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A High Gain X-Band Horn Antenna Array with Wide-Angle Beam Steering in E-Plane

Thi Huong NGO[1], Dinh Son NGUYEN, Van Phu NGUYEN,
Minh Duc HOANG, Van Loi NGUYEN
Viettel High Technology Industry Corporation, Hanoi, Vietnam
ORCiD ID: Thi Huong Ngo https://orcid.org/0009-0004-3025-1027

Abstract. This proposal presents a high gain array antenna of double-ridged horn for X-band radar applications. The antenna array consists of 5184 radiating elements divided into 1296 subarrays, each subarray has 4 horn elements fed by a 4-port waveguide power divider in horizontal plane. The subarray is integrated with calibration signal to improve the system accuracy. The measurement results of 72×72 horn array in a bandwidth of 7% matching with the simulation results indicate an effective design approach: the design antenna has achieved a good active return loss (S_{11}) less than -10 dB when beamforming upto $\pm 55^0$, a peak gain of 42.7 dBi, a pencil beam with half-power beamwidth (HPBW) less than 1.4^0 in both E and H plane in the operating bandwidth.

Keywords. Horn array antenna, double-ridged horn antenna, subarray, T-junction, monopulse

1. Introduction

Nowadays, the requirements for antenna performance increase rapidly because of the development of modern communication systems. For instance, in some specific circumstances, the antennas are required to have simple geometric shape, costless, low profile but at the same time providing broadband and wide angle steering. Accordingly, there are many studies on broadband, low-profile and wide scan volume planar antenna.

The planar phase array antennas are commonly used in the modern communication systems, especially in radar applications. Several different types of planar antennas have been reported [1-5]. The Vivaldi array antennas have wide bandwidth and scan volume but the structure with exponential taper and slots requires high-precision fabrication. The conventional patch array antennas also have wide scan angle but the bandwidth is narrow. To broad the bandwidth, the cavity is inserted however the structure is more complex. Thus, the planar horn array antennas have attracted because of many benefits.

Planar array consists of huge horn antennas number provides high directionality, high gain and the directivity is almost the same as its gain because there is very low losses in the horn antenna [6]. These horn antennas have low weight and a directional radiation with high gain so the multipath effects will be reduced. Besides, the horn antennas are not resonated so it can achieve a broad bandwidth [7]. The simple design is

[1] Corresponding Author: Ngo Thi Huong, huongnt107@viettel.com.vn.

also another strong point of this horn antenna. Therefore, planar array based on horn antenna structure is investigated.

In this paper, a 72×72 planar horn array has been proposed. The radiating elements are fed in paralleled by a transmit and receive system and by the use of a combination of subarrray. Each subarray has four horn elements and a 4-port waveguide power divider. Hence, instead of using a transmit and receive system with 5184 channels we only need a system with 1296 channels to feed for the array. The design goals are to obtain a good active return loss less than -10 dB when beamforming in the range of $\pm 55^0$, a peak gain of 42.7 dBi in the frequency band from 8.2 GHz to 8.8 GHz. In addition, HPBW is less than 1.4^0 in both horizontal and vertical plane with uniform distribution.

2. Antenna Design

2.1. Horn antenna element and power divider

The 4-element subarray is made up of four horn antennas and a T-junction waveguide power divider. The subarray is designed to operate in the X-band centered at 8.5 GHz with a broadside beam.

It's known that, the bandwidth of the ordinary horn antennas is limited. To improve the voltage standing wave ratio (VSWR) and increase the antenna's bandwidth, the ridges are designed in the E-plane of horn antenna. These ridges are attached into the horn to convert the wave impedance in the waveguide to the impedance of free space so the characteristics of the antenna are improved [8] [9] [10]. The ridges which keep up till the end of the horn and attached in the broadside, have triangle shape.

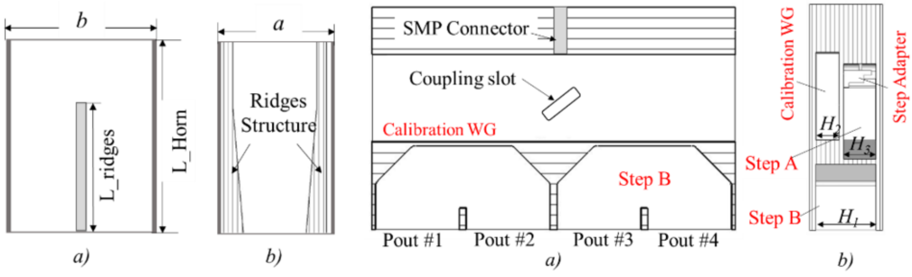
For peak directivity and gratinglobe suppression, the spacing between radiators are required to be less than 0.5λ in vertical plane (E-plane) because grating lobe peaks will be eliminated in the visible region if element spacing is restricted as follow:

