º. Then, an transmitarray antenna consists of the proposed elements is designed, manufactured, and measured. The experiment results show that the maximum gain of the transmitarray antenna is 25.7dB, and the corresponding aperture efficiency is 46.6%. The measured 1-dB gain bandwidth is 14.9% (8.7GHz-10.1GHz).



***Index Terms*** **─** High-efficient, transmitarray antenna, wideband.


## I. INTRODUCTION

In recent years, planar array antenna has attracted more and more attention due to its light weight and easy installation. The planar array antenna includes the reflectarray antenna (RA) and the transmitarray antenna (TA). Compared with the RA [1-3], the feed horn of the TA and the transmitted wave are not on the same side, so it has higher aperture efficiency and lower side lobe. However, the bandwidth of the TA is narrow.

In order to improve the broadband characteristics of TA, scholars have proposed a variety of methods [4-12]. In [4], a four layers TA using double split-ring slot is presented. The 1-dB gain bandwidth of the TA is 7.4% and the aperture efficiency is 55%. [5] presents a four layer TA using a double square ring as the element. It has 7.5% 1-dB gain bandwidth. [6] using triple-layer spiral-dipole to realize the 360º transmission phase, but the transmission amplitude of the TA element is less than -4dB. In [7], a triple-layer TA without substrate is proposed. The proposed TA realized 15.5% 1-dB bandwidth and 55% efficiency. In [8], a novel TA element based on bandpass filter is designed. The TA element consists of two triple-layer frequency selective surfaces. Experimental results that the TA has 16% 1-dB gain bandwidth and 60% aperture efficiency. Other studies on transimitarray antenna is proposed in [9-12]. [13-17] are metasurface application on antenna array and MIMO antennas. From the above report, in order to improve the bandwidth of the TA, it is necessary to use the multi-layer patch to realize the 360º transmission phase and desired transmission amplitude. That will results to higher processing costs and increased installation complexity.

In this paper, a double-layer high-efficient wideband transmitarray antenna is present. The transmitarray element consists of two layers of Jerusalem cross patches and four metal vias. The metal vias are used to improve the internal coupling of the TA element. The structure of the article is as follows: Section I is the introduction of transmitarray antenna. Section Ⅱ is the design and simulation of the TA element. To verify the validity of the proposed element, a transmitarray antenna is designed and measured. The transmitarray prototype and measurement results are given in Section III. Section IV is the summary of the whole design.

## II. DOUBLE-LAYER TRANSMITARRAY ANTENNA ELEMENT DESIGN

### A. Element structure

Figure 1 is a plane geometric model of the proposed


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TA element. The purpose of the TA element design is to realize the transmission phase of 360° with the least number of patch layers. The TA element consists of two Jerusalem cross patches. The dielectric constant of the substrate is 2.2 and the tangent of loss angle is 0.0009. Four symmetrical metal vias are used to connect the two-layer of patch. The metal vias are made of copper. Two layers of patches are printed on both sides of the substrate. The role of the metal vias are improve the internal coupling of the TA element.

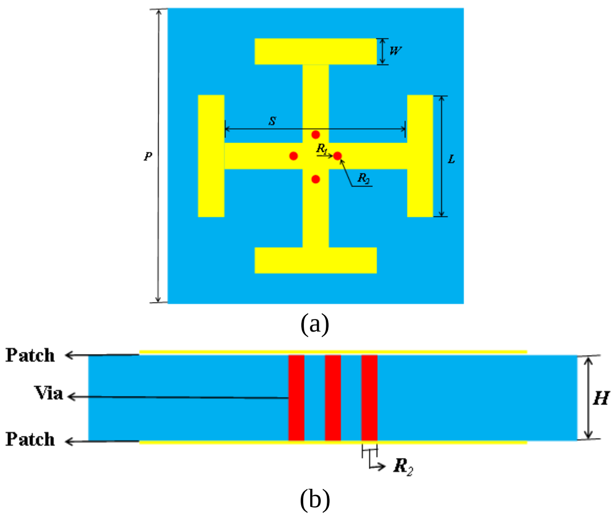



Fig. 1. Geometric model of the TA element: (a) vertical view and (b) lateral view.

