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A K-Band Flat Transmitarray Antenna with a Planar Microstrip Slot-Fed Patch Antenna Feeder

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Abstract—A thin phase-correcting element that consists of four identical metallic layers and three identical dielectric layers is presented for the design of microwave and millimeter-wave transmitarrays. The metallic layers consist of octagon conducting strips, which are tuned to obtain the desired phase compensation on an incident wave, while maintaining high amplitude of transmission coefficient. A transmitarray has been designed at K band with the use of the element. Fed by a standard horn and three planar slot-fed patch antennas with different beamwidths alternately, the wave-focusing performance of the transmitarray was demonstrated by simulations and experiments.

1. INTRODUCTION

With the modern wireless communication technology developed enormously, microwave and millimeter-wave flat transmitarray antennas have been widely studied in recent years, which will find their applications in modern broadband wireless communications, aircraft navigation and radio astronomy, etc. Like traditional dielectric lens [1–5], the microwave and millimeter-wave flat transmitarray [6–8] can transform quasi-spherical waves from a feeding source at the focal point to quasi-plane waves by adjusting the phase distributions across the surface of the transmitarray. There are two basic types of transmitarrays: one is based on the transparent-opaque Fresnel zone plate, and the other is designed using phase-correcting techniques. Traditional dielectric Fresnel zone plate and flat phase-correcting lens antennas usually enjoy high aperture efficiency but suffer from the primary disadvantages of bulky volume and heavy weight, while the transparent-opaque Fresnel zone plate lens antennas normally have a low profile and a light weight but low aperture efficiency. They are less applied to microwave and millimeter-wave communication systems. Recently developed thin phase-correcting lenses [9, 10] are planar, have low-profile, light-weight, high aperture efficiency and can be applied to the design of lenses at microwave and millimeter-wave frequency.

On the other hand, almost all the feeding sources of lens antennas in literatures are horn antennas [11, 12], leading to bulky antennas. To make lens antennas and the corresponding systems compact and have beam-steering performance for commercial moving systems, planar feeding sources or arrays are in need.

In this paper, a thin flat transmitarray antenna with a small planar feeder [13] is proposed for possible millimeter-wave applications. Four identical octagon metallic strips printed on three identical dielectric layers, with no air gap, are proposed to construct a thin element of the transmitarray. The proposed element can provide the required correcting transmission phase when designing the transmitarray. A planar slot-fed patch antenna was developed to feed the transmitarray antenna. Simulations and experiments were conducted to demonstrate the broadband and high-gain performance of the proposed compact transmitarray antenna.

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2. THE TRANSMITARRAY ELEMENT

In order to realize a broadband flat phase-correcting transmitarray antenna, a flat element periodically forming the transmitarray is required to offer a compensated transmission phase range of 360°. An element based on rectangular metallic strips was applied to the designs [10–12] of transmitarrays, where a minimum of three metallic strip layers with different sizes were used. If multiple identical strip layers were usd, it was found that the maximum transmission magnitude was worse than -3 dB in order to reach a phase-shifting range of 360°. In this paper, an element based on octagon metallic strips is proposed for better transmission, which will result in transmitarrays with better aperture efficiency. The configuration of the proposed transmitarray unit cell is shown in Fig. 1, which consists of four identical metallic layers printed on three identical dielectric layers. An F4B substrate is applied to the design of the transmitarray, which has a relative permittivity (ε_r) of 2.55, thickness (ts) of 1 mm, and 35 µm copper tapes on both sides. The side length of the square element of the transmitarray, depicted in Fig. 1(b), is denoted by parameter S, which normally takes the value of half wavelength of the operating frequency. The four identical metallic layers have an octagon shape. By tuning width b and fixing width a, the specified transmission phase can be obtained. In this work, the proposed transmitarray was designed to operate at K band, centered at 22 GHz. The characterization of the element and simulations of the transmitarray below were carried out with the use of the commercial software Ansys HFSS.

