IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

Received June 12, 2018, accepted July 11, 2018, date of publication July 25, 2018, date of current version August 28, 2018.

Digital Object Identifier 10.1109/ACCESS.2018.2859835

mm-Wave High Gain Cavity-Backed Aperture-Coupled Patch Antenna Array

JIANFENG ZHU[1,2], CHEN-HAO CHU[2], LI DENG[1], CHEN ZHANG[1], YANG YANG[3], (Senior Member, IEEE), AND SHUFANG LI[1], (Senior Member, IEEE)

[1]Beijing Key Laboratory of Network System Architecture and Convergence, Beijing University of Posts and Telecommunications, Beijing 100876, China
[2]State Key Laboratory of Millimeter Waves, Electronic Engineering Department, City University of Hong Kong, Hong Kong
[3]School of Electrical and Data Engineering, University of Technology Sydney, Sydney, NSW 2007, Australia

Corresponding author: Shufang Li (bupt_paper@126.com)

This work was supported in part by the National Natural Science Foundation of China under Grant 61427801 and Grant 61601040, in part by the 111 Project under Grant B17007, and in part by the Beijing Nova Program under Grant Z181100006218039.

ABSTRACT A wideband and high gain cavity-backed 4 × 4 patch antenna array is proposed in this paper. Each patch antenna element of the array is enclosed by a rectangular cavity and differentially-fed by the slot underneath. By optimizing the geometry of the radiating patch and the cavity, a very uniform E-field distribution at the antenna aperture is achieved, leading to the high array aperture efficiency and thus the gain. Taking advantages of the higher-order substrate integrated cavity excitation, the elements of the array are efficiently fed with the same amplitude and phase in a simplified feeding mechanism instead of the conventional bulky and lossy power-splitter-based feeding network. Measured results show the antenna bandwidth is from 56 to 63.1-GHz (16.1%) with the peak gain reaching 21.4 dBi. The radiation patterns of the array are very stable over the entire frequency band and the cross-polarizations are as low as −30 dB. These good characteristics demonstrate that the proposed array can be a good candidate for the future 60-GHz communication system applications.

INDEX TERMS mm-wave, cavity-backed, aperture coupled, substrate integrated waveguide, array antenna, higher order mode.

I. INTRODUCTION

With the unprecedented rapid development of the fifth generation (5G) wireless communications in recent years, mm-Wave frequency band, the 60-GHz band in particular, has emerged as one of the most promising candidates for the multi-gigabit wireless indoor communication systems. Due to the continues and the sufficient bandwidth, the communication systems at 60-GHz are capable of achieving a high data rate up to multiple gigabits per seconds, which opens the door to the future wireless data transfer, particularly for the transmission of the uncompressed high-definition video and ultra-fast file [1], [2]. As a vital portion of the communication systems, mm-Wave antennas or arrays that feature low cost, wideband and high gain are in increasing demand. To date, various types of antennas with good performances for mm-Wave applications have been proposed [3]–[29], such as patch antennas [3]–[7], grid antennas [8]–[11], aperture antennas [12]–[14], dipole antennas [15], [16], slot antennas [17]–[23], and cavity-backed antennas [24]–[31].

Although the 60-GHz technology offers various advantages over currently proposed or existing communications systems, it has the disadvantage of the lossy channel with the excess loss approximately up to 15dB/km due to oxygen absorption [32]. Therefore, increasing the transmitter or receiver antenna gain is not only desirable but inevitable to compensate the significant propagation loss caused by the oxygen absorption and ensure that a sufficient margin exists to overcome other loss, such as rain-induced fading. Generally, there are two approaches to increase the antenna gain. One is increasing the radiating aperture size of the antenna while the other is improving the antenna aperture efficiency. The latter is more favorable as antennas with large physical size are usually cost-ineffective and bulky in structure, which is difficult to be integrated into the front-end of the transceiver. To improve the aperture efficiency, cavity-backed antennas have been demonstrated an efficient approach [33]–[35]. By optimizing the cavity geometry and size, a very uniform E-field distribution can be achieved