$$d = \frac{\lambda}{1 + |\cos\theta_{0\max}|} \tag{1}$$

Where θ_{0max} is the maximum main beam steering angle with respect to the line of the array, λ is the wave length at the lowest frequency band. If scanning to endfire (θ_{0max} = 0, 180^0) is desired, then $d < 0.5\lambda$ [11]. Subsequently, the aperture of proposed horn antenna is less than 0.5λ with the taper section is the most important and complex part of double ridges horn antenna, shown in Figure 1.

A simulated return loss of horn antenna in the infinite array with and without double-ridged are presented in Figure 2. With double ridges, the return loss of horn antenna is less than -20 dB with a bandwidth of 24.4% (from 7.55 – 9.65 GHz).

The power divider is based on H-plane T-junction waveguide, in which four outputs area equally in amplitude and phase. Its overview model is shown in Figure 1.



Horn antenna *Power divider*

Figure 1. The prototype of double-ridged horn antenna and waveguide power divider: a) – top view, b) – side view

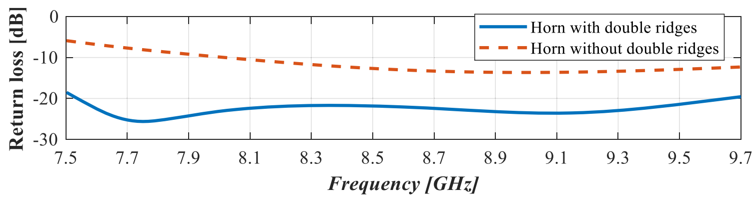
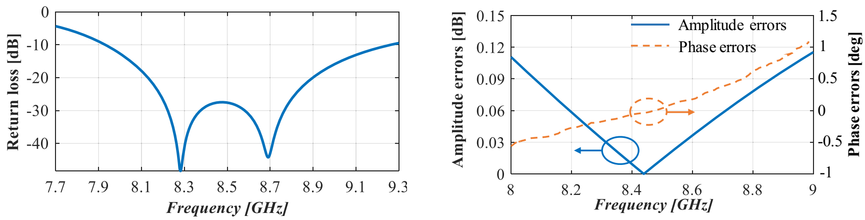


Figure 2. Horn antenna's simulated return loss with and without double-ridged.

