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Research Article

High Gain and High Efficient Stacked Antenna Array with Integrated Horn for 60 GHz Communication Systems

Hamsakutty Vettikalladi, Waleed Tariq Sethi, and Majeed A. Alkanhal

Electrical Engineering Department, King Saud University, Saudi Arabia

Correspondence should be addressed to Hamsakutty Vettikalladi; hvettikalladi@ksu.edu.sa

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In order to achieve wide bandwidth and high gain, we propose a stacked antenna structure having a microstrip aperture coupled feeding technique with a mounted Horn integrated on it. With optimized parameters, the single antenna element at a center frequency of 60 GHz, exhibits a wide impedance bandwidth of about 10.58% (58.9–65.25 GHz) with a gain and efficiency of 11.78 dB and 88%, respectively. For improving the gain, we designed a 2×2 and 4×4 arrays with a corporate feed network. The side lobe levels were minimized and the back radiations were reduced by making use of a reflector at $\lambda/4$ distance from the corporate feed network. The 2×2 array structure resulted in improved gain of 15.3 dB with efficiency of 83%, while the 4×4 array structure provided further gain improvement of 18.07 dB with 68.3% efficiency. The proposed design is modelled in CST Microwave Studio. The results are verified using HFSS, which are found to be in good agreement.

1. Introduction

Soon after the development of 60 GHz standard that provides a 7 GHz license-free bandwidth worldwide, its popularity became evident at millimeter waves spectrum due to its usage in high data-rate wireless communications at gigabit per second [1, 2]. The huge amount of bandwidth availability attracted the researchers for its use in many terrestrial and space applications. In this modern era of consumer electronic gadgets, even telephony and cable operated devices in offices and homes are trending towards wireless technology. The demand for higher data rate of these multimedia technologies can be resolved with 60 GHz standard as being a viable candidate.

In any radio communication or wireless systems, antenna plays a vital part [3–5]. Since its development, the microstrip planar antennas [6] have gained popularity in telecommunication and radar applications due to its lightweight and low profile configurations. Microstrip patch antennas are among the best candidates for implementing in microwave and millimeter waves (MMW) frequency and they are good candidates for arrays as well. There are several reports devoted to the design and explanation of such antennas using arrays [7–12]. However, the traditional microstrip antennas have reached their maximum usability as they offer narrow bandwidth (3%) and low gain. Researchers investigated new methods and came up with coupling techniques to improve impedance bandwidth. The proposed solution by Pozar [13] is provided with wide bandwidth and high gain as compared to conventional microstrip antennas. The aperture coupling method enabled the patch antennas to be easily integrated into arrays, with active circuits, to minimize spurious radiations from the feed, and to introduce more freedom of substrates selections. Many techniques have been explained in the literature for improving bandwidth and gain at MMW [14–20].

In this paper, a stacked microstrip antenna utilizing aperture-coupled technique with a mounted Horn on FR-4 substrate is presented, at a center frequency of 60 GHz. By employing this technique, a wide impedance bandwidth of about 10.58% (58.9–65.25 GHz) is achieved with high gain and efficiency. The gain and efficiency of the single element antenna are further increased by presenting a corporate fed network of 2×2 and 4×4 arrays. The 2×2 array structure resulted in improved gain of 15.3 dB with efficiency of 83%. While the 4×4 array structure provided further gain improvement of 18.07 dB with 68.3% efficiency. This paper