The presented transmitarray is polarization-sensitive, and the polarization of the incident wave is along the x-axis, as shown in Fig. 1. When characterizing the transmitarray element, periodic boundary conditions were applied to four sides of the element. After carrying out the appropriate parametric studies, the dimensions of the element were determined to be: $S = 7$ mm, $ts = 1$ mm, $a = 0.8$ mm, and $d = 1$ mm. The transmission magnitude and phase were then calculated by varying parameter b of the element and plotted in Fig. 2. It can be found that a transmission phase range of 410° is achieved by varying parameter b from 0.8 mm to 4.5 mm, and the transmission coefficient magnitude is less than 2.5 dB within the concerned phase range. The varying phase range and magnitude can be applied to the design of a high-efficiency transmitarray.

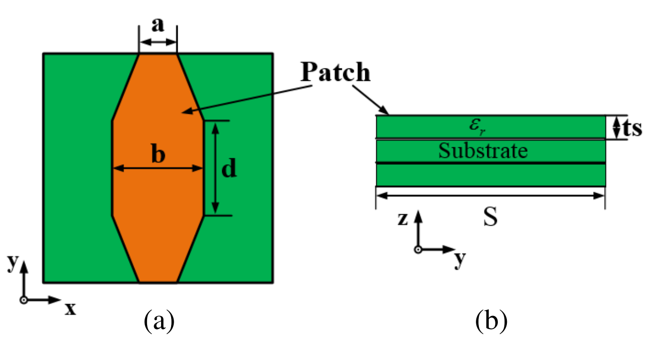


Figure 1. The configuration of the proposed transmitarray element. (a) Top view. (b) Side view.

3. SLOT-FED PATCH ANTENNA FEEDER

In this section, a planar source feed antenna is developed for the transmitarray antenna with a compact structure. Fig. 3 shows the configuration of a slot-fed patch antenna, which mainly consists of two substrates with no air gap. The rectangular patch radiator is printed on the top surface of the upper substrate (substract II). A microstrip feedline is on the bottom surface of the lower substrate (substract I), which feeds the patch through a rectangular slot on the PEC (perfect electric conductor) ground plane between the two substrates. Both substrates use F4B, which has the relative permittivity of 2.55 and thicknesses of t and ht, respectively. The parameters of the antenna are depicted in Fig. 3. After optimizing the initial values of parameters of the slot-fed antenna, the final dimensions are obtained. The values of the primary parameters are: $w = 34.5$ mm, $L = 19$ mm, $dx = 5$ mm, $dy = 3$ mm, $ls = 12$ mm, $ws = 8$ mm, $w1 = 1.8$ mm, $l1 = 25.5$ mm, $w2 = 4$ mm, $l2 = 0.3$ mm, $t = 0.5$ mm, and $ht = 1.5$ mm.

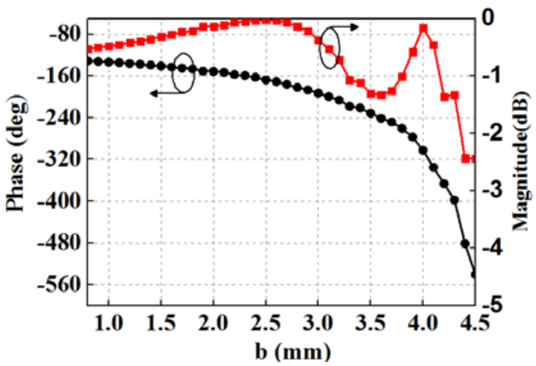


Figure 2. Transmission coefficient magnitude and phase versus parameter b for the proposed element.

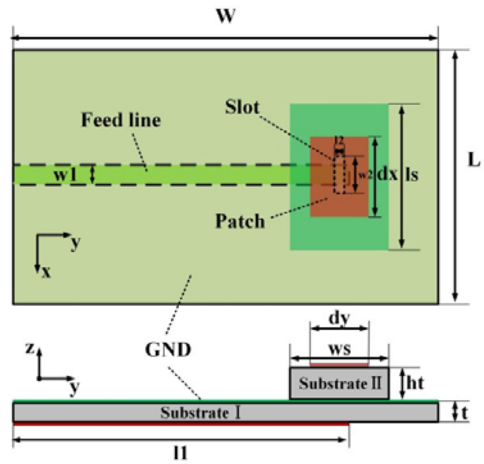


Figure 3. Geometry of the slot-fed patch antenna.

