IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received May 14, 2018, accepted June 11, 2018, date of publication June 25, 2018, date of current version July 25, 2018.

Digital Object Identifier 10.1109/ACCESS.2018.2850309

A Novel Corporate-Feed Horn Sub-Array Antenna for the 77 GHz-Band

BAO-JIAN GAO[1], YU-HUI REN[1], HAN-DONG WU[2], XUE LIAO[1], KE LI[1], AND FU-WEI WANG[1]
[1]School of Information Science and Technology, Northwest University, Xi'an 710127, China
[2]Xi'an Hengda Microwave Technology Development Company, Xi'an 710100, China

Corresponding author: Yu-Hui Ren (ryhui13579@163.com)

This work was supported in part by the National Key Research and Development Plan of China under Grant 2017YFB1400301 and in part by the Shaanxi Provincial Natural Science Foundation of China under Grant 2018JM6077.

ABSTRACT A novel 2 × 2-element corporate-feed horn sub-array antenna for the 77-GHz band is proposed in this paper. The stair-stepping horn is employed instead of a traditional pyramid horn to reduce the profile of the array. A set of composite structure composed of waveguide divider and cavity is designed and fabricated integrally with a computer numerical control milling technique to simplify the feed-network. Most of all, a metallic cross bar with the wall is innovatively loaded to reduce the mutual coupling and suppress the side lobe level of the sub-array. Measured results show that the proposed antenna achieves a -10 dB $|S_{11}|$ with a bandwidth of 72–85 GHz which is corresponding to 16.6%. Moreover, the average gain of the antenna is about 19 dB, and the side lobe level of the antenna is less than -9.3 dB within the working band.

INDEX TERMS Planar array, corporate feeding, stair-stepping horn antenna, mutual coupling.

I. INTRODUCTION

With the rapid development of diverse application requirements, the design of modern radar system is increasingly moving toward miniaturization and high resolution. Since the antenna is the vital part of radar system, it is particularly critical for the entire system to achieve the small size and high resolution. The planar array antennas with different types of radiation elements have gradually become the preferred form of radar antennas, due to its compact structure, small-sized, and low profile. In addition, operating frequencies of radar systems moves to higher frequencies, such as millimeter-wave and submillimeter wave band, where radar antennas are easy to achieve high resolution, miniaturization, narrow beam, and high gain. On the other hand, the processing difficulty and manufacturing cost are increased owing to the small sized antenna.

Microstrip patch, waveguide slot, printed dipole, and horn are usually employed as the antenna element for planar array antennas [1]–[9]. Specifically, the microstrip antenna has the advantages of small volume, low cost, and simple structure, but it is also limited by the narrow band, the low efficiency and the low power capacity. In [1] and [2], the polarization-adjustable array antennas were employed based on a microstrip feeding network. However, because of increasingly line-to-line coupling and transmission loss, microstrip line may be not an ideal choice at higher frequencies. A Ka-band 2×2 microstrip antenna array integrated with single-layer substrate integrated waveguide (SIW) feeding network is designed and tested in [3]. Different polarization status can be yielded from variable excited signals, and SIW is also used in mutual coupling control among array elements. Nevertheless, the antenna has a very narrow bandwidth of 3∼4%. For the waveguide slot antenna, a high power capacity and a low transmission loss can be achieved. In [4], a wideband high-gain high-efficiency 16×16-element slot antenna array is presented for 60-GHz band applications. The antenna achieve about 12% of reflection coefficient bandwidth with more than 70% antenna efficiency. But, the bandwidth of conventional waveguide slot arrays is still relatively narrow because of the long line effect of the series feed network [4], [6]. The printed dipole presented in [7]–[9] can work within a wide frequency range, but it has a much higher profile, and even larger coupling as formed arrays. Horn antenna is attractive because it has not only achieved high power level and efficiency, but also a widely bandwidth. Moreover, if a non-standard size horn is used, the aperture size and height of the element will also be greatly reduced, which makes it easier to form an array.