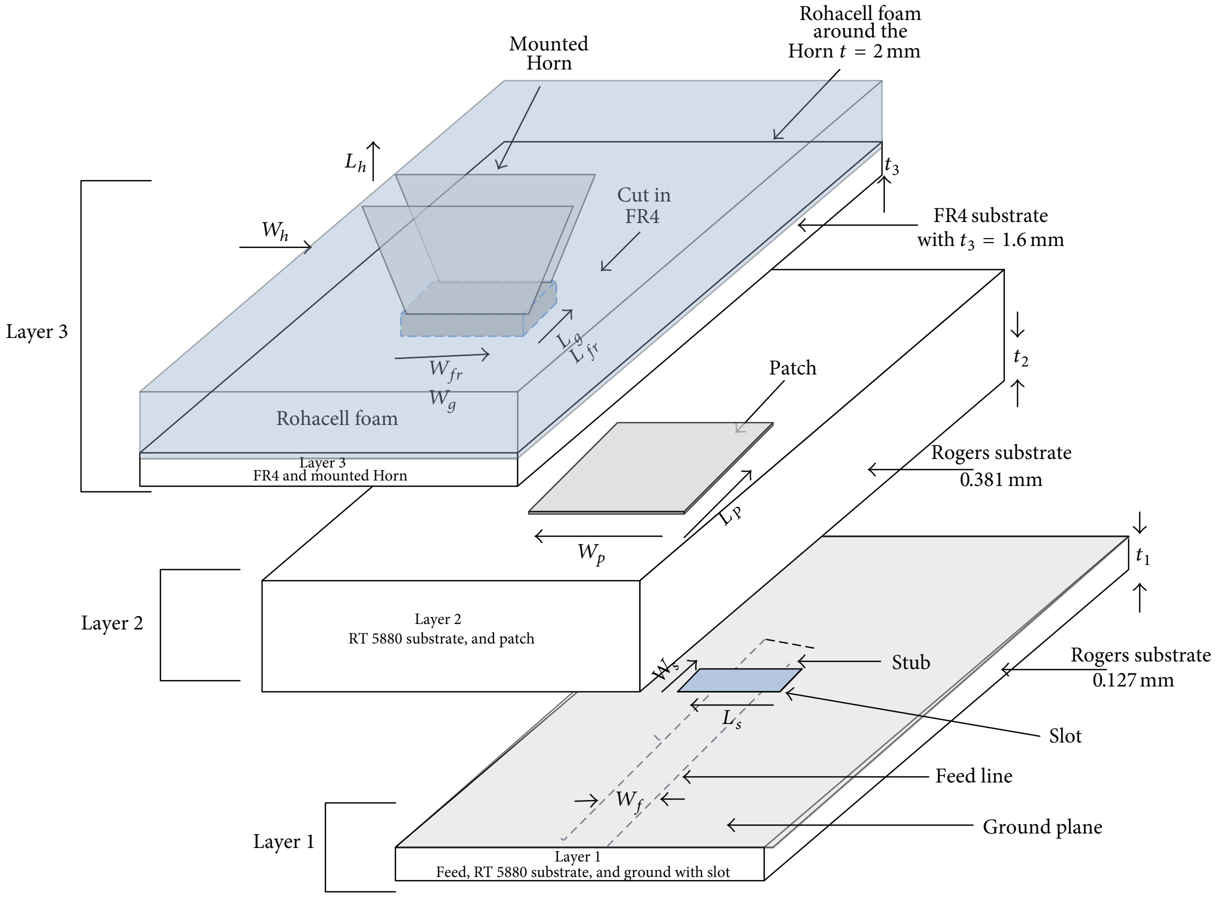


Figure 1: Exploded view of proposed multilayer ACMPA with mounted Horn.

is an extended work of our previous results [21], which had limited bandwidth. Comparing with previous results [21], the proposed single element antenna's simulation results show improvement in terms of bandwidth and gain at millimeter waves (MMW).

2. Design of Antenna Element

The geometry of the single antenna element is shown in Figure 1. The design is a combination of aperture coupled microstrip antenna (ACMPA) and a Horn antenna mounted on FR4 substrate, where the waveguide part of the horn is integrated into FR4 substrate. The model was designed and optimized using RF simulation software CST Microwave Studio and the results were reconfirmed via HFSS. The antenna is tuned to operate in a wide band of frequencies at 60 GHz. The multilayer antenna has three substrates with layers I and II having Rogers Duroid RT-5880 with $\epsilon r = 2.2$ and $\tan\delta = 0.003$ and thickness $t_1 = 0.127$ mm and $t_2 = 0.381$ mm while the third layer has FR-4 as a substrate with $\epsilon r = 4.3$ and thickness $t_3 = 1.6$ mm and a mounted Horn. The addition of FR4 has no other effect, except to provide support to the mounted Horn on the antenna performance. The ground with thickness ($t = 2 \times 0.0175$ mm) is made of conducting metal with a rectangular slot perpendicular to the microstrip feed having dimensions of L_s and W_s as given in Table 1. Coupling efficiencies between the aperture in the ground and the patch can be improved as investigated in [22]. The patch is located on the top of the substrate, at layer II, and has dimensions of L_p and W_p as given in Table 1. The dimensions of substrates and ground are taken as $30 \times 30\,\text{mm}^2$. The 50 Ω microstrip feed line at the bottom of lower substrate has a feed width of $W_f = 0.386$ mm as calculated from Ansoft designer [23]. Table 1 shows the optimized values for the proposed antenna.

With the aid of simulation tools, the proposed multilayer antenna was numerically optimized and the results were obtained. The objective was to achieve a wide bandwidth, high gain, and efficiency. Compared to [21], the impedance bandwidth improved significantly with almost the same gain. Due to the addition of 0.381 mm thickness substrate, the impedance bandwidth achieved was about 10.58% (58.9–65.25 GHz) with gain and efficiency of 11.78 dB and 88%, respectively. The simulation has taken into account the substrate and metallic losses. Figure 2 shows the bandwidth and gain comparison between two simulators for the single element antenna design. The two resonances seen in Figure 2 at 59.7 GHz and 63.5 GHz are due to the patch on layer II and the aperture of the Horn antenna integrated on it. Since this design is an extension of [21], the dimensions of the

Table 1: Parameters of proposed antenna in mm.

Design	Antenna element	Dimensions/parameters
Layer I	Microstrip feed	Feed width, $W_f = 0.386$
		Thickness, $t = 0.0175$
		Stub length, $L_{fs} = 0.45$
	Substrate	RT Duroid 5880
		Length, $L = 30$
		Width, $W = 30$
		$\epsilon r = 2.2$
		$\tan\delta = 0.003$
		Thickness, $t_1 = 0.127$
	Ground	Thickness, $t = 0.0175$
		Length $L = 30$
		Width $W = 30$
		Thickness, $t = 0.0175$
	Rectangular slot	Slot length, $L_s = 1$
		Slot width, $W_s = 0.2$
Layer II	Substrate	RT Duroid 5880
		Thickness, $t_2 = 0.381$
		$\epsilon r = 2.2$
		$\tan\delta = 0.003$
		Length, $L = 30$
		Width, $W = 30$
	Patch	Length, $L_p = 1.2$
		Width, $W_p = 1.2$
Layer III	Substrate	FR 4
		Thickness, $t_3 