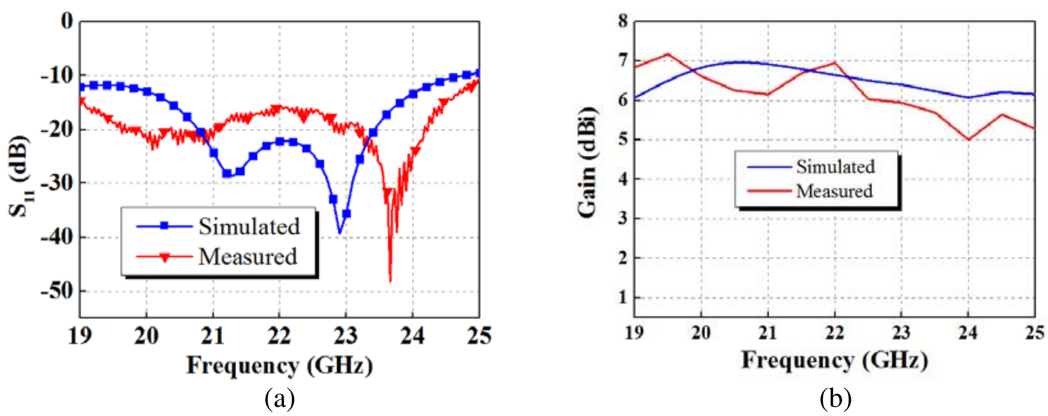


Figure 4. (a) Reflection coefficients of the slot-fed patch antenna; (b) Gains.

A prototype of the slot-fed patch antenna was fabricated and measured. The measured reflection coefficient and gain, obtained using the $\sim$ 40 GHz vector network analyzer AV3629 made from the 41st Institute of China Electronics Technology Group Corporation and a far-field antenna measurement system in a chamber respectively, are plotted in Figs. 4(a) and (b), respectively, together with the simulated results for comparison. It can be seen that good agreements are obtained. The slot-fed patch antenna has a wide bandwidth for $S_{11} < -10$ dB, from 19 GHz to 25 GHz. The gain varied between 5.0 and 7.2 dBi within the bandwidth.

4. DESIGN OF THE TRANSMITARRAY AND THE NUMERICAL RESULTS

Based on the above investigations, a transmitarray was designed. The transmitarray consists of 29×29 elements and operates at a center frequency of 22 GHz. The dimension of the square transmitarray is 203 mm $\times$ 203 mm $\times$ 3 mm ($15\lambda \times 15\lambda \times 0.22\lambda$). A linearly-polarized pyramidal horn with a gain of 12 dBi at 24 GHz and the planar slot-fed patch antenna designed above were employed as the source feed alternately. The focal distance F is 130 mm, and F/D ratio of the antenna is 0.64. The compensation phase of each element was obtained using the following equation [14]:

$$\varphi_i = k\left(R_i - F\right) \pm 2n\pi + \varphi_0$$

where φ_i and φ_0 are the compensation phases of the ith and center elements of the transmitarray, respectively; R_i and F are the distances between the phase center of the feeder and the centers of the ith and center elements respectively; N is a integer number to make sure that $0 < \varphi_i < 2\pi$.

The transmitarray antenna was first validated numerically and simulated using the Ansys HFSS. To provide a deep insight into the physical mechanism of the antenna, the electric fields in the H plane at 22 GHz were simulated and plotted in Fig. 5 for the transmitarray with both feeders alternately. As expected, both the curved phase fronts, from the source horn and the planar antenna respectively, became a much more uniform or quasi-planar after passing through the transmitarray, demonstrating potential high-gain performance. The 3-D radiation pattern and HFSS model of the transmitarray fed by the patch antenna are shown in Fig. 6, showing the high-gain and narrow beam performance.