In this paper, a planar array antenna working in W-band (center frequency $f_0 = 77$GHz) with the size of $790 \times 70 \times 20$ mm^3 is proposed. Considering the power, efficiency, and bandwidth, a horn antenna is employed as an

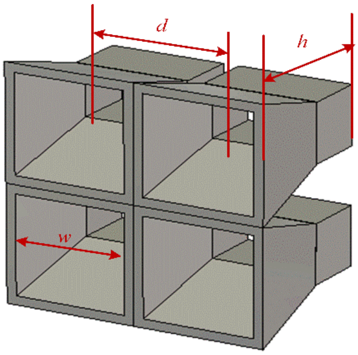


FIGURE 1. Configuration of conventional pyramidal horn arrays.

array element. And then the quantity of antenna elements is estimated after the parameters on side lobe and gain analyzed, which is about 64×8 elements. However, if a traditional pyramid horn as shown in Fig. 1 is used to form the array, which leads to the questions:

1) When the number of elements soars, the feed network in the millimeter band may be distributed complicatedly, even difficultly to design.
2) If the antenna aperture size w is extended, the element quantities would be reduced and the process of designing feed network would be simplified accordingly. However, the increased element spacing d is may lead to the higher side lobe, even for grating lobes [10].
3) The element height h should be as small as possible due to the limited profile of planar array antenna in the research. While the height of the pyramidal horn element may not meet the requirements.

In conclusion, a novel 2×2-element sub-array fed by the corporate-feed structure is proposed in this paper, which could be used as the basic element of a large planar array antenna. Specifically, the design methods are as follows:

1) In order to simplify the design process of the feed-network significantly, the 2×2-element sub-array that consists of four stair-stepping horns is proposed, and each horn is fed by a set of composite structure composed of waveguide divider and cavity. Moreover, the 2×2-element sub-array is integrally fabricated with computer numerical control milling (CNC) technique.
2) The pyramid horn is replaced by a stair-stepping horn to satisfy the limited of h, thus the profile of the planar array antenna is greatly reduced.
3) A metallic cross bar with the wall is innovatively loaded in the sub-array aperture, and then the aperture is divided into four units. On the one hand, the phase difference between the center and the edge in aperture could be reduced, and the distribution of the field in the aperture could be made more uniform. On the other hand, the mutual coupling between the elements and the side lobe of the sub-array are efficiently suppressed.

II. ANTENNA CONFIGURATION

The three-dimensional (3D) view of 2×2-element sub-array antenna designed in this paper is shown in Fig. 2. This sub-array is integrated with three layers: ***E***-plane H-junctions waveguide feed network, coupled feeding cavity, and a metallic cross bar with the wall, from bottom to top, respectively.

E-plane H-junctions waveguide feed network is placed in the bottom layer, and the power is fed from waveguide port which is divided into four ways after getting through the feed network. And in the curved portion of whole feeding network, the right-angle waveguide acts as a stepped impedance transformation structure to improve the impedance matching is employed, which could miniaturize the size of network compared to conventional circularly curved waveguide.

The coupled feeding cavity structure is designed in the middle layer. It is used mainly to couple power from power-divider network to the cavity through the coupling shot. While if the electromagnetic energy in the cavity could be directly radiated out through the horn, similar to the traditional design shown in Fig. 1, which may bring on the problems:(1) There is a great phase difference as with increasing the aperture size. (2) The isolation between the elements gets worse. Both of which would increase the side lobe of the antenna and deteriorate the radiation characteristics.

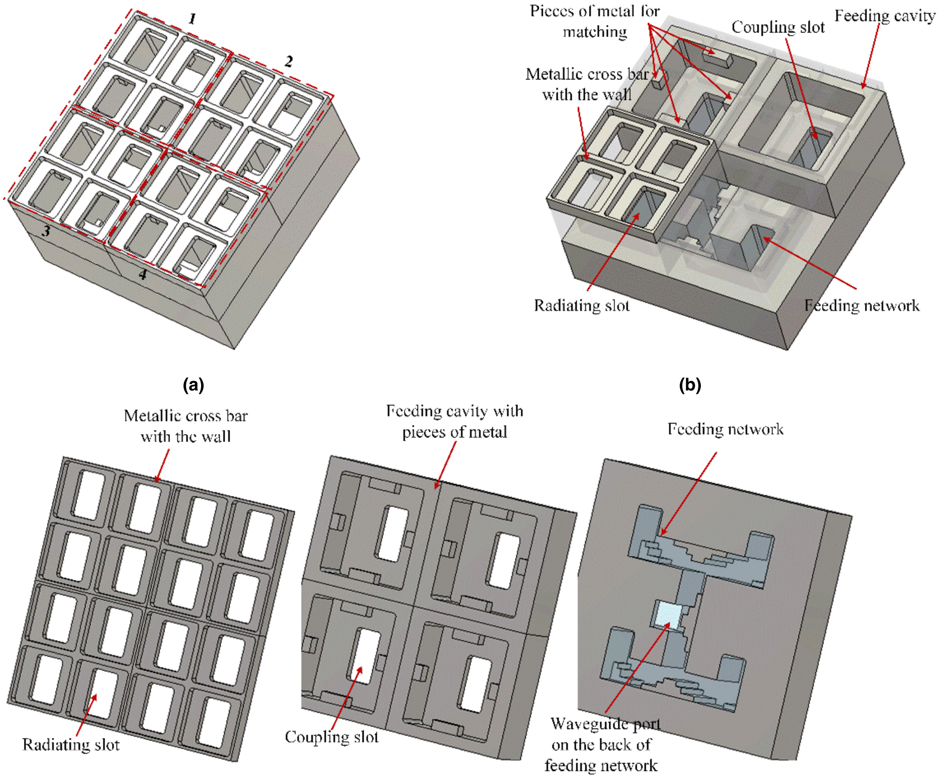
In order to solve these problems, this paper based on [11]–[13] presents a metallic cross bar with the wall placed above the coupled feeding cavity, and four units are gained in the horn aperture. The potential benefits of this method are that the field of horn aperture is distributed uniformly and the mutual coupling among the radiating elements is restrained by the bulging edges of the metallic cross bar with the wall. Furthermore, pieces of metal loaded in the cavity are utilized to adjust the matching between the cavity and metallic cross bar.