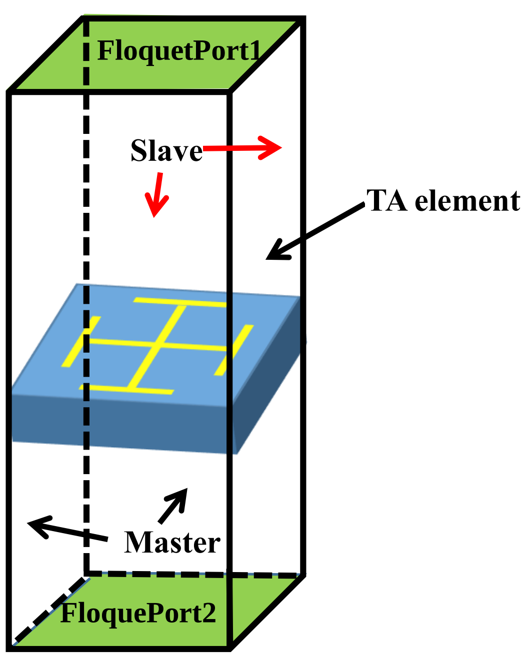



Fig. 2. The TA element simulation settings.

Table 1: Design parameters of the TA element

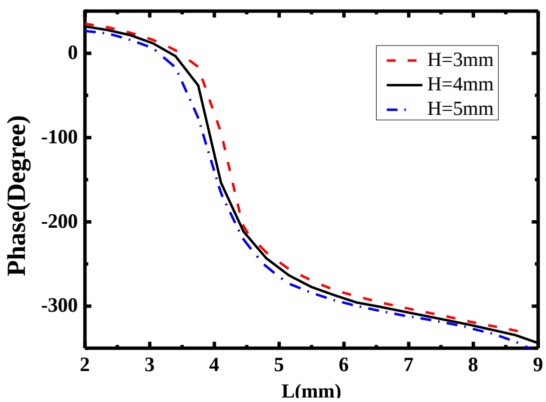
| Parameter | Value |
|---|---|
| *P* | 17mm |
| *W* | 1.5mm |
| *L* | 2~9mm |
| *S* | L+3.5mm |
| $R_1$ | 1.55mm |
| $R_2$ | 0.6mm |
| *H* | 4mm |

Ansoft HFSS is used to simulate and optimize the proposed element. In order to simulate the electromagnetic characteristics of elements in infinite period arrangement, the master-slave boundary is adopted. Because of transmitarray antenna needs to consider both transmission and phase shift characteristics, two Floquet-port excitations need to be set, as shown in Fig. 2. Figure 3 is the transmission characteristics of TA element with different structure parameters. As shown in (a), the thicker the substrate, the better the linearity of the phase shift curve. But the increase in the substrate thickness will lead to the reduction of the radiation efficiency of the TA. Therefore, the substrate thickness is 4mm. In order to avoid the generation of grating lobe, the TA element period is generally greater than 0.5λ. As shown in (b), when *P*=17mm (0.53λ), the phase shift curve is the most linear. It is can be seen from (c) and (e) that, the size and position of the metal vias have little effect on the linearity of the phase shift curve. In (d) and (f), it can be concluded that the size and position of the metal vias have a great influence on the transmission performance of the TA element. After a series of parameter optimization, the geometric dimensions of the element are shown in table 1.

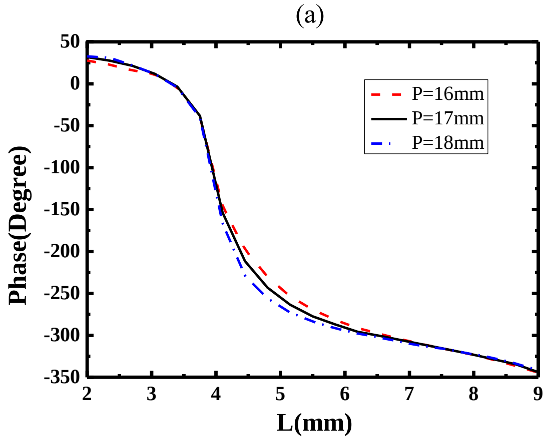
## B. Element transmission characteristic