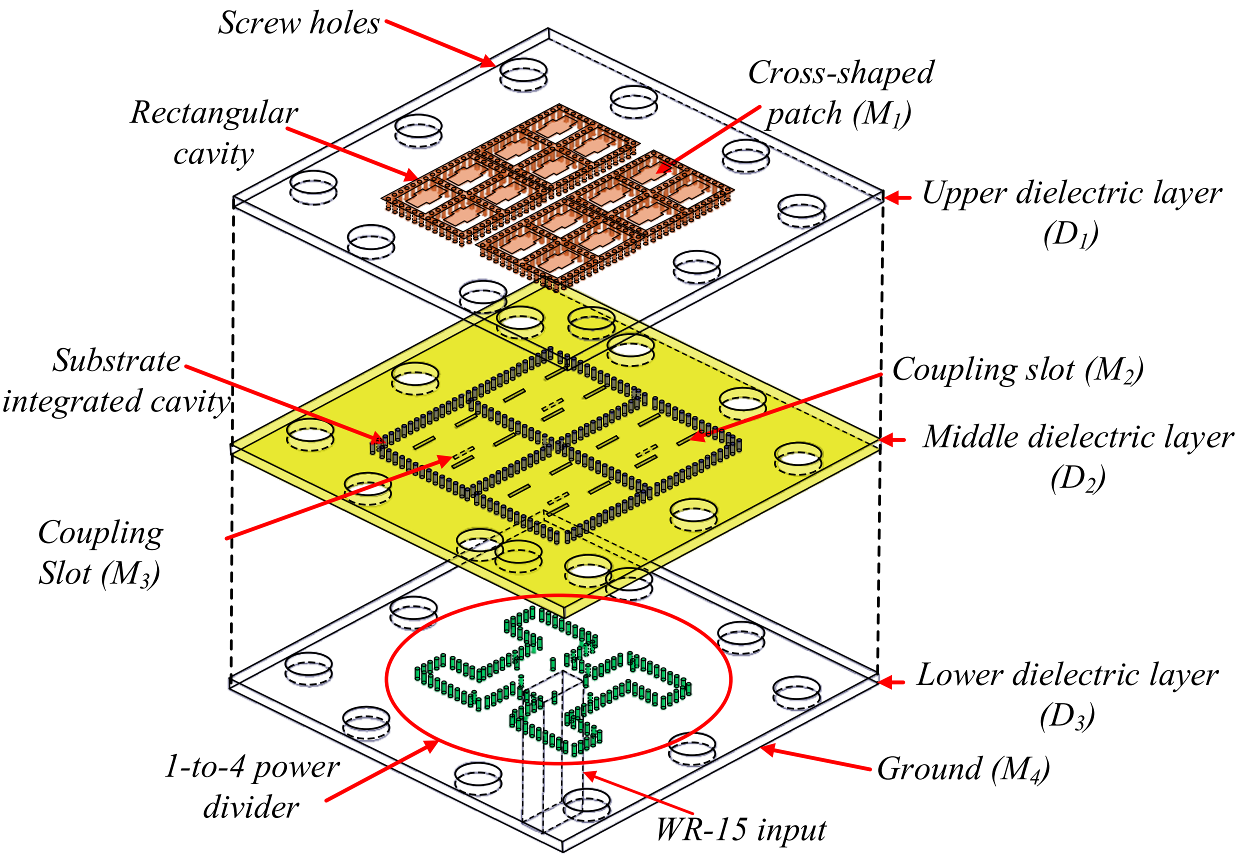


FIGURE 1. 3-D view of the proposed 4×4 antenna array.

at the aperture, leading to a high aperture efficiency [13], [36]–[38]. Moreover, the cavity can suppress the surface wave propagate along the substrate and also reduce the mutual coupling between the adjacent radiating elements of the array, which leads to a high radiation efficiency and stable radiation pattern over the wide frequency bandwidth.

Besides antenna gain and efficiency, the effect of the fabrication tolerance on antenna performance should not be neglected because of the very small wavelengths. Therefore, a highly accurate fabrication technology is required. Otherwise, the antenna performance including matching, gain as well as efficiency will be deteriorated. To alleviate the fabrication tolerance on the antenna performance, higher-order-mode substrate integrated cavity (SIC) excitation was proposed in [39] and [40] instead of other complicated feed networks to reduce the number of metal posts in the cavity for feeding elements of the antenna array. Nevertheless, their impedance bandwidths can be further improved for widespread applications.

In this paper, a new wideband cavity-backed patch antenna array with very high aperture efficiency as well as the gain is proposed for the 60-GHz applications. Firstly, a 2×2-element cavity-backed aperture-coupled patch antenna array is demonstrated, which exhibits high aperture efficiency as well as gain. Taking advantages of the higher-order-mode cavity excitation, the elements of the array are efficiently excited with the same amplitude and phase in a simple TE_{340} mode cavity, which eases the burdens of the conventional bulky and lossy feednetwork containing multiple power splitters and SIW-lines. The higher-order-mode cavity resonance is excited by a simple slot aperture located in the bottom center of the cavity. Then, the 2×2 –element patch array is used as subarray to built a 4×4-element array, as shown in Fig. 1. Measured results show the antenna bandwidth is from 56 to 63.1-GHz (16.1%) with peak gain reaching 21.4 dBi. The radiation patterns of the array are very stable over the entire frequency band and the cross-polarizations are as low as −30 dB. These good characteristics demonstrate the proposed array can be a good candidate for the future 60-GHz communication systems.

II. THE 2 × 2-ELEMENT SIC-EXCITED ARRAY

The geometry of the proposed 2×2-element cavity-backed patch antenna subarray is shown in Fig. 2. The array consists of three Rogers 5880 layers with a dielectric constant of 2.2 and thickness of 0.787mm. The 2×2 cross-shaped radiating patch antenna array incorporated with its rectangular cavity is located in the upper substrate (D_1). Each cross-shaped patch is differentially fed by the coupling slot right underneath the patch. The coupling slot is cut on the top wall

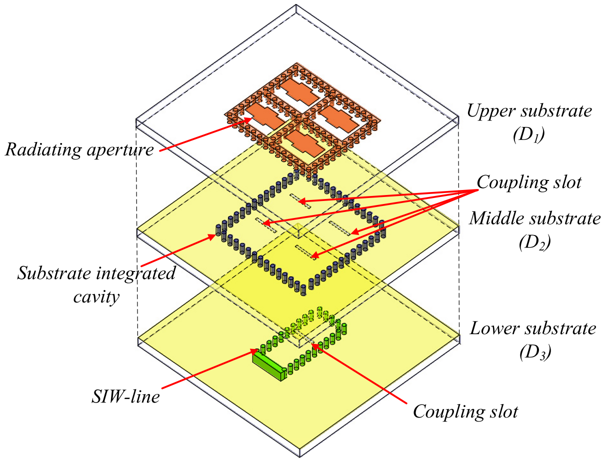


FIGURE 2. 3-D view of the proposed 2 × 2-element cavity-backed aperture-coupled patch antenna array.

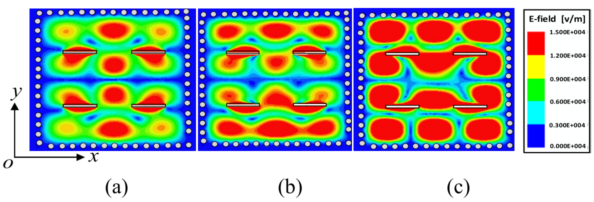


FIGURE 3. Electric field distributions in the cavity at (a) 57-GHz (b) 60-GHz and (c) 63-GHz.

of the substrate integrated cavity (SIC), which is implemented on the middle substrate (D_2) with metallized vias as sidewalls and metals as its top and bottom. The cavity is excited by the center slot in the bottom plane and the slot is cut on the top wall of the lower SIW lines. In order to obtain enough space to arrange the four cavity-backed antenna elements while maintaining a compact size simultaneously, the size of the SIC is adopted as 8.5 mm×8.5mm. In this case, TE_{340} mode is excited in the cavity. The complex E-field distributions in the cavity at 57, 60 and 63-GHz are shown in Fig. 3. It is seen the TE_{340} mode exists over the operating frequency band although the mode slightly deteriorates as the frequency varies. In fact, the radiation performance of the array will not be affected by the mode deterioration due to the fact that the slots cut on the top of the cavity are symmetrical along the center plane, and thus the radiating elements are always excited with the same phase and amplitude.