III. DESIGN AND ANALYSIS OF ANTENNA

A. STAIR-STEPPING HORN ARRAY ELEMENT

The 2×2 sub-array antenna designed in this paper is shown in Fig. 2(a), and it is composed of four horns fed by a composite structure. Fig. 3 shows the basic structure of the array element. The operational mechanism of antenna can be explained in this way: The electromagnetic energy in the waveguide power division network is coupled to the cavity through the coupling slot, and then is divided equally into four radiation units by the metallic cross bar. Accordingly, this is essentially a stair-stepping horn element which is similar to that of a waveguide stepped impedance transformation [14]. The distinct advantage, compared with traditional pyramidal horn antennas, is that the height could be greatly reduced.

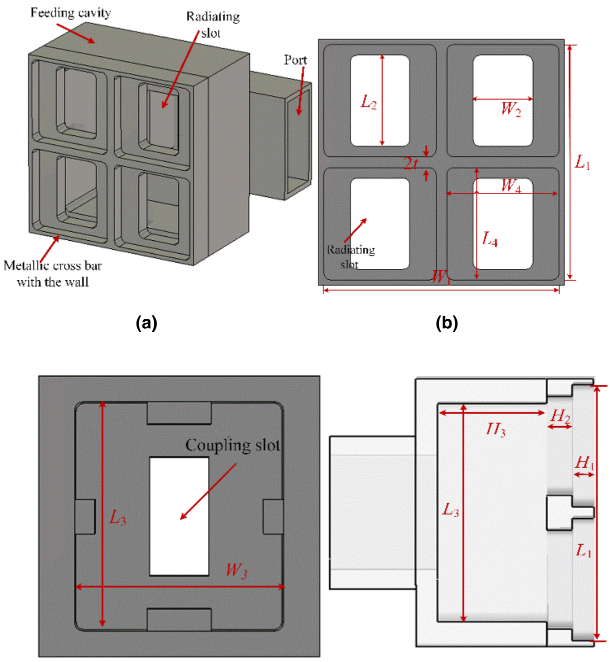
As mentioned above, the bulging edges of the metallic cross bar could suppress the mutual coupling. Referring to the array shown in Fig. 2(a), the mutual coupling effects reducing method of the radiating elements is analyzed. Firstly, element 1 is excited and the S-parameters of the array is simulated with the height of the wall (H_1) varies. The simulation result is shown in Fig. 4, and it can be observed that for the elements 1 and 2 arranged in the direction of the electric field,



(a) (b)

(c)

FIGURE 2. Configuration of the 2 × 2-element sub-array. (a) global view, (b) perspective view, (c) exploded view.



(a) (b)

(c) (d)

FIGURE 3. Configuration of the horn array element. (a) global view, (b) top view of metallic cross bar, (c) top view of feeding cavity, (d) side view.

the raised metal walls can reduce the mutual coupling (S_{21}) by about 4 dB. For elements 1 and 3 arranged along the direction