The transmission amplitude and transmission phase versus L of the proposed TA element is shown in Fig. 4. As shown in this figure, the transmission phase of the element is greater than 360°. Within the range of 360° phase shift, the transmission amplitude of the element is always greater than -3.5dB. By adjusting the size of the TA element, the phase shift curve is parallel in a wide frequency band, which widens the frequency band width of the transmission array antenna. The transmission phase curves of the TA element at different frequencies are shown in Fig. 5. It can be seen from the figure that the transmission phase curves of different frequencies are approximately parallel. Therefore, the designed TA element has broadband characteristics. In order to observe the aperture efficiency of the TA element, the current distribution on the surface of the element is shown in the Fig. 6. As can be seen from the figure, the element surface current distribution is relatively uniform, so the TA has high efficiency. In addition, the current at the element edge is weak, which can reduce the coupling between the TA elements and improve the gain of the TA.

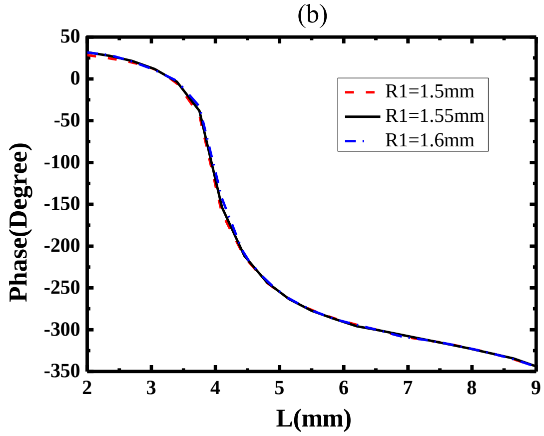
Since most of the TA elements are irradiated by oblique incident electromagnetic waves, the oblique incident characteristics of the element must be considered when designing the element. $\theta$ and $\varphi$ are the angles of the incident wave with Z-axis and X-axis, respectively. Figure 7 shows the transmission amplitude and phase of the TA element at different incident angles. As shown in this figure, within the range of 15°, the transmission phase of the cell is always greater than 360°, and the corresponding transmission phase is greater than -3.5dB.



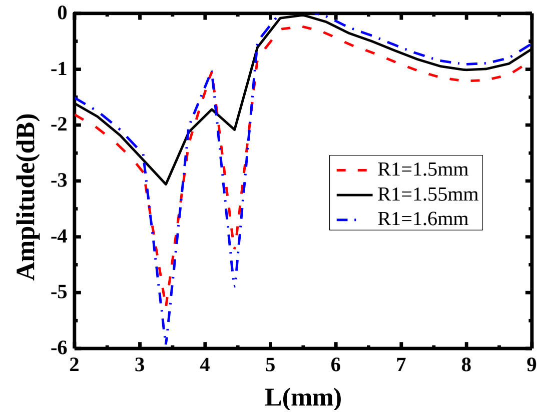

(a)



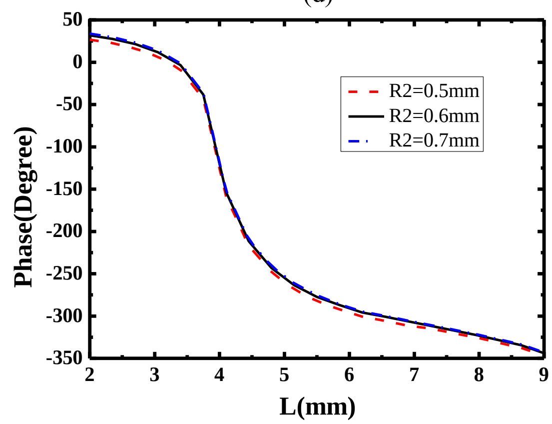

(b)



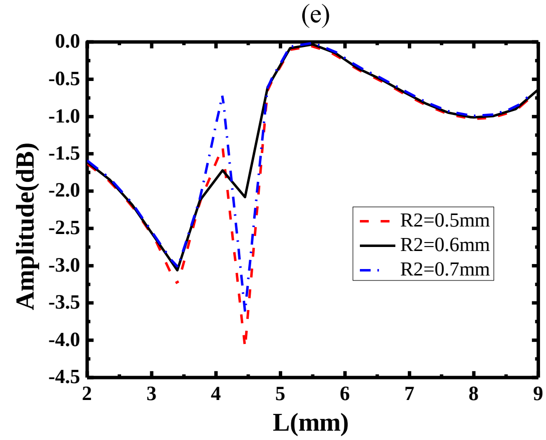

(c)