To evaluate the performance of the proposed subarray, the simulated gains is shown in Fig. 4. It is observed that the gains are escalated from 14.3 to 15.3 dBi with its peak occurring at 60-GHz. In fact, this high gain is achieved due to the uniform E-field distributions at the antenna aperture, which can be easily realized by optimizing the cavity size and the patch geometry that enclosed. To better demonstrate this, the E-field distributions at the top surface of the antenna aperture are shown in Fig. 5. A very uniform

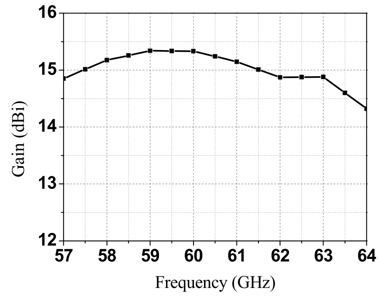


FIGURE 4. Simulated gain versus frequency of the proposed 2×2 antenna array.

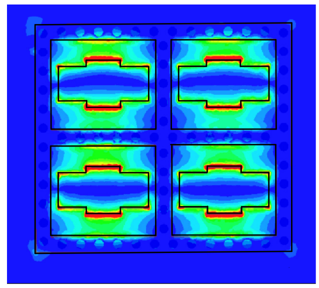


FIGURE 5. Surface E-field distributions at the array aperture.

TABLE 1. Dimensions of the proposed antenna array.

Parameter	s	l_1	l_2	l_3	l_4	l_5	l_6
Value (mm)	40	1.50	3.41	2.84	1.89	2.0	3.24
Parameter	l_7	l_8	l_9	l_{10}	l_{11}	w_1	w_2
Value(mm)	2.45	8.47	1.86	2.68	3.0	1.09	1.11
Parameter	w_3	w_4	w_5	w_6	w_7	w_8	w_9
Value(mm)	0.5	0.16	0.18	0.72	0.56	0.49	0.68
Parameter	d	d_1	d_2	g_x	g_y		
Value (mm)	0.3	1.26	0.2	30	30		

E-field distributions can be observed in each cavity, indicating that the high aperture efficiency as well as the gain can be achieved.

III. THE 4×4-ELEMENT SIC-EXCITED ARRAY

Based on the proposed 2×2 cavity-backed subarray, the 4×4-element array is proposed and verified, as shown in Fig. 1. 4×4 cross-shaped radiating patch array together with its cavity is implemented on the upper layer (D_1). They are excited by the four substrate integrated cavities that are realized in the middle substrate (D_2). The 1-to-4 SIW-based power splitter is implemented on the lower layer (D_3), which is directly fed at the center by the WR-15 waveguide. The distances between the adjacent subarrays are 8.5 mm in both the x-direction and y-direction. Top view of each layer of the array is shown in Fig. 6 and the detailed dimensions of the proposed 4×4 array are given in Table 1.

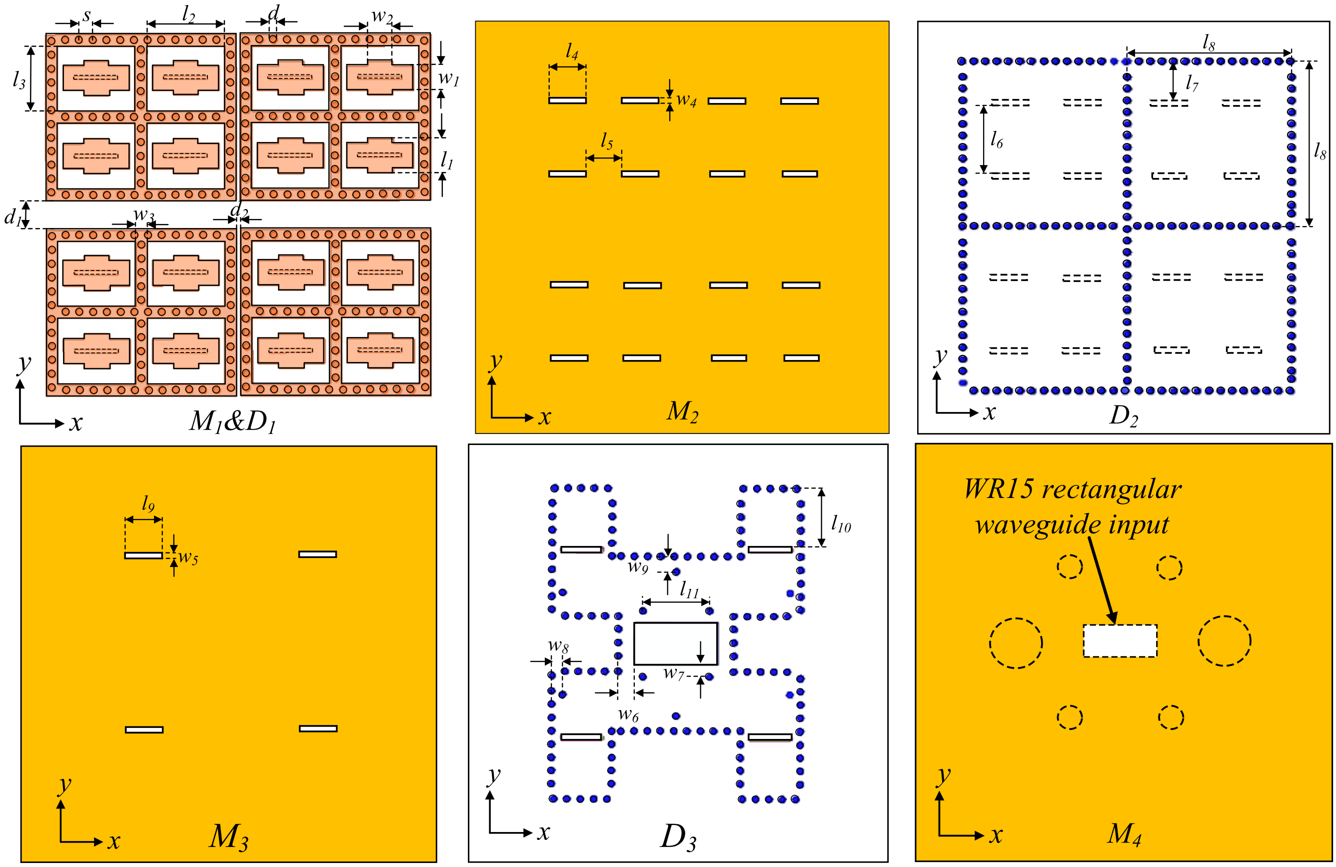


FIGURE 6. Top view of each layer of the array.