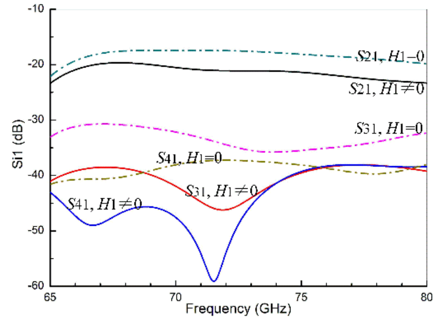
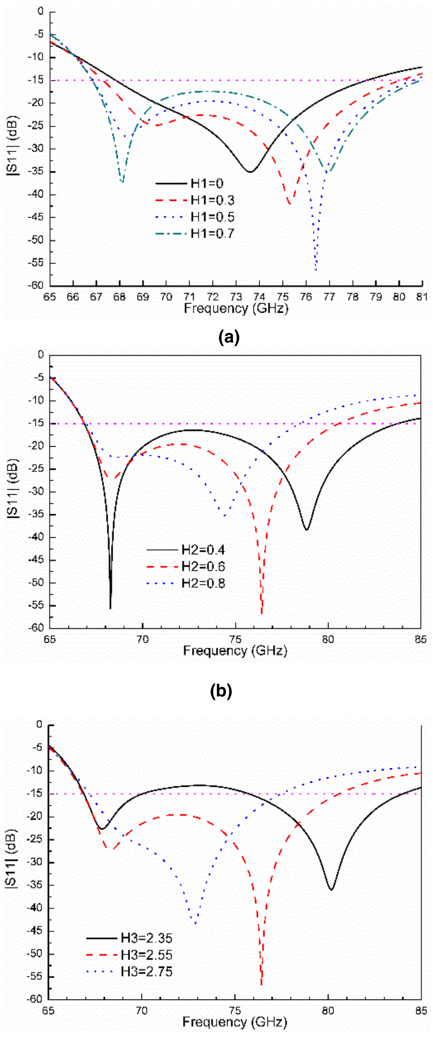


FIGURE 4. Mutual Couplings among four elements.

of the magnetic field, the raised metal walls reduce the mutual coupling (S_{31}) by about 10 dB. The mutual coupling (S_{41}) between the elements 1 and 4 placed diagonally is reduced by a maximum of 20 dB and suppressed to below −45 dB.

Fig. 5 shows the influence of the element parameters H_1, H_2, and H_3 on the reflection coefficient ($|S_{11}|$) of the antenna. As shown in Fig. 5(a), it implies that the low-frequency resonance shifts toward higher frequency and the high-frequency resonance shifted towards lower frequency with the H_1 decreases, which eventually narrowed the bandwidth. As shown in Fig. 5(b), when H_2 increases from 0.4 *mm* to 0.8 *mm*, the high-frequency resonance of the antenna gradually shifts toward the low frequency. At the same time, the matching at the low-frequency resonance point



(a)

(b)

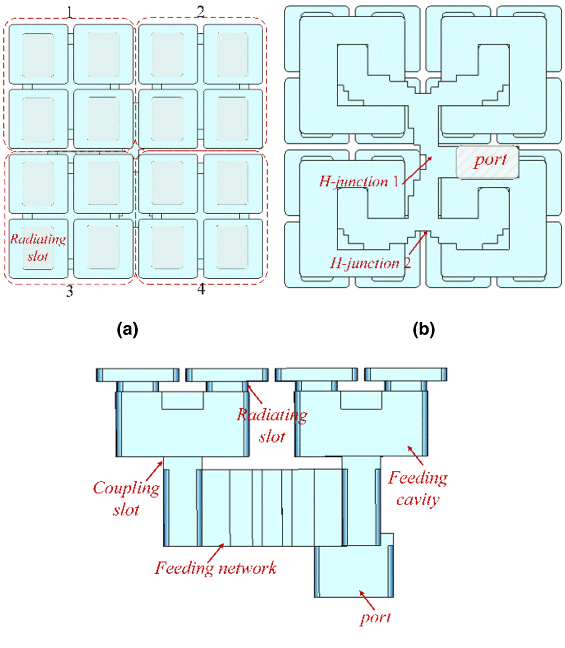
(c)

FIGURE 5. Simulated reflection coefficient of the proposed array element for different dimensions.

deteriorates, and the $|S_{11}|$ increases. When H_3 changes from 2.35 *mm* to 2.75 *mm*, Fig. 5(c) shows that the trend of high-frequency resonance is similar with 'H_2', while the low-frequency resonance stays stable.

B. 2×2-ELEMENT HORN SUB-ARRAY ANTENNA

Ultimately, the 2×2-element sub-array consisted of the four array elements and the waveguide power divider network is presented as shown in Fig. 2, and Fig. 6 shows the internal hollow structure of the sub-array. The 2×2 stair-stepping horn array elements are fed by waveguide ***E***-plane H-junction power divider, and the metallic step wedges in the elbow part of waveguide are used to adjust impedance matching. Fig. 7 describes the simulated *S*-parameters of the feed network. It can be seen that the simulated reflection bandwidth is 26.7% (65GHz∼85GHz) for $|S_{11}|<-20$dB. It means that *VSWR* is less than 1.2 in the same bandwidth. The transmission coefficient of the every output ports ($|S_{21}| \sim |S_{51}|$) is stable at -6dB, and the difference among them is about 0.6dB.