(d)




(e)




(f)

Fig. 3. The transmission characteristics of TA element with different structure parameters (9.5 GHz), (a) transmission phase of different substrate thickness (*P*=17mm, $R_1$=1.55mm, $R_2$=0.6mm), (b) transmission phase of different element periods (*H*=4mm, $R_1$=1.55mm, $R_2$=0.6mm), (c) transmission phase of different metal vias location (*H*=4mm, *P*=17mm, $R_2$=0.6mm), (d) transmission amplitude of different vias location (*H*=4mm, *P*=17mm, $R_2$=0.6mm), (e) transmission phase of different vias size (*H*=4mm, *P*=17mm, $R_1$=1.55mm), and (f) transmission amplitude of different vias size (*H*=4mm, *P*=17mm, $R_1$=1.55mm).

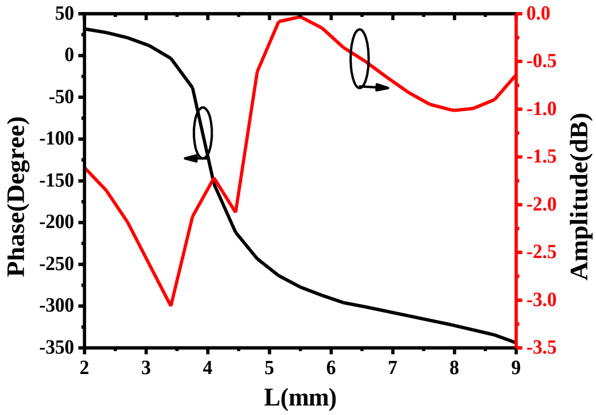



Fig. 4. Transmission characteristics of the TA element versus L.

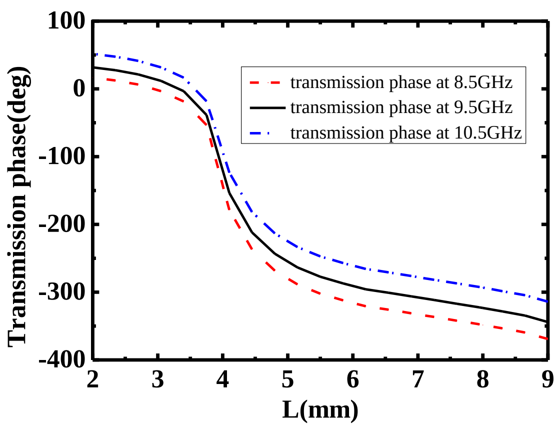



Fig. 5. Transmission phase of the TA element at different frequencies.

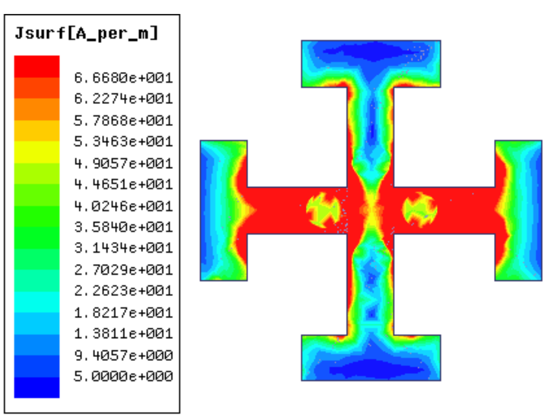



Fig. 6. The current distribution of the TA element.

## C. Metal vias

Four vertical metal vias are placed symmetrically between the Jerusalem cross patches, they create a strong coupling between the two patches. The four metal vias can be used as an additional coupling structure, which can reduce the number of patch layers of the TA element. The decrease of the number of patch layers will result in the decrease of transmission amplitude and phase. Currently, no TA element with only two layers of patches can achieve 360°'s transmission phase and desired transmission amplitude [18].