To obtain a more compact antenna structure, the performance of the transmitarray fed by the planar patch antenna with different beamwidths was investigated as well. First, planar slot-fed patch antennas with three different beamwidths in the H plane were designed. As shown in Fig. 3, by tuning the parameter L, which is the width of the lower substrate, different beamwidths can be obtained in the H plane of the antenna. The different values of parameter L, 16 mm, 19 mm, and 23.8 mm, have been chosen for the demonstration, resulting in three planar antennas with different beamwidths in the H plane. Fig. 7(a) shows the simulated reflection coefficients for the three cases. It can be found that all

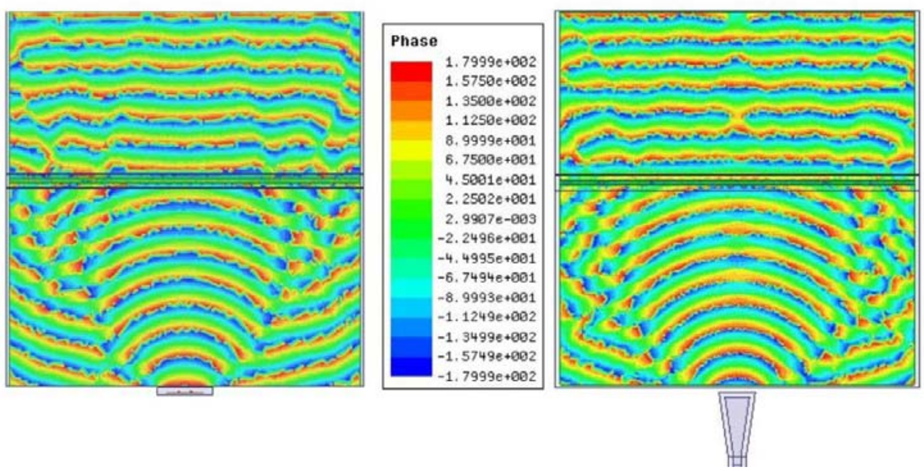


Figure 5. Electric field phase distributions at 22 GHz: (a) with the planar feeder; (b) with the horn feeder.

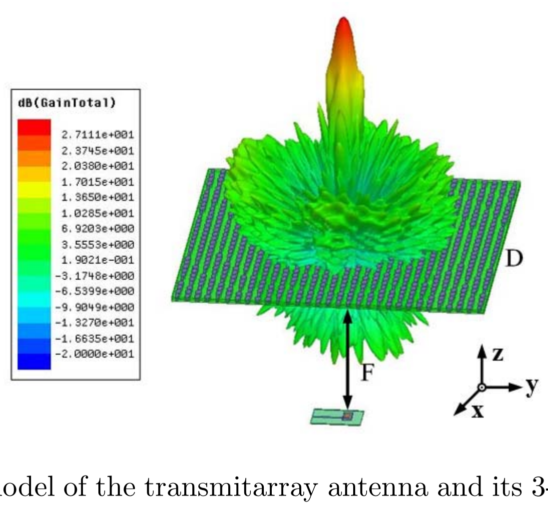


Figure 6. The 3-D HFSS model of the transmitarray antenna and its 3-D radiation pattern at 22 GHz.