(a)

(b)

(c)

FIGURE 6. Internal hollow structure of the 2×2-element sub-array. (a) top view, (b) upward view, (c) side view.

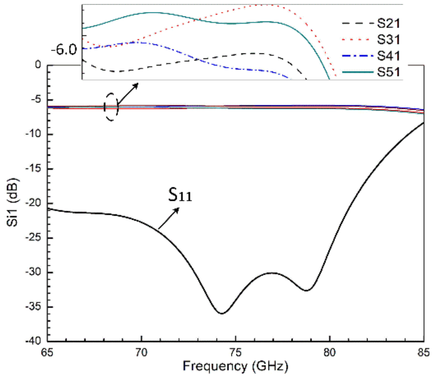
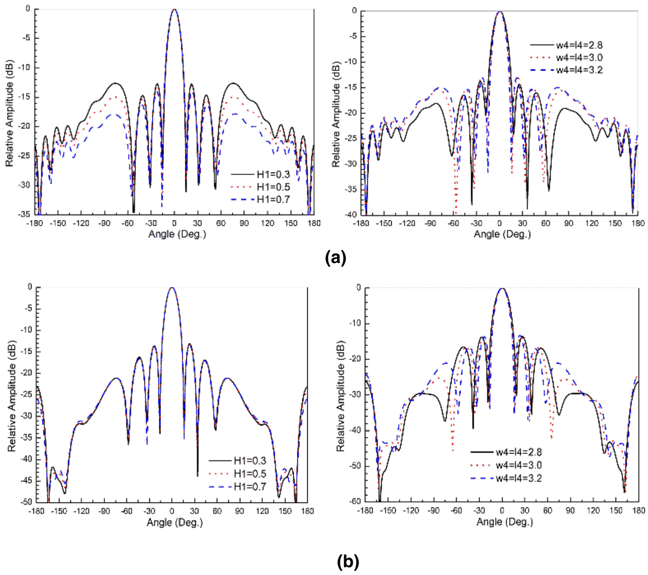


FIGURE 7. Simulated S-parameters of the feed network.

TABLE 1. Dimensions of the proposed antenna.

Parameters	W_1	W_2	W_3	W_4	L_1	L_2
Values/mm	6.7	1.6	5.7	3.2	6.7	2.6
Parameters	L_3	L_4	H_1	H_2	H_3	
Values/mm	5.2	3.2	0.5	0.4	2.55	

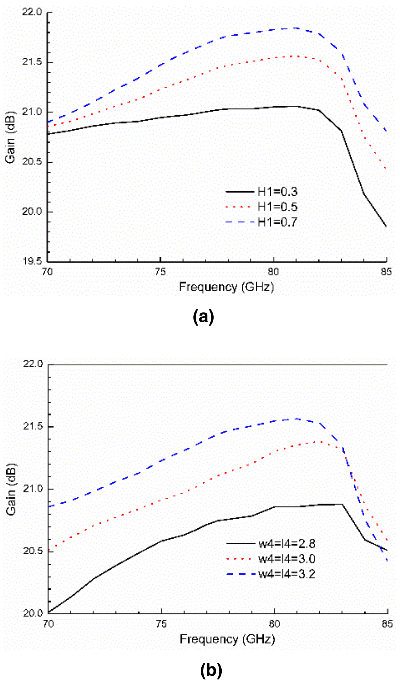
Fig. 8 shows the influence of parameters H_1, W_4, and L_4 on the radiation pattern of the antenna at 77 GHz in both ***E***-plane and ***H***-plane. And the effect of these parameters on the gain is shown in Fig. 9. The side lobe level of sub-array antenna on



(a)

(b)

FIGURE 8. Simulated radiation patterns of the proposed array for different dimensions (f_0 = 77 GHz). (a) *E*-plane,(b) *H*-plane.