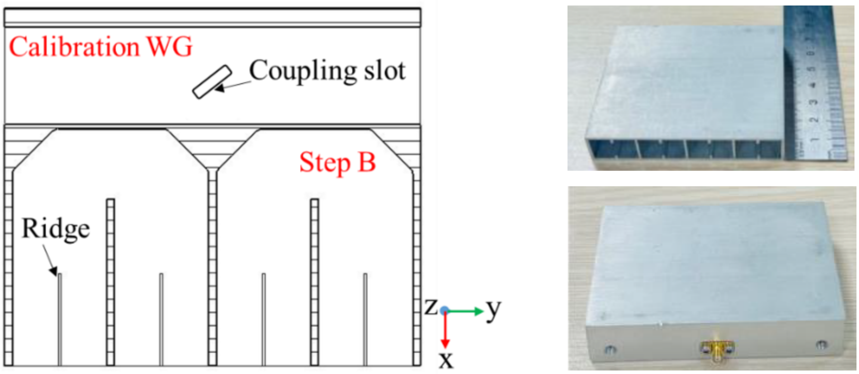


a) Return loss b) The maximum amplitude and phase errors

Figure 3. The simulation of waveguide power divider

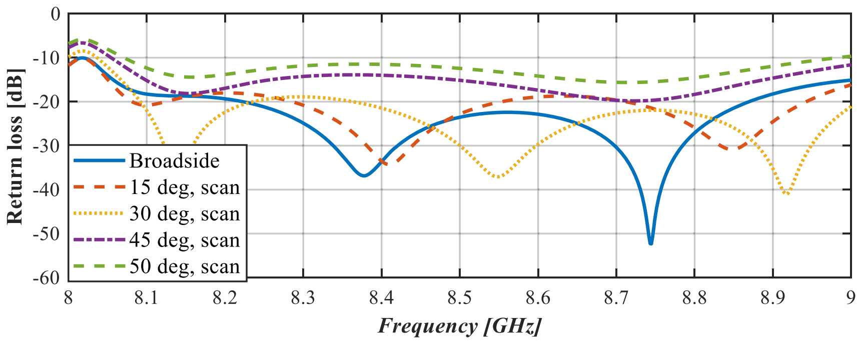
As it is known, in the phased array antenna, the calibration plays an essential role in considering the variation of antenna element characteristics. Therefore, in the structure of the power divider shown in Figure 1, the waveguide power divider consists of two steps: step A with the height is shorter than step B' height so it has enough space to insert a waveguide calibration structure. The dimensions of four step B outputs are designed to match with the feeding section of the horn elements. Additionally, at the input of the power divider, an adapter with three steps is optimized to provide good impedance matching over the bandwidth of 7% (8.2 – 8.8 GHz) with return loss less than -27.5 dB, shown in Figure 3a. The simulated amplitude and phase errors of four output ports are presented in Figure 3b with the difference of amplitude between four output ports is less than 0.12 dB and the difference of phase between four output ports is less than 1.2^0 over the operating bandwidth.

A subarray composed of four horn elements and a waveguide power divider is presented in Figure 4 with outline dimensions are 72 × 70 × 18 mm^3 (length × depth × height). It is fabricated using 6061 Aluminum material shown in Figure 4b.

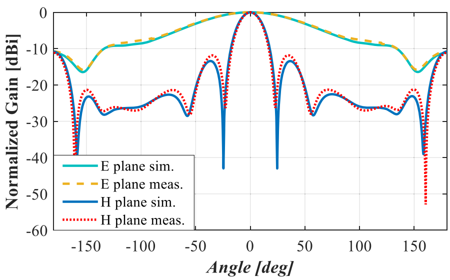


a) *b)*

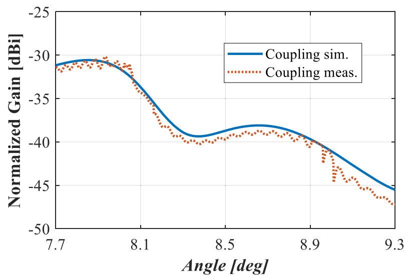
Figure 4. The sketch of 4-horn subarray: a) – top view, b) – fabricated 4-horn subarray.



a) Return loss



b) Radiation pattern



c) Coupling coefficient

Figure 5. Simulated of 4-horn subarray in the infinite array.

The simulated return loss results in the infinite array are shown in Figure 5a. It can achieve the return loss less than -22 dB without beamforming and less than -10 dB when scans up to ±55 degree in the E-plane over the operating bandwidth. There is no scan blindness observed within the scanning volume. The simulation and measurement results of radiation patterns at center frequency in both the horizontal and vertical plane (H and E-plane) are shown in Figure 5b. The simulated and measured coupling coefficient of subarray is shown in Figure 5c. The figures shown that, the simulation results are quite similar to the measurement results, and the subarray has a bandwidth of 7% (from 8.2 –

8.8 GHz) with return loss less than -22 dB in the infinite array, coupling coefficient is 39±1 dB and HPBW in E-plane and H-plane is 112^0 and 20^0.

2.2. Plannar horn array antenna

A linear subarray shown in Figure 6 is obtained by grouping 18 four-horn subarrays in the horizontal plane (H-plane) and a planar horn array antenna is proposed by composing 72 linear subarrays in the vertical plane (E-plane). As results, the planar horn array antenna consists of 1296 four-horn subarrays.

Because a subarray consists of four horn elements, the subarray spacing in horizontal plane is larger than two wavelengths leading to grating lobes in the array factor especially with wide scan angle [12]. However, the beamforming in the horizontal plane can be done by mechanically slewing using a positioning system. In vertical plane (E-plane), to adapt to rapid tracking in radar, planar array must provide wide scanning angle (without grating lobes) with optimized HPBW and gain. For that reason, the distance between adjacent linear subarrays is selected carefully, since this parameter puts a significantly impact on antenna's radiation pattern. The optimized spacing between linear subarrays is corresponding to $0.49\lambda_0$ with λ_0 is the shortest wavelength. With this spacing, the horn array antenna has the scanning volume without grating lobes upto $\pm55^0$ and the simulated active return loss S11 less than -10 dB is obtained. The overall dimensions of the horn array are approximately $1.4 \times 1.3 \times 0.07$ m^3 (Width × height × depth).

The planar horn array is fabricated and installed on the frame. Each of its four-horn subarray is connected to an output of the transmit and receive system. Each independent Tx/Rx channels allowing active phase and beam control. This planar horn array has 1296 four-horn subarrays fed by 1296 channels of the transmit and receive system.