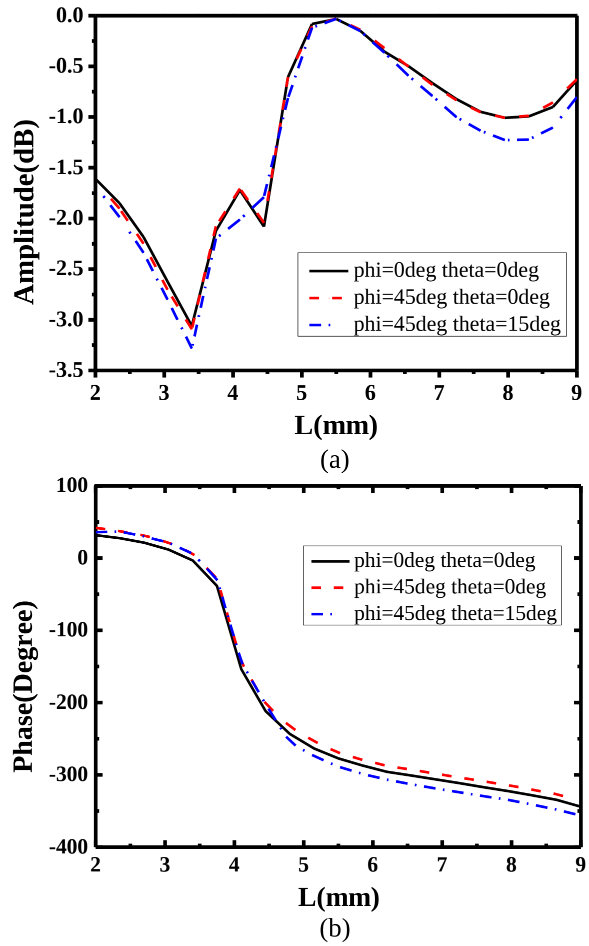
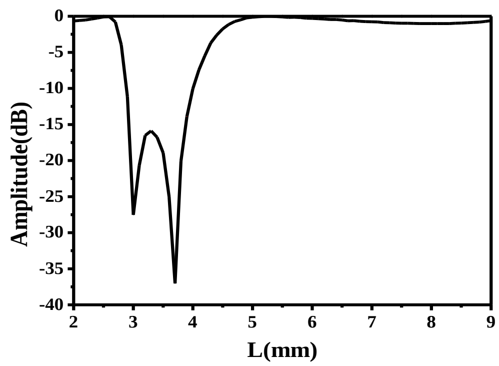
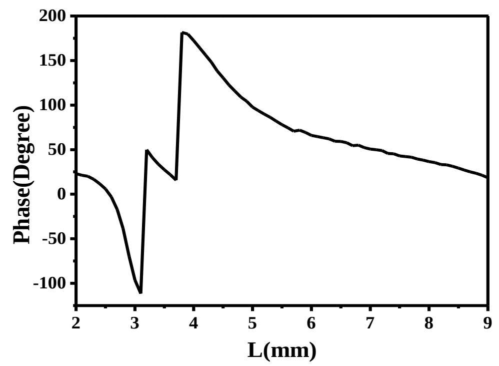



Fig. 7. Transmission characteristics of the TA element at different incident angles: (a) transmission amplitude, and (b) transmission phase.

Figure 8 is the transmission characteristic curve of the TA element without metal vias. It is obvious from the figure that the transmission amplitude is very small and the transmission phase is less than 360°. This is because the coupling between the upper and lower Jerusalem cross patches is weak. Therefore, it can be concluded that the introduction of metal vias can reduce the number of patch layers and improve the transmission performance of the TA element.




(a)




(b)

Fig. 8. Transmission characteristic of the TA element without metal vias: (a) transmission amplitude, and (b) transmission phase.

## III. DOUBLE-LAYER TRANSMITARRAY ANTENNA DESIGN AND MEASUREMENT

### A. Design of the TA

To verify the validity of the proposed TA element, a transmitarray antenna working at 9.5GHz is designed. The transmitarray antenna consists of 15×15 TA elements and the dimension size is 255mm×255mm×4mm. The focal length is 400mm and the corresponding focal diameter ratio is 1.57. Focal length is the distance from the feed to the transmitarray. Once the position of the feed is determined, the compensation phase of the TA element can be calculated by formula [19]. Figure 9 is the compensated phase distribution diagram of the transmitarray. The value of L corresponding to the compensation phase can be obtained from Fig. 4. As the value of L is obtained, the size of each TA element in the transmitarray can be determined. The feed of this design is a wideband pyramidal horn. The aperture dimension of the pyramidal horn is 187mm×60mm. The operating frequency of the horn is 8GHz-11GHz and its gain at 9.5GHz is 16dB.