A. WAVEGUIDE-FED 1-TO-4 POWER SPLITTER

The amplitude and phase balance of the 1-to-4 power splitter are crucial to the antenna performance. Therefore, the proposed differentially-fed 1-to-4 power splitter is carefully designed and evaluated, as shown in Fig. 7. The simulated performance of the 1-to-4 power divider together with the WR15-to-SIW transition is given in Fig. 8. It is seen that the S_{11} is below -15 dB from 57 to 64-GHz. The energy is equally divided into the four output ports and the phase imbalance is less than 0.5°, indicating the good performance of the proposed waveguide-fed 1-to-4 power splitter.

B. EXPERIMENTAL RESULTS

A prototype is fabricated and measured to verify the design, as shown in Fig. 9. Three Rogers 5880 laminates are fabricated independently and then stacked together by screw holes. Thermally & Electrically Conductive Adhesive (TECA) films are used to bond the dielectric layers and wipe out the possible air between them. The reflection coefficient of the array, which is measured by a Vector Network Analyzer MS4646B, is shown in Fig. 10. The simulated -10 dB bandwidth is from 57 to 64.2-GHz (17.7%) and the measured result is from 56 to 63.1-GHz (16.1%). The antenna gain versus frequency is shown in Fig. 11. The gains are escalated from 19.6 to 21.6 dBi for simulation and from 19.9 to 21.4 dBi for measurement. The formula for calculating aperture efficiency

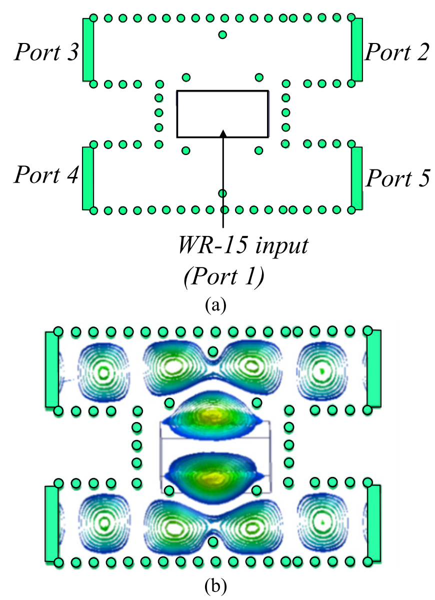
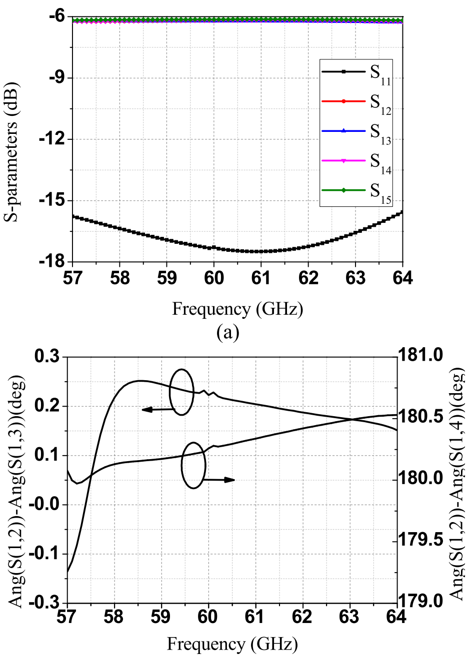


FIGURE 7. (a) WR-15 differentially-fed 1-to-4 power splitter. (b) E-field distributions in the waveguide.

TABLE 2. Comparison of Different arrays working at 60 GHz.

Ref.	Antenna Type	Feeding Network	No. of layer	Volume (length × width ×height) (mm^3)	-10dB Impedance Bandwidth	Peak Gain (dBi)	Aperture efficiency	Radiation efficiency
[3]	L-probe patch(LTCC)	stripline	10	14.1×14.4×1 (2.82×2.88×0.2λ_0)	29%	17.5	Not given	>80%
[4]	Patch array	CPW	1	17×17×3.8 (3.4×3.4×0.76λ_0)	25.5%	16.7	Not given	Not given
[8]	Grid array	Microstrip line	6	15×15×0.6 (3.0×3.0×0.12λ_0)	11.5	17.7	59.9%	Not given
[21]	Slot (PCB)	SIW (Series)	1	30.7×30.7×0.508 (6.1×6.1×0.1λ_0)	4,1%	22	41.2%	68%
[25]	Slot antenna (PCB)	SIW (Parallel)	1	14×13.5×0.635 (2.8×2.7×0.13λ_0)	11.6%	12.2	Not given	Not given
[28]	Cavity (LTCC)	SIW (Parallel)	20	24.6×31×2.0 (4.9×6.2×0.4λ_0)	17.1%	22.1	42.3%	44.4%
[30]	Cavity-backed patch antenna(PCB)	SIW (Parallel)	4	16.3×17.1×2.3 (3.26×3.42×0.46λ_0)	22.6%	19.6	80%	54.5%
This work	Cavity-backed patch (PCB)	SIW (higher-order-mode)	3	30×30×2.4 (6.0×6.0×0.48λ_0)	>18.2%	21.4	70.3%	95%(Sim)



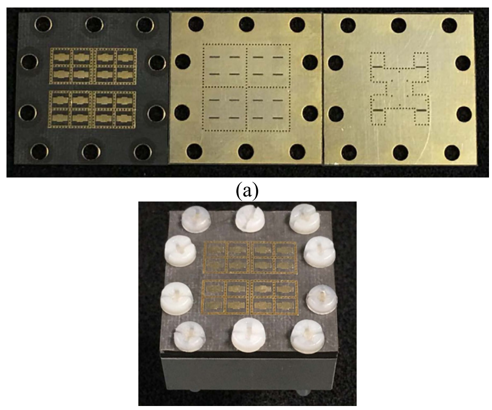
(b)

FIGURE 8. (a) S-parameters of the 1-to-4 power splitter. (b) Phase imbalance of the output ports.

of an aperture antenna ε_{ap} is given by [41]:

$$\varepsilon_{ap} = \frac{G\lambda^2}{4\pi A_p} \tag{1}$$

where G and Ap are the gain and the physical aperture of the antenna, respectively. Considering that the relatively large area (30 × 30 mm^2) of the proposed array is due to the peripheral area occupied by the screw holes and this peripheral area contributes little to the antenna gain, we simulated the antenna boresight gain with dielectric margins that are occupied by the screw hole removed, as shown in Fig. 11. Under this circumstance, the size of the physical radiating area is 20 mm × 20 mm and the calculated aperture efficiency is about 70.3% at 61 GHz, which is acceptable for the array antenna.