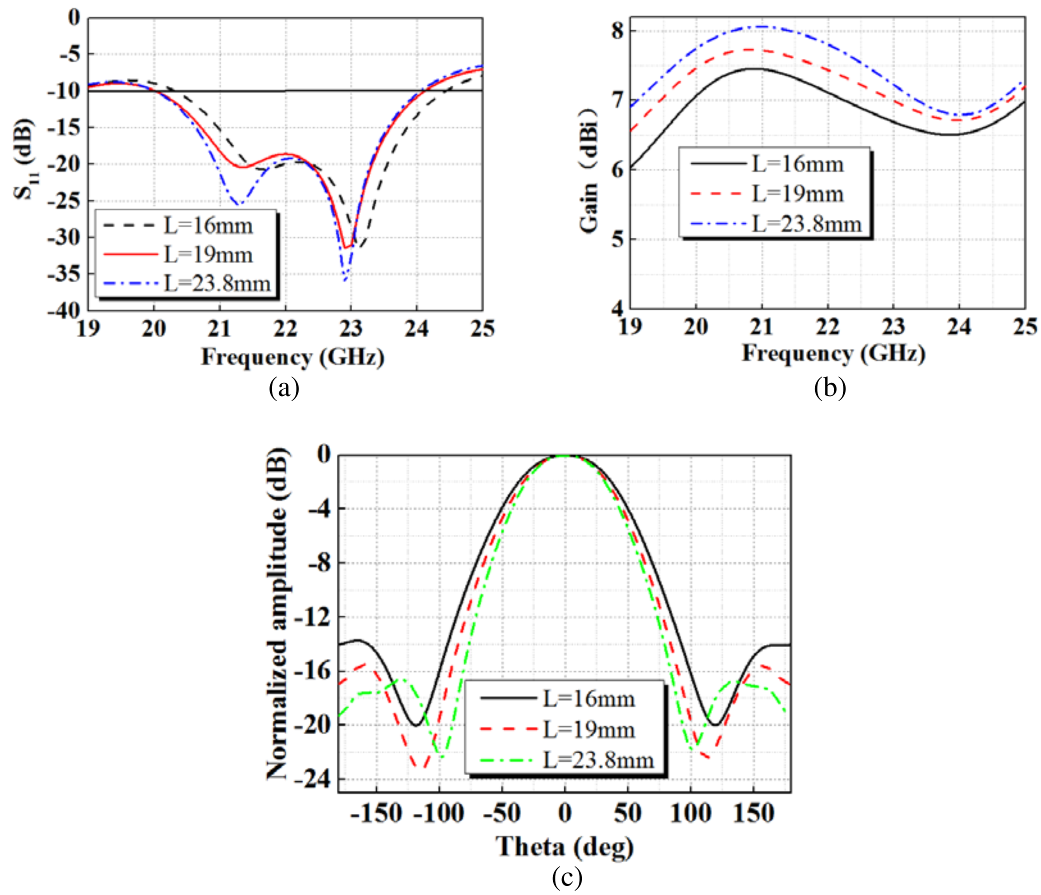


Figure 7. Performance of the slot-fed patch antennas with three different beamwidths: (a) simulated input reflection coefficients; (b) simulated gains; (c) simulated radiation patterns.

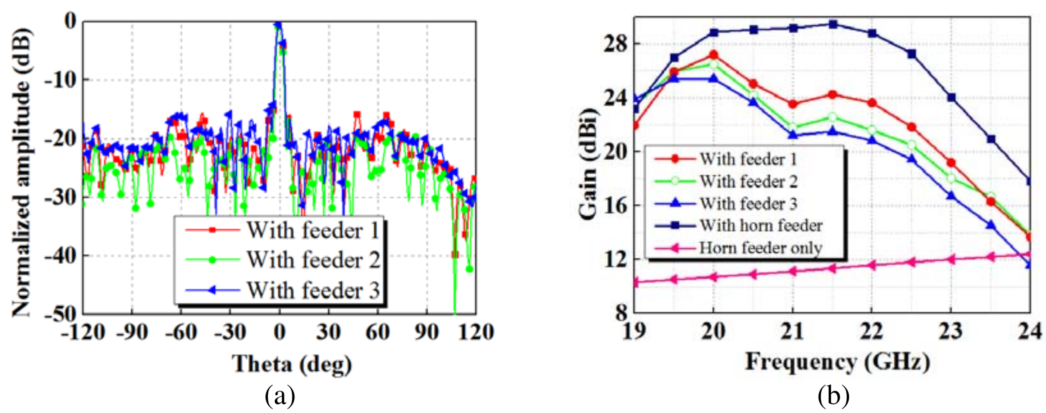


Figure 8. Radiation performance for the three cases: (a) radiation patterns; (b) gains.

the three antennas have wide bandwidths, from 20 GHz to about 24.3 GHz for $S_{11} < 10$ dB. Fig. 7(b) shows the gain curves of the three antennas. The simulated radiation patterns are plotted in Fig. 7(c). The 3-dB beamwidths for the three cases are 88°, 80°, and 72°, respectively. With the increase of parameter L, the gain of the slot-fed antenna increases, while the beamwidth becomes narrow.