### B. Experimental results

The TA prototype was measured in a microwave anechoic chamber at Xidian University. The test system is shown in the Fig. 10, Tx is the transmitting horn and Rx is the receiving horn. The polarization modes of Tx and Rx are vertical polarization, the center of Tx, Rx and TA is aligned, which can ensure the effectiveness of the test system. The distance from Tx, Rx and TA to the ground is 1.5 meters, the distance between Rx and TA is 3 meters. The simulated and measured normalized radiation patterns at 9.5GHz is shown in Fig. 11. In Fig. 11 (a), the sidelobe level and the cross-polarization of the E-plane radiation pattern is 17dB and 37dB, respectively. In Fig. 11 (b), the sidelobe level and the cross-polarization of the H-plane radiation pattern is 16dB and 36dB, respectively. The simulated and measured gain versus frequency is shown in Fig. 12. The measured maximum is 25.7dB at 9.5GHz and the corresponding aperture efficiency is 46.6%. The measured 1-dB gain bandwidth is 14.9%. The measured maximum gain is 0.33dB lower than the simulated maximum gain. There are two main reason: 1. There is an error in the size of the patch during processing, which will result in an error between the theoretical phase compensation value and the actual phase compensation value, resulting in an increase in sidelobe and a decrease in gain. 2. The phase center of the horn is not stable.

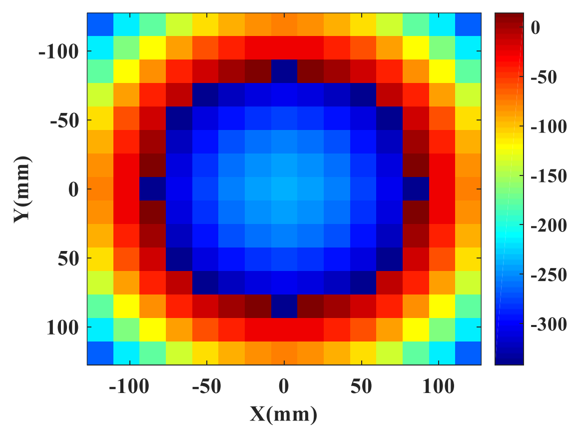



Fig. 9. Transmission phase distribution.

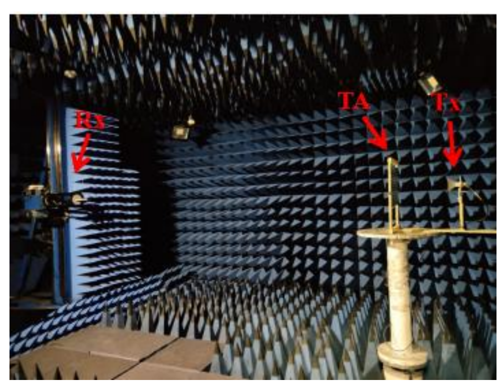
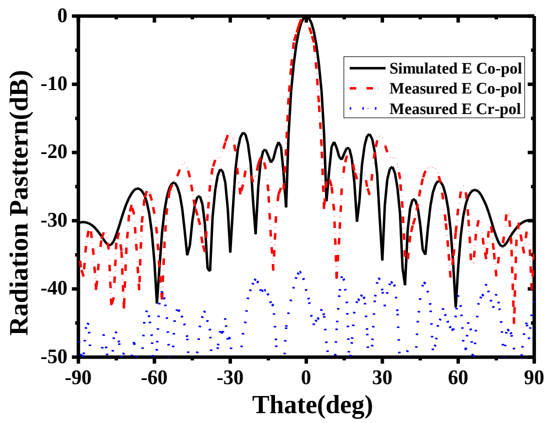
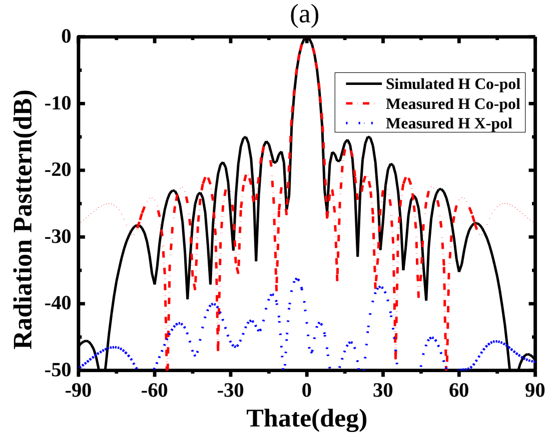



Fig. 10. The test system in microwave anechoic.