(b)

FIGURE 9. Prototype of the antenna array. (a) Top view of each layer. (b) Assemble view.

The radiation patterns of the array at 57, 60 and 63-GHz are given in Fig. 12. The patterns are measured by using the far-field mm-Wave measurement system. Due to the system limitation, only half of the sphere is measured. It is seen the patterns are generally symmetrical with its main beam and the highest gain fixed at its boresight. Cross polarizations

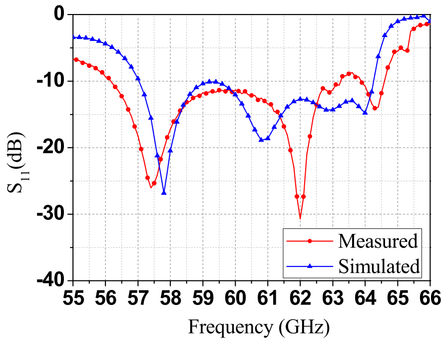


FIGURE 10. simulated and measured reflection coefficient.

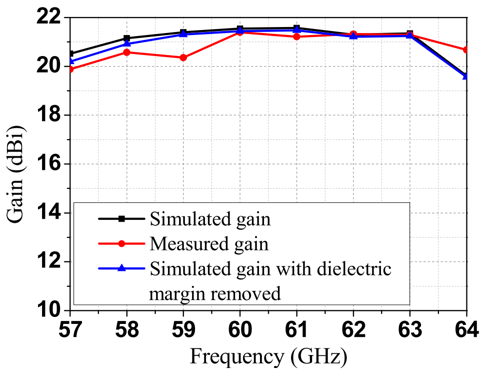


FIGURE 11. Simulated and measured antenna gains.

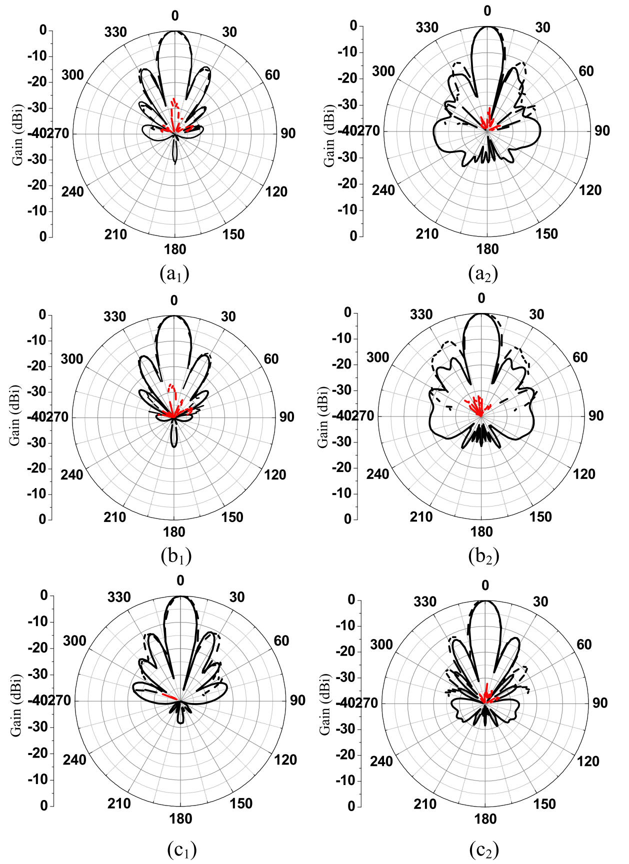


FIGURE 12. Simulated and measured radiation patterns of the proposed array. (Simulated: solid line. Measured: dash line). (a_1) XOZ-plane@58-GHz. (a_2) YOZ-plane @58-GHz. (b_1) XOZ-plane @ 60-GHz. (b_2) YOZ-plane @ 60-GHz. (c_1) XOZ-plane @ 63-GHz. (c_2) YOZ-plane @ 63-GHz.

are lower than −40 dB and −30 dB for the simulation and measurement, respectively. The sidelobes are generally below −12 dB at both planes. The discrepancy between the simulation and measurement is due to the fabrication tolerance and other uncertainties such as dielectric change of the substrate, etc.

The simulated radiation patterns and the gain of the array without the top patch are also given in the Fig. 13 and 14, respectively. As can be seen, the side lobes of the radiation patterns deteriorate at high frequencies. At 60 and 63-GHz, the side lobe levels are worse than −10 dB. The gain of the array also shows about 1.6 to 2 dB drop over the frequency band compared with the proposed design. Therefore, we can conclude that adding the top patch can help to improve the radiation performance of the array through properly adjusting the geometry of the patch.

C. DISCUSSION

Table 2 compares the key characteristics of the proposed antenna array with other 60-GHz antenna arrays. Although patch antenna array with L-probe feed [3], CPW feed [4] and grid array antenna with microstrip feed [8] show many excellent performances including wide impedance matching and good radiation patterns. The aperture efficiency and the gain are lower than the proposed one. Besides, CPW and microstrip line are relatively lossier in 60-GHz frequency band compared with SIW feeding, especially at the discontinuities. In order to obtain high aperture efficiency as well as high gain, patch antennas that are enclosed by the cavity are used in many array designs [21], [25], [29], [30]. Although these designs can achieve very good performance including wide impedance matching, high gain as well as aperture efficiency, they are usually equipped with large SIW (parallel) based feeding network, which consists of plenty of SIW-based power dividers and long SIW lines. Therefore, the loss of the feed network is nonnegligible, which will eventually give rises to the drop of the antenna radiation efficiency. Compared with these works, the proposed design exhibits two advantages. Firstly, the proposed array shows higher radiation efficiency because it uses less power dividers by taking advantages of the high-order-mode cavity excitation. More importantly, the proposed array can be extended to larger array design, such as 8×8 and 16×16-element array using even higher resonant modes without sacrificing the radiation efficiency much. Secondly, the proposed array uses fewer vias compared with the design in [30]. This reduces the cost of the antenna. Moreover, at 60-GHz, the effect of the fabrication tolerance on antenna performance should not be neglected because of the very small wavelengths. The fabrication tolerance will affect the antenna performance including