The transmitarray with the three planar antenna feeds is simulated separately. Fig. 8(a) shows the simulated radiation patterns at 22 GHz in the H plane for three different feeders, feeders 1, 2 and 3, whose beamwidths in the H plane are 88°, 80°, and 72°, respectively, corresponding to the planar patch antennas with $L = 16$ mm, 19 mm and 23.8 mm, respectively. It is observed that all the three radiation patterns are stable and symmetrical, with sidelobe levels of about 15 dB below the main lobe. The 3-dB beamwidths in the H plane corresponding to the three feeders are 3°, 3.5°, and 3.8°, respectively, indicating that the transmitarray antenna has a good focusing performance, and the beamwidth becomes narrower with the increase of the beamwidth of the feeder. The simulated gain curves are plotted in Fig. 8(b), together with those of the three feeders for comparison. It can be seen that the transmitarray antenna with feeder 1 gives the best peak gain, which is 27.2 dBi, about 20 dB higher than that of feeder 1. With the increase of the beamwidth of the feeder, the gain of the transmitarray antenna will be improved, indicating that a shorter focal length F can be applied, and hence a more compact configuration of the transmitarray antenna can be achieved when using a source feeder with a wide beamwidth, without compromising the radiation performance.

5. EXPERIMENTAL RESULTS

A prototype of the transmitarray of 29×29 elements and the slot-fed patch antenna designed in Section 3 were fabricated. Using the source feeders of the patch antenna and a standard horn alternately, the transmitarray antenna was measured in our chamber. The measurement system and the prototype antenna are shown in Fig. 9. The square transmitarray has a side length D of 203 mm, and F/D is 0.64. The planar feeding antenna or the horn is mounted 130 mm away from the surface of the transmitarray. The polarization is vertical in the measurements. Fig. 10 shows the measured radiation patterns at 22 GHz for the transmitarray with the two feeders respectively. The measured results show that the transmitarray has a 3-dB beamwidth of 3.9° for both feeding cases, and the sidelobe levels are about 15 dB below the main lobe. The measured radiation patterns in the E-plane at four different frequencies

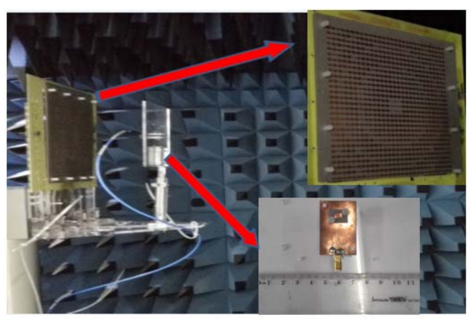
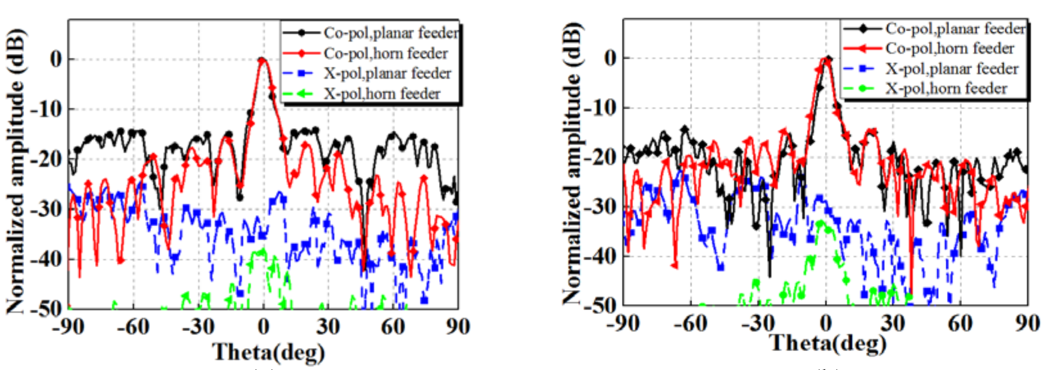


Figure 9. The transmitarray prototype and the measurement system.