(a)




(b)

Fig. 11. The simulated and measured normalized radiation patterns at 9.5GHz: (a) E-plane and (b) H-plane.

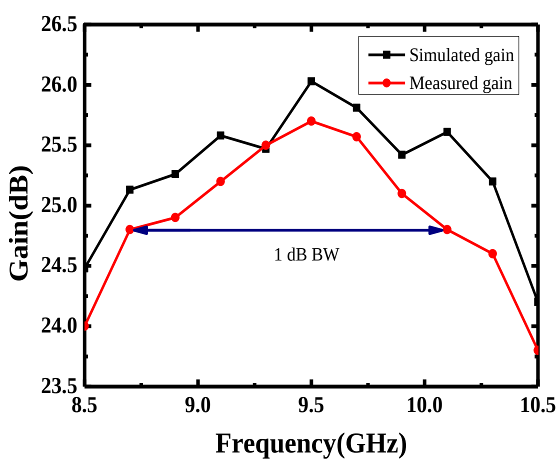



Fig. 12. The simulated and measured gain versus frequency.

Table 2 shows the performance comparison between the proposed antenna and other antennas. It can be concluded from the table that the proposed TA has the advantages of high efficient and broadband with only two layers of patches compared to the published antenna in [4], [12], [20-21].

Table 2: The comparison between the proposed TA and other published TA

| Ref. | Freq. (GHz) | Numbers of Layers | Gain (dB) | Aperture Efficiency (%) | 1dB gain Bandwidth (%) |
|---|---|---|---|---|---|
| [4] | 12.5 | 4 | 18.9 | 20.9 | 9.6 |
| [12] | 13.58 | 3 | 23.9 | 55 | 7.4 |
| [20] | 6.1 | 3 | 20.1 | 27 | 8.3 |
| [21] | 10 | 3 | 21.9 | 36 | 4 |
| This work | 9.5 | 2 | 25.7 | 46.6 | 14.9 |

## IV. CONCLUSION

In this paper, a double-layer high-efficient wideband transmitaray antenna with vias is designed and measured. The designed transmitarray element consists of two-layer Jerusalem cross patche and four metal vias. The introduction of metal vias could effectively improve the transmission performance of the element. After a series of design and simulation, a transmitarray antenna consisting of 255-element is fabricated and measured. The measurement and simulation results are basically consistent. The measured maximum gain is 25.7dB at 9.5GHz and the corresponding aperture efficiency is 46.6%. The 1-dB gain bandwidth of the transmitarray antenna is 14.9% (8.7GHz-10.1GHz). Since the designed element has only two-layers patch, the complexity of the design can be simplified and the production cost can be reduced.

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## REFERENCES

[1] Q. Wang, Z. H. Shao, Y. Jian Cheng, and P. K. Li, “Broadband low-cost reflectarray using modified double-square loop loaded by spiral stubs,” *IEEE Trans. Antennas Propag.*, vol. 63, no. 9, pp. 4224-4229, Sep. 2015.

[2] X. Xia and Q. wu, “Wideband millimeter-wave microstrip reflectarray using dual-resonance unit cells,” *IEEE Antennas Wireless Propag. Lett.*, vol. 16, pp. 4-7, 2017.