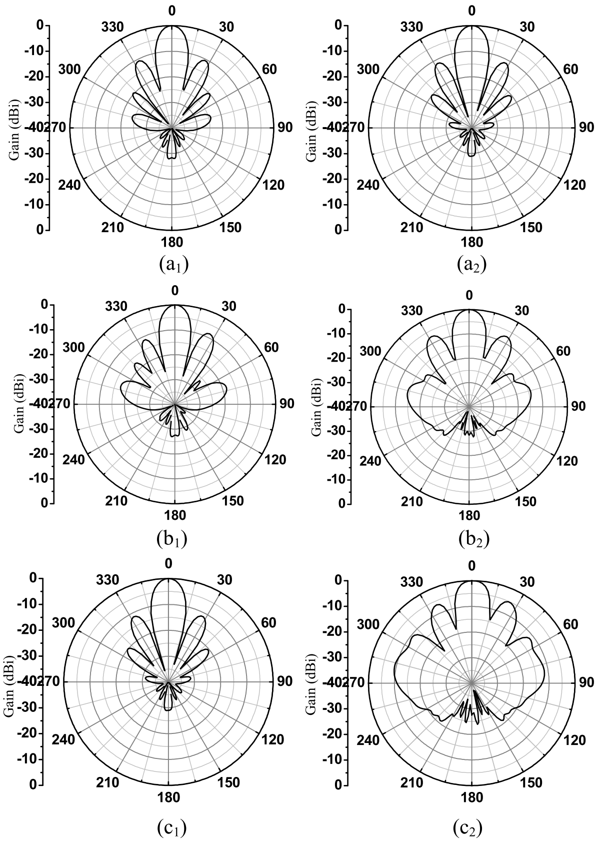


FIGURE 13. Simulated radiation patterns of the array without the top patch. (a_1) XOZ-plane@58-GHz. (a_2) YOZ-plane @58-GHz. (b_1) XOZ-plane@60-GHz. (b_2) YOZ-plane @60-GHz. (c_1) XOZ-plane@63-GHz. (c_2) YOZ-plane @63-GHz.

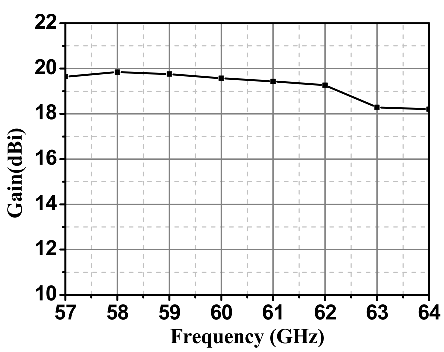


FIGURE 14. Simulated antenna boresight gain of the array without top patch.

matching, gain as well as efficiency. Therefore, the proposed array that uses fewer vias can generally have more stable performance. With these good features, the proposed cavity-backed patch antenna array can be used in the future 60-GHz communication systems.

IV. CONCLUSION

In summary, a wideband high gain cavity-backed patch antenna array is proposed and demonstrated in this paper. By optimizing the geometry of the radiating patch and the cavity, a very uniform E-field distribution at the antenna aperture is achieved, resulting in the high array aperture efficiency and thus the gain. Taking advantages of the higher-order substrate integrated cavity excitation, the elements of the array are efficiently fed with the same amplitude and phase with a simplified feeding network. Measured results show the antenna bandwidth is from 56 to 63.1-GHz (16.1%) with peak gain reaching 21.4 dBi. The radiation patterns of the array are very stable over the entire frequency band and the cross-polarizations are as low as −30 dB.

ACKNOWLEDGMENT

(Jianfeng Zhu and Chen-Hao Chu contributed equally to this work.)

REFERENCES

[1] P. Smulders, "Exploiting the 60 GHz band for local wireless multimedia access: Prospects and future directions," *IEEE Commun. Mag.*, vol. 40, no. 1, pp. 140–147, Jan. 2002.

[2] D. Liu, B. Gaucher, U. Pfeiffer, and J. Grzyb, Eds., *Advanced Millimeter-Wave Technologies: Antennas, Packaging and Circuits*. Hoboken, NJ, USA: Wiley, 2009, pp. 170–172.

[3] L. Wang, Y. X. Guo, and W. X. Sheng, "Wideband high-gain 60-GHz LTCC L-probe patch antenna array with a soft surface," *IEEE Trans. Antennas Propag.*, vol. 61, no. 4, pp. 1802–1809, Apr. 2013.

[4] M. Li and K.-M. Luk, "Low-cost wideband microstrip antenna array for 60-GHz applications," *IEEE Trans. Antennas Propag.*, vol. 62, no. 6, pp. 3012–3018, Jun. 2014.

[5] H. Jin, W. Che, K.-S. Chin, G. Shen, W. Yang, and Q. Xue, "60-GHz LTCC differential-fed patch antenna array with high gain by using soft-surface structures," *IEEE Trans. Antennas Propag.*, vol. 65, no. 1, pp. 206–216, Jan. 2017.

[6] Y. Li, Z. N. Chen, X. Qing, Z. Zhang, J. Xu, and Z. Feng, "Axial ratio bandwidth enhancement of 60-GHz substrate integrated waveguide-fed circularly polarized LTCC antenna array," *IEEE Trans. Antennas Propag.*, vol. 60, no. 10, pp. 4619–4626, Oct. 2012.

[7] M. Li and K.-M. Luk, "A low-profile unidirectional printed antenna for millimeter-wave applications," *IEEE Trans. Antennas Propag.*, vol. 62, no. 3, pp. 1232–1237, Mar. 2014.

[8] B. Zhang and Y. P. Zhang, "Grid array antennas with subarrays and multiple feeds for 60-GHz radios," *IEEE Trans. Antennas Propag.*, vol. 60, no. 5, pp. 2270–2275, May 2012.

[9] M. Sun, Y. P. Zhang, D. Liu, K. M. Chua, and L. L. Wai, "A ball grid array package with a microstrip grid array antenna for a single-chip 60-GHz receiver," *IEEE Trans. Antennas Propag.*, vol. 59, no. 6, pp. 2134–2140, Jun. 2011.