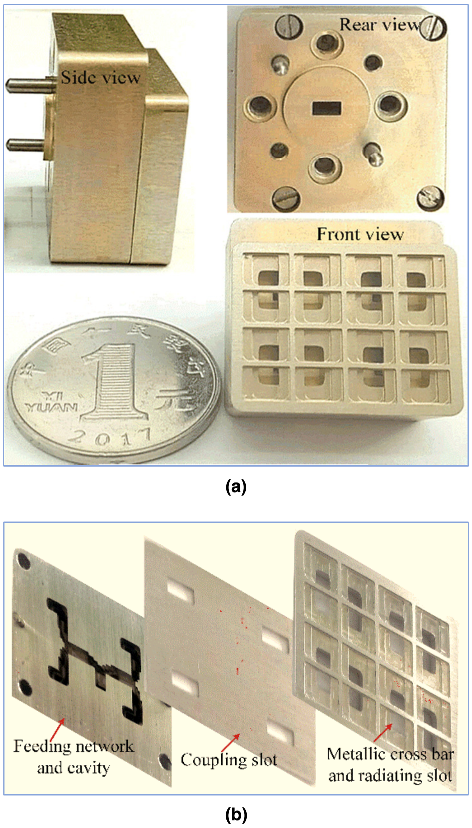


(a)

(b)

FIGURE 9. Simulated gain of the proposed array for different dimensions.

the ***E***-plane, as H_1 increased, is significantly reduced, while the gain is improved greatly. Besides, it has little effect on radiation performance on the ***H***-plane. Meanwhile, W_4 and L_4 are designed to be equal in the design, so that the beam width of the ***E***-plane and the ***H***-plane could be the same. As the value of W_4 and L_4 varies from 2.8 *mm* to 3.2 *mm*, the beam width has been narrowed and the gain has been grown clearly. After simulation and optimization on the parameters and performance of the antenna, the structural dimension parameters of the antenna are ultimately gotten in Table 1.



(a)

(b)

FIGURE 10. Photograph of the fabricated array by CNC milling. (a) Overall structure at different view, (b) exploded view.

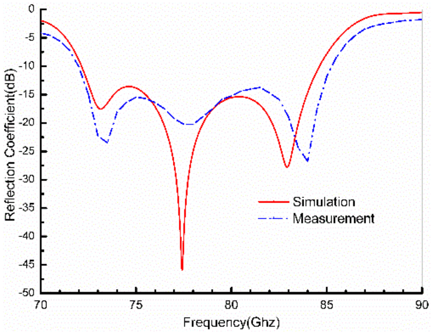


FIGURE 11. Simulated and measured reflection coefficient of the proposed array.

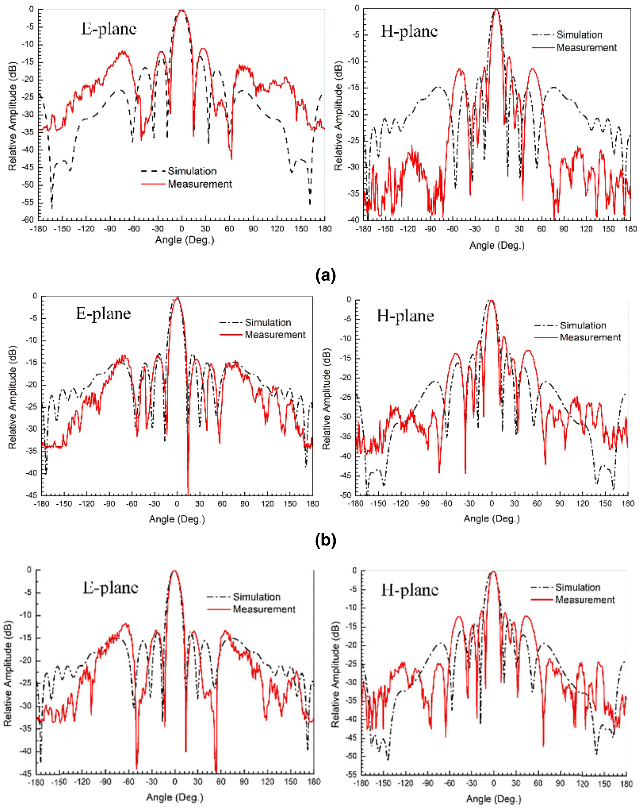
IV. EXPERIMENTAL RESULTS

The prototype of the proposed antenna is manufactured and measured. Fig. 10 shows the photo of the antenna, and the three parts shown in Fig. 10(b) are fabricated by CNC technique, respectively. The metal cylinders and round holes in rear view have been designed for installation and location. Taking into account the waveguide wall thickness, the presented 2×2 sub-array size is 21.2 *mm* × 21.2*mm* × 10.2*mm*.

The simulated and measured reflection coefficient of the 2×2 sub-array are shown in Fig. 11. The antenna exhibits about 16.6% bandwidth (from 72 to 85 GHz) for

TABLE 2. Detailed parameters of proposed antenna.