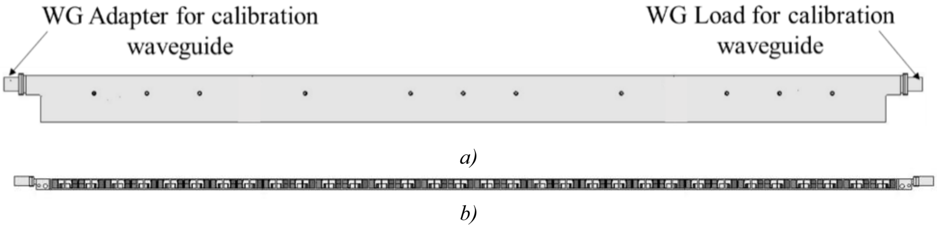


Figure 6. The structure of a linear subarray: a) – top view, b) – front view.

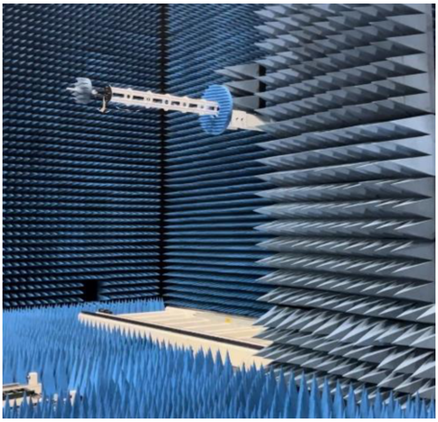


Figure 7. A scanning probe of measurement in chamber room.

3. Antenna Measurements

The proposed planar horn array antenna has large size, directional radiation pattern and beam steering in both the horizontal and vertical plane. Therefore, to improve the accuracy measurements, the radiation patterns of the antenna are measured in the chamber room by the planar near field method. Beam steering has been performed by changing the elements phase in the array corresponding to the beam scanning angle (θ_0, ϕ_0). The phase shifts between the array elements are calculated by using formula:

$$(\psi_a, \psi_b) = (360/\lambda * a * \sin\theta_0 * \cos\phi_0, 360/\lambda * b * \sin\theta_0 * \sin\phi_0) \qquad (2)$$

The setup and measurement of the horn array steering beam in chamber room with a scanning probe is presented in Figure 7. The measured 3D radiation pattern of steering beam at 55^0 in the vertical plane is presented in Figure 9. Figure 10 illustrates the measurement patterns of the planar horn array when scanning beams from 0^0 - 55^0 in the vertical plane at difference frequencies. The measured patterns of scanning beams from 0^0 - 5^0 in the horizontal plane are presented in Figure 11. Its measured gain and HPBW are demonstrated in Table 1. As can be noticed from the figures and table, when scanning angle increases, beamwidth slightly rises and gain drops approximately 3.5 dB at 55^0. A Taylor amplitude distribution to achieve sidelobe level of 25 dB (then use "Taylor 25 dB" for short) is applied across the array as presented in Figure 8. The figure shows that the measured sidelobe level of array antenna is less than -24.7 dB. The phase and amplitude at each four-horn subarrays are controlled by Trans-Receive System.

To calculate the azimuth and elevation of the target more precisely, the monopulse method is used. Figure 12 shows the sum and difference radiation patterns with beam steering. As can be seen, when scan angle is increased, null depth is decreased, HPBW and asymmetry pattern difference is increased correspondingly. It is also realized that the sum beam peak and difference pattern null have a small spatial deviation.

Table 1. Measured gain and HPBW of the plannar horn array in E-plane.

Scan angle in E-plane, deg	**Gain at 8.2 GHz, dBi**	**Gain at 8.5 GHz, dBi**	**Gain at 8.8 GHz, dBi**	**HPBW at 8.2 GHz, deg**	**HPBW at 8.5 GHz, deg**	**HPBW at 8.8 GHz, deg**
0	42.27	42.51	42.73	1.33	1.29	1.25
15	42.05	42.38	42.50	1.38	1.34	1.29
25	41.67	41.98	42.08	1.47	1.42	1.38
35	41.22	41.46	41.60	1.62	1.57	1.53
45	40.66	40.94	41.21	1.88	1.82	1.77
55	39	39.2	39.3	2.32	2.24	2.16

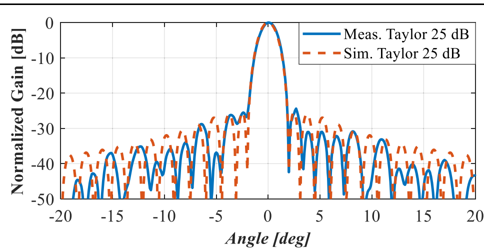


Figure 8. Measured radiation pattern in the vertical plane with Taylor 25 dB distribution at 8.5 GHz.