[10] B. Zhang, Y. P. Zhang, D. Titz, F. Ferrero, and C. Luxey, "A circularly-polarized array antenna using linearly-polarized sub grid arrays for highly-integrated 60-GHz radio," *IEEE Trans. Antennas Propag.*, vol. 61, no. 1, pp. 436–439, Jan. 2013.

[11] M. Sun, Y. P. Zhang, Y. X. Guo, K. M. Chua, and L. L. Wai, "Integration of grid array antenna in chip package for highly integrated 60-GHz radios," *IEEE Antennas Wireless Propag. Lett.*, vol. 8, pp. 1364–1366, 2009.

[12] J. Zhu, S. Li, S. Liao, and B.-L. Bu, "High-gain series-fed planar aperture antenna array," *IEEE Antennas Wireless Propag. Lett*, vol. 16, pp. 2750–2754, 2017.

[13] S. Liao, P. Wu, K. M. Shum, and Q. Xue, "Differentially fed planar aperture antenna with high gain and wide bandwidth for millimeter-wave application," *IEEE Trans. Antennas Propag.*, vol. 63, no. 3, pp. 966–977, Mar. 2015.

[14] J. Zhu, S. Liao, Y. Yang, S. Li, and Q. Xue, "60 GHz dual-circularly polarized planar aperture antenna and array," *IEEE Trans. Antennas Propag.*, vol. 66, no. 2, pp. 1014–1019, Feb. 2018.

[15] Y. Li, J. Wang, and K.-M. Luk, "Millimeter-wave multibeam aperture-coupled magnetoelectric dipole array with planar substrate integrated beamforming network for 5G applications," *IEEE Trans. Antennas Propag.*, vol. 65, no. 12, pp. 6422–6431, Dec. 2017.

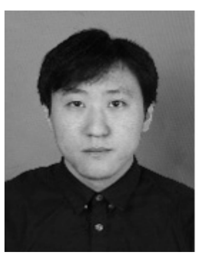
[16] M. Li and K.-M. Luk, "Wideband magneto-electric dipole antenna for 60-GHz millimeter-wave communications," *IEEE Trans. Antennas Propag.*, vol. 63, no. 7, pp. 3276–3279, Jul. 2015.
[17] Y. J. Cheng, W. Hong, and K. Wu, "Millimeter-wave half mode substrate integrated waveguide frequency scanning antenna with quadri-polarization," *IEEE Trans. Antennas Propag.*, vol. 58, no. 6, pp. 1848–1855, Jun. 2010.
[18] X. Bai, S.-W. Qu, and K. B. Ng, "Millimeter-wave cavity-backed patch-slot dipole for circularly polarized radiation," *IEEE Antennas Wireless Propag. Lett.*, vol. 12, pp. 1355–1358, Oct. 2013.
[19] S. Liao, P. Chen, P. Wu, K. M. Shum, and Q. Xue, "Substrate-integrated waveguide-based 60-GHz resonant slotted waveguide arrays with wide impedance bandwidth and high gain," *IEEE Trans. Antennas Propag.*, vol. 63, no. 7, pp. 2922–2931, Jul. 2015.
[20] Y.-J. Cheng, J. Wang, and X. L. Liu, "94 GHz substrate integrated waveguide dual-circular-polarization shared-aperture parallel-plate long-slot array antenna with low sidelobe level," *IEEE Trans. Antennas Propag.*, vol. 65, no. 11, pp. 5855–5861, Nov. 2017.
[21] X. P. Chen, K. Wu, L. Han, and F. He, "Low-cost high gain planar antenna array for 60-GHz band applications," *IEEE Trans. Antennas Propag.*, vol. 58, no. 6, pp. 2126–2129, Jun. 2010.
[22] J. Zhu, Q. Xue, and S. Liao, "Substrate integrated waveguide based monopulse slot antenna arrays for 60 GHz applications," *ZTE Commun.*, vol. 14, no. S1, p. 1, 2016.
[23] J. Zhu, S. Liao, S. Li, and Q. Xue, "60-GHz substrate integrated waveguide based monopulse slot antenna arrays," *IEEE Trans. Antennas Propag.*, to be published, doi: 10.1109/TAP.2018.2847324.
[24] J. Zhu, S. Li, and S. Liao, "Circularly polarized 2-arm spiral antenna for 60-GHz applications," *Microw. Opt. Technol. Lett.*, vol. 59, no. 12, pp. 3119–3123, 2017.
[25] K. Gong, Z. N. Chen, X. Qing, P. Chen, and W. Hong, "Substrate integrated waveguide cavity-backed wide slot antenna for 60-GHz bands," *IEEE Trans. Antennas Propag.*, vol. 60, no. 12, pp. 6023–6026, Dec. 2012.
[26] J. Zhu, B. Peng, and S. Li, "Cavity-backed high-gain switch beam antenna array for 60-GHz applications," *IET Microw. Antennas Propag.*, vol. 11, no. 12, pp. 1776–1781, Sep. 2017.
[27] X. Bai, S.-W. Qu, S. Yang, J. Hu, and Z.-P. Nie, "Millimeter-wave circularly polarized tapered-elliptical cavity antenna with wide axial-ratio beamwidth," *IEEE Trans. Antennas Propag.*, vol. 64, no. 2, pp. 811–814, Feb. 2016.
[28] J. F. Xu, Z. N. Chen, X. M. Qing, and W. Hong, "Bandwidth enhancement for a 60 GHz substrate integrated waveguide fed cavity array antenna on LTCC," *IEEE Trans. Antennas Progag.*, vol. 59, no. 3, pp. 826–832, Mar. 2011.
[29] B. Cao, H. Wang, Y. Huang, and J. Zheng, "High-gain L-probe excited substrate integrated cavity antenna array with LTCC-based gap waveguide feeding network for W-band application," *IEEE Trans. Antennas Propag.*, vol. 63, no. 12, pp. 5465–5474, Dec. 2015.
[30] Y. Li and K.-M. Luk, "Low-cost high-gain and broadband substrate-integrated-waveguide-fed patch antenna array for 60-GHz band," *IEEE Trans. Antennas Propag.*, vol. 62, no. 11, pp. 5531–5538, Nov. 2014.
[31] J. Zhu, S. Li, S. Liao, and Q. Xue, "60 GHz wideband high-gain circularly polarized antenna array with substrate integrated cavity excitation," *IEEE Antennas Wireless Propag. Lett*, vol. 17, no. 5, pp. 751–755, May 2018.
[32] K.-C. Huang and D. J. Edwards, *Millimetre Wave Antennas for Gigabit Wireless Communications: A Practical Guide to Design and Analysis in a System Context*. Hoboken, NJ, USA: Wiley, 2008.
[33] S.-W. Qu, J.-L. Li, Q. Xue, and C. H. Chan, "Wideband cavity-backed bowtie antenna with pattern improvement," *IEEE Trans. Antennas Propag.*, vol. 56, no. 12, pp. 3850–3854, Dec. 2008.
[34] G. Q. Luo, Z. F. Hu, L. X. Dong, and L. L. Sun, "Planar slot antenna backed by substrate integrated waveguide cavity," *IEEE Trans. Antennas Propag.*, vol. 7, pp. 236–239, 2008.
[35] Y. Lang, S.-W. Qu, and J.-X. Chen, "Wideband circularly polarized substrate integrated cavity-backed antenna array," *IEEE Antennas Wireless Propag. Lett.*, vol. 13, pp. 1513–1516, 2014.
[36] N. Bayat-Makou and A. A. Kishk, "Substrate integrated horn antenna with uniform aperture distribution," *IEEE Trans. Antennas Propag.*, vol. 65, no. 2, pp. 514–520, Feb. 2017.
[37] Z. Tao, W. X. Jiang, H. F. Ma, and T. J. Cui, "High-gain and high-efficiency GRIN metamaterial lens antenna with uniform amplitude and phase distributions on aperture," *IEEE Trans. Antennas Propag.*, vol. 66, no. 1, pp. 16–22, Jan. 2018.
[38] W. L. Stutzman and G. A. Thiele, *Antenna Theory and Design*. Hoboken, NJ, USA: Wiley, 2012.
[39] W. Han, F. Yang, R. Long, L. Zhou, and F. Yan, "Single-fed low-profile high-gain circularly polarized slotted cavity antenna using a high-order mode," *IEEE Antennas Wireless Propag. Lett.*, vol. 15, pp. 110–113, 2016.
[40] J. Xu, Z. N. Chen, X. Qing, and W. Hong, "A single-layer SIW slot array antenna with TE20 mode," in *Proc. Asia–Pacific Microw. Conf.*, 2011, pp. 1330–1333.
[41] C. A. Balanis, Ed., *Modern Antenna Handbook*. Hoboken, NJ, USA: Wiley, 2008.