Frequency (GHz)			75	76	77	78	79
Gain (dB)		Sim.	21.23	21.32	21.40	21.47	21.50
		Meas.	18.96	19.37	19.55	19.63	19.91
-3dB Beam Width (deg.)	E-plane	Sim.	13.70	13.60	13.40	13.40	13.20
		Meas.	14.08	13.16	12.71	12.68	12.26
	H-plane	Sim.	14.60	14.40	14.20	14.00	13.80
		Meas.	10.39	9.68	10.01	10.09	10.29
Side Lobe Level (dB)	E-plane	Sim.	-12.80	-13.00	-13.00	-13.40	-13.40
		Meas.	-11.20	-11.58	-13.29	-12.07	-11.67
	H-plane	Sim.	-13.30	-13.30	-13.30	-13.20	-13.00
		Meas.	-9.30	-9.46	-9.50	-9.89	-10.66



(a)

(b)

(c)

FIGURE 12. Simulated and measured radiation patterns of the proposed 2×2 sub-array. (a) 75 GHz, (b) 77 GHz, (c) 79 GHz.

$|S_{11}| \leq -10$ dB. In addition, good agreement between simulated and measured results has been obtained.

Fig. 12 shows the simulated and measured radiation patterns of the proposed antenna at 75 GHz, 77 GHz and 79 GHz both at ***E***-plane and ***H***-plane. It can be observed that good agreement between simulated and measured results is achieved at 77GHz and 79GHz. However, they are greatly different at 75 GHz. It may be caused by machining errors. Moreover, the grating lobes are inspired, because the element spacing d is $1.8\lambda_0$ (λ_0 is the wavelength corresponding to f_0). Usually, to suppress the grating-lobe, two potential ways could be adopted: (1) Reducing the element spacing d to be less than λ_0, which is rather difficulty for the millimeter feed network design. (2) Reducing the mutual coupling to make the aperture field distributed evenly. Therefore, a compromise between the complexity of the entire design and the side lobe level of the antenna has been made, which is adjusting the height H_1 to decrease the mutual coupling, and changing the aperture size of W_4 and L_4 to improve field distribution. Table 2 shows the whole pattern characteristics of the antenna designed in this paper.

V. CONCLUSION

A 2×2-elements horn array for the 77 GHz band has been designed, fabricated, and measured. The metallic cross bar with the wall is employed to uniformize the aperture field distribution, reduce the mutual coupling between the elements, and suppress the grating lobes level. The measured results show that the proposed antenna achieves a -10 dB $|S_{11}|$ bandwidth of 72 GHz-85 GHz (16.6%). It also shows the average gain of the antenna is about 19 dB over the operating frequency band. The array not only could be used separately, but also to form a planar array antenna.

REFERENCES

[1] Y.-J. Chi and F.-C. Chen, "60-GHz polarization-adjustable antenna arrays," *IEEE Trans. Antennas Propag.*, vol. 63, no. 7, pp. 2887–2894, Jul. 2015.

[2] I. Slomian, K. Wincza, and S. Gruszczynski, "Series-fed microstrip antenna lattice with switched polarization utilizing butler matrix," *IEEE Trans. Antennas Propag.*, vol. 62, no. 1, pp. 145–152, Jan. 2014.

[3] F. C. Ren, W. Hong, K. Wu, D. Yu, and Y. T. Wan, "Polarization-adjustable planar array antenna with SIW-fed high-order-mode microstrip patch," *IEEE Trans. Antennas Propag.*, vol. 65, no. 11, pp. 6167–6172, Sep. 2017.

[4] D. Zarifi, A. Farahbakhsh, A. U. Zaman, and P. S. Kildal, "Design and fabrication of a high-gain 60-GHz corrugated slot antenna array with ridge gap waveguide distribution layer," *IEEE Trans. Antennas Propag.*, vol. 64, no. 7, pp. 2905–2913, Jul. 2016.

[5] R. V. Gatti and R. Rossi, "A dual-polarization slotted waveguide array antenna with polarization-tracking capability and reduced sidelobe level," *IEEE Trans. Antennas Propag.*, vol. 64, no. 4, pp. 1567–1572, Apr. 2016.

[6] H. Guan-Long, Z. Shi-Gang, C. Tan-Huat, and Y. Tat-Soon, "Broadband and high gain waveguide-fed slot antenna array in the Ku-band," *IET Microw., Antennas Propag.*, vol. 8, no. 13, pp. 1041–1046, Oct. 2014.