(a) (b)

Figure 10. Measured radiation patterns at 22 GHz in: (a) E-plane (b) H-plane.

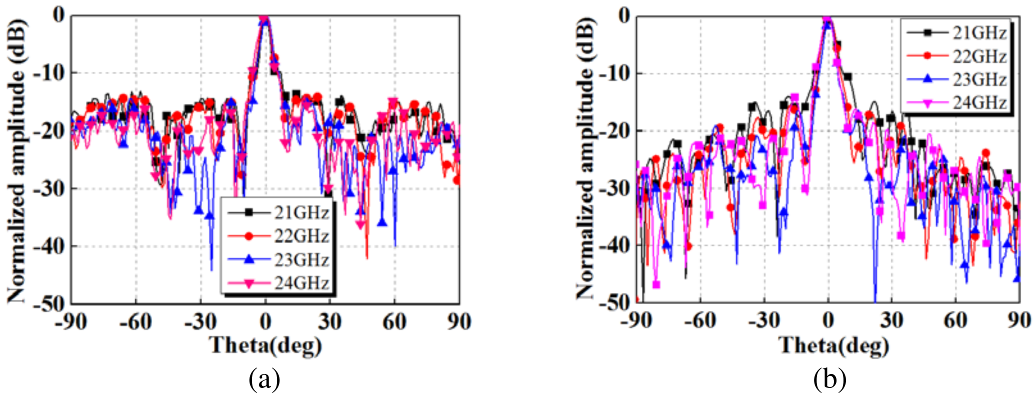


Figure 11. Measured radiation patterns in the E-plane at four different frequencies, (a) planar feeder; (b) horn feeder.

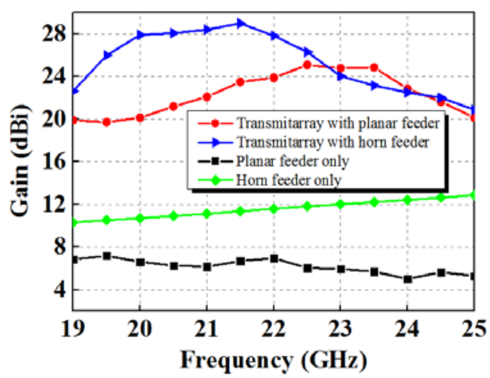


Figure 12. Measured gains of the transmitarray antennas and feeders.

for the two feeders are plotted Figs. 11(a) and (b), respectively.

The measured gains of the transmitarray antenna and the slot-fed patch antenna, as well as that of the standard horn, are plotted in Fig. 12. It can be seen that the transmitarray with a horn feeder has a better peak gain, up to 29.1 dBi, while that with the feeder of planar antenna has a less peak gain, about 25.1 dBi, and a more uniformly varied gain curve. The reason is that the horn has a more uniform and symmetrical electric field distribution in both the E and H planes, as shown in Fig. 5(b), which is close to that of the ideal feed source applied [14] to determine the compensation phases for each element of the transmitarray, while the fields from the planar antenna is only uniform in the H plane, as shown in Fig. 5(a), and not uniform in the E plane. The 3-dB gain bandwidths for both cases are about 14.6%.

6. CONCLUSIONS

A K-band flat transmitarray antenna with a novel octagon strip element has been successfully designed, manufactured and tested in this paper. A standard horn and three planar microstrip slot-fed patch antennas, which are developed with different beamwidths in the H plane, are used as the feeding source alternately. In addition to the demonstration of the wave-focusing performance of the transmitarray by simulations and experiments, it is also demonstrated that the gain of the transmitarray antenna will increase with the beamwidth of the planar source feeder, indicating that a potentially more compact transmitarray antenna is feasible when using a planar source feeder with a wide beamwidth, and it will be investigated in the future. Experimental results show that the transmitarray with a planar source feed achieves a 3-dB gain bandwidth about 14.6%, 1-dB gain bandwidths about 7.3%, and a peak gain of 25.1 dBi.

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