JIANFENG ZHU was born in Changsha, Hunan, China. He received the B.Eng. degree in communication engineering from the Beijing University of Posts and Telecommunications, Beijing, China, in 2013, where he is currently pursuing the Ph.D. degree. Since 2015, he has been a Research Assistant with the Department of Electronic Engineering, City University of Hong Kong. His research interests include mm-wave antennas, MIMO antennas, metamaterial, and graphene.

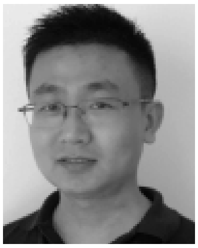
CHEN-HAO CHU was born in Nantong, Jiangsu, China. He received the B.E. degree from the Nanjing University of Science and Technology, Nanjing, China, in 2015, and the M.S. degree (Hons.) from the City University of Hong Kong, Hong Kong, China, in 2017.

Since 2017, he has been a Research Assistant with the State Key Laboratory of Millimeter Waves, Department of Electronic Engineering, City University of Hong Kong. His research interests include dual-band and dual-polarized antennas and antenna-in-package at mm-waves.

LI DENG was born in Sichuan, China, in 1982. He received the B.Eng. and M.Eng. degrees in communication engineering from Beijing Jiaotong University in 2004 and 2007, respectively, and the Ph.D. degree in communication engineering from the Beijing University of Posts and Telecommunications (BUPT), Beijing, China, in 2010. In 2012, he joined BUPT. He is currently an Associate Professor with the School of Information and Communication Engineering, BUPT. His research interests include electromagnetic theory, and metamaterial and transformation optics.



CHEN ZHANG received the B.Eng. degree in electrical and information engineering from Tianjin Chengjian University, China, in 2010, and the M.Eng. degree in information engineering from the Hebei University of Technology, China, 2014. He is currently pursuing the Ph.D. degree with the Beijing Key Laboratory of Network System Architecture and Convergence, Beijing University of Posts and Telecommunications, China. His current research interests include design, modeling, and simulation of electromagnetic metamaterials.



YANG YANG (S'11–M'14–SM'17) was born in Inner Mongolia, China. He received the Ph.D. degree from Monash University, Melbourne, VIC, Australia, in 2013. From 2012 to 2015, he was an Asia-Pacific GSP Engineer with Rain Bird, Deer Park, VIC, Australia. From 2015 to 2016, he served as a Senior Research Associate with the Department of Engineering, Macquarie University, Sydney, NSW, Australia. In 2016, he joined the State Key Laboratory of Millimeter Waves, City University of Hong Kong, Hong Kong, as a Research Fellow. In 2016, he was involved in the National Basic Research Program of China (973 Program) and appointed as an Honorary Research Fellow with the Shenzhen Institute, City University of Hong Kong. In 2016, he joined the University of Technology Sydney, Sydney, NSW, Australia, as a Lecturer. His current research interests include radio frequency integrated circuits, microwave and millimeter-wave circuits and systems, reconfigurable antennas, wearable antennas, and wearable sensing devices and technologies. He was a recipient of the Global GSP Success Award in 2014.

SHUFANG LI (SM'09) received the Ph.D. degree from the Department of Electrical Engineering, Tsinghua University, Beijing, China, in 1997. She is currently the Director of the Ubiquitous Electromagnetic Environment Center of Education Ministry, China, and the Director of the Joint Lab, State Radio Monitoring Center, Beijing University of Posts and Telecommunications, China. She has published 100s of papers interiorly and overseas, and several textbooks, translation works, and patents. Her research interests include the theory and design technology of radio frequency circuits in wireless communication, EMI/EMC, and simulation technology and optimization for radiation interfere on high-speed digital circuit. She received the Young Scientists Reward sponsored by the International Union of Radio Science. She is the Guest Editor of the IEEE Transactions on Electromagnetic Compatibility.