[7] Y.-H. Ren, J. Ding, C.-J. Guo, Y.-C. Song, and Y. Qu, "A wideband gain-enhanced dual-polarized printed antenna based on log-periodic parasitic directors (LPPDs)," *J. Electromagn. Waves Appl.*, vol. 30, no. 8, pp. 1021–1031, 2016.

[8] Y.-H. Ren, J. Ding, C.-J. Guo, Y. Qu, and Y.-C. Song, "A wideband dual-polarized printed antenna based on complementary split-ring resonators," *IEEE Antennas Wireless Propag. Lett.*, vol. 14, p. 410-413, 2014.

[9] X. S. Wei, J. H. Liu, and Y. L. Long, "Printed log-periodic monopole array antenna with a simple feeding structure," *IEEE Antennas Wireless Propag. Lett.*, vol. 17, no. 1, pp. 58–61, Jan. 2017.

[10] R. J. Mailloux, *Phased Array Antenna Handbook*, 2nd ed. Norwood, MA, USA: United States, Artech House, 2005.

[11] D. Kim, J. Hirokawa, M. Ando, J. Takeuchi, and A. Hirata, "4×4-element corporate-feed waveguide slot array antenna with cavities for the 120 GHz-band," *IEEE Trans. Antennas Propag.*, vol. 61, no. 12, pp. 5968–5975, Dec. 2013.

[12] Z. Shi-Gang, H. Guan-Long, P. Zhao-Hang, and L.-J. Ying, "A wideband full-corporate-feed waveguide slot planar array," *IEEE Trans. Antennas Propag.*, vol. 64, no. 5, pp. 1974–1978, May 2016.

[13] K. Tekkouk *et al.*, "Corporate-feed slotted waveguide array antenna in the 350-GHz band by silicon process," *IEEE Trans. Antennas Propag.*, vol. 65, no. 1, pp. 217–225, Jan. 2017.

[14] B. Zhang, Y.-X. Guo, H. Sun, and Y. Wu, "Metallic, 3D-printed, k-band-stepped, double-ridged square horn antennas," *Appl. Sci.*, vol. 8, no. 1, pp. 33–39, 2017.

BAO-JIAN GAO was born in Baoji, Shaanxi, China, in 1963. He received the B.S. degree in mathematics from Northwest University, Xi'an, in 1985, and the M.S. degree in electronic and communications systems from Xidian University, Xi'an, in 1988.

From 1988 to 2001, he was a Senior Engineer with the Telemeter and Telecontrol Laboratory, Xi'an Electromechanical Institute. Since 2001, he has been an Associate Professor with Northwest University. He is the author of one book and over 64 articles. His research interests include physical-layer security, antenna design, and microwave circuit.

YU-HUI REN received the B.S. degree in communication engineering from the China University of Geosciences, Wuhan, China, in 2003, the M.S. degree in signal and information processing from Northwest University, Xi'an, China, in 2010, and the Ph.D. degree in electromagnetic wave and microwave technology from Northwestern Polytechnical University, Xi'an, in 2017. He is currently an Associate Professor with the School of Information Science and Technology, Northwest University. He has authored or co-authored over 10 papers in SCI journals. His research interests include antenna array designs, metamaterials, and UWB antennas.

HAN-DONG WU was born in Dongtai, Jiangsu, China, in 1952. He received the B.E. degree in microwave technology from the Beijing Institute of Technology, Beijing, China, in 1976. From 1977 to 1992, he was an Engineer with the North Electronics Research Institute, Norinco Group. He founded Xi'an Hengda Microwave Technology Development Company Ltd., where he has been a Chief Engineer since 1993. He has authored over 80 articles. His research interests include microwave measurements, phased-array antenna design, and microwave circuit designs.

XUE LIAO was born in 1992. He is currently pursuing the M.S. degree with the School of Information Science and Technology, Northwest University, Xi'an, China. Her research interests include millimeter-wave antennas and arrays.

KE LI received the B.S. degree in electronic information engineering and the Ph.D. degree in electromagnetic wave and microwave technology from Xidian University, Xi'an, China, in 2011 and 2016, respectively. She is currently a Lecturer with the School of Information Science and Technology, Northwest University, Xi'an. Her research interests include multiband antenna design, reconfigurable antennas, and metamaterials.

FU-WEI WANG received the B.S. degree in electronic information engineering and the Ph.D. degree in electromagnetic wave and microwave technology from Xidian University, Xi'an, China, in 2009 and 2014, respectively. He is currently a Lecturer with the School of Information Science and Technology, Northwest University, Xi'an. His research interests include antenna scattering, antenna RCS reduction, and metamaterials.

• • •