[3] Q. Gao and J. Wang, “A multiresonant element for

bandwidth enhancement of circularly polarized reflectarray antennas," *IEEE Antennas Wireless Propag. Lett.*, vol. 17, no. 5, pp. 727-730, May 2018.
[4] G. Liu, H. Wang, J. Jiang, F. Xue, and M. Yi, "A high-efficiency transmitarray antenna using double split ring slot elements," in *IEEE Antennas and Wireless Propagation Letters*, vol. 14, pp. 1415-1418, 2015.
[5] C. G. M. Ryan, M. R. Chaharmir, J. Shaker, J. R. Bray, Y. M. M. Antar, and A. Ittipiboon, "A wideband transmitarray using dual-resonant double square rings," in *IEEE Transactions on Antennas and Propagation*, vol. 58, no. 5, pp. 1486-1493, May 2010.
[6] A. H. Abdelrahman, A. Z. Elsherbeni, and F. Yang, "High-gain and broadband transmitarray antenna using triple-layer spiral dipole elements," in *IEEE Antennas and Wireless Propagation Letters*, vol. 13, pp. 1288-1291, 2014.
[7] C. Tian, Y. Jiao, G. Zhao, and H. Wang, "A wideband transmitarray using triple-layer elements combined with cross slots and double square rings," in *IEEE Antennas and Wireless Propagation Letters*, vol. 16, pp. 1561-1564, 2017.
[8] Q. Luo, S. Gao, M. Sobhy, and X. Yang, "Wideband transmitarray with reduced profile," in *IEEE Antennas and Wireless Propagation Letters*, vol. 17, no. 3, pp. 450-453, Mar. 2018.
[9] B. Rahmati and H. R. Hassani, "High-efficient wideband slot transmitarray antenna," *IEEE Trans. Antennas Propag*., vol. 63, no. 11, pp. 5149-5155, Nov. 2015.
[10] W. An, S. H. Xu, F. Yang, and M. K. Li, "A double-layer transmitarray antenna using Malta crosses with vias," *IEEE Trans. Antennas Propag*., vol. 64, no. 3, pp. 1120-1125, Mar. 2016.
[11] K. Pham, et al., "Design of wideband dual linearly polarized transmitarray antennas," *IEEE Trans. Antennas Propag*., vol. 64, no. 5, pp. 2022-2026, May 2016.
[12] J. F. Yu, L. Chen, J. Yang, and X.W. Shi, "Design of a transmitarray using split diagonal cross elements with limited phase range," *IEEE Antennas Wireless Propag. Lett*., vol. 15, pp. 1514-1517, 2016.
[13] F. Liu, J. Guo, L. Zhao, G. Huang, Y. Li, and Y. Yin, "Dual-band metasurface-based decoupling method for two closely packed dual-band antennas," in *IEEE Transactions on Antennas and Propagation*.
[14] J. Guo, F. Liu, L. Zhao, Y. Yin, G. Huang, and Y. Li, "Meta-surface antenna array decoupling designs for two linear polarized antennas coupled in H-plane and E-plane," in *IEEE Access*, vol. 7, pp. 100442-100452, 2019.
[15] S. Luo, Y. Li, Y. Xia, and L. Zhang, "A low mutual coupling antenna array with gain enhancement using metamaterial loading and neutralization line structure," in *Applied Computational Electromagnetics Society Journal*, vol. 34, no. 3, pp. 411-418, 2019.
[16] K. Yu, Y. Li, and X. Liu, "Mutual coupling reduction of a MIMO antenna array using 3-D novel meta-material structures," in *Applied Computational Electromagnetics Society Journal*, vol. 33, pp. 758-763, 2018.
[17] T. Jiang, T. Jiao, and Y. Li, "A low mutual coupling MIMO antenna using periodic multi-layered electromagnetic band gap structures," in *Applied Computational Electromagnetics Society Journal*, vol. 33, pp. 305-311, 2018.
[18] X. Yi, T. Su, B. Wu, J. Chen, L. Yang, and X. Li, "A double-layer highly efficient and wideband transmitarray antenna," in *IEEE Access*, vol. 7, pp. 23285-23290, 2019.
[19] A. Clemente and L. Dussopt, "Wideabnd 400-element eletronically reconfigurable trasmitarray in X band," *IEEE Trans. Antennas Propag*., vol. 61, no. 10, pp. 5017-5026, Nov. 2013.
[20] X. Zhong, L. Chen, Y. Shi, and X. Shi, "Design of multiple-polarization transmitarray antenna using rectangle ring slot elements," in *IEEE Antennas and Wireless Propagation Letters*, vol. 15, pp. 1803-1806, 2016.
[21] C. Tian, Y. Jiao, and G. Zhao, "Circularly polarized transmitarray antenna using low-profile dual-linearly polarized elements," in *IEEE Antennas and Wireless Propagation Letters*, vol. 16, pp. 465-468, 2017.

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