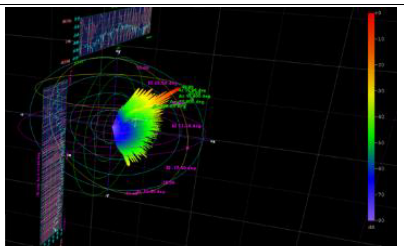
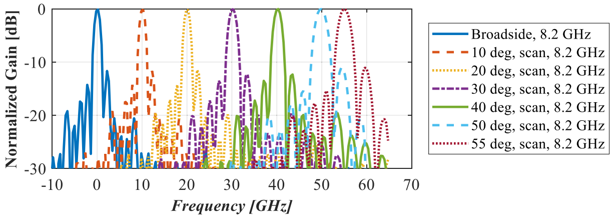
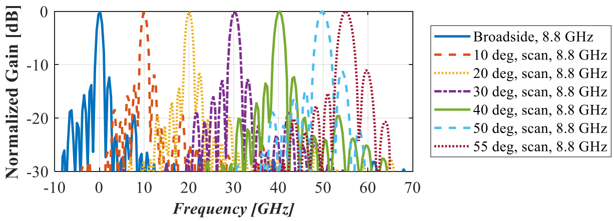


Figure 9. Measured 3D radiation pattern of steering beam at 55^0 in the vertical plane.

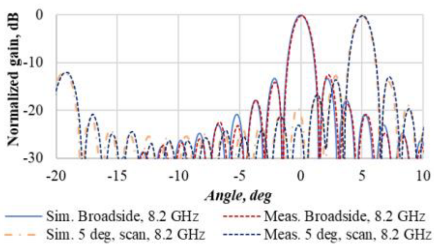


a) at 8.2 GHz

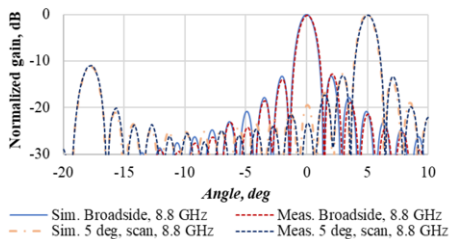


b) at 8.8 GHz

Figure 10. Measured scanning radiation pattern of the array antenna in the E plane with rectangle distribution

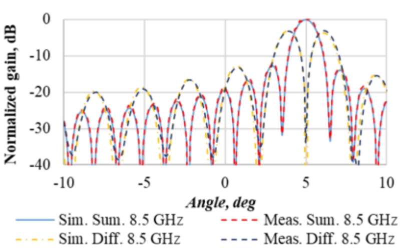


a) at 8.2 GHz

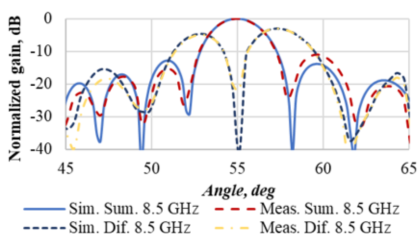


b) at 8.8 GHz

Figure 11. Scanning radiation pattern of the array antenna in the H plane with rectangle distribution



a) with 5 degree scan in the horizontal plane.



b) with 55 degree scan in the vertical plane.

Figure 12. Sum and difference radiation pattern of the array antenna at center frequency

As can be noticed that the results of measuring the planar horn array antenna are well satisfied to the specifications of antenna system for radar applications: the peak gain of 42.7 dBi, a pencil beam with narrow beamwidth, wide scan angle and broad bandwidth.

4. Summary

The authors have proposed a planar horn array antenna for radar applications. The horn array antenna composed of 5184 horn elements divided into 72 linear subarrays which consisting of 18 four-horn subarrays, each subarray is fed by one in 1296 channels of Trans-Receive System. To confirm the performance of the design, the antenna has been fabricated and measured in chamber room. The results indicate that the antenna has measured gain higher than 42 dBi, the measured HPBW is less than 1.4 degree in both the E and H-plane, wide scan angle without grating lobe in the vertical plane and a broad bandwidth of 7% (8.2 – 8.8 GHz) with active VSWR ≤ 1.5 in phase and active VSWR ≤ 2 when scanning upto ±55 degree. The proposed horn array antenna itself proves a perfect structure for radar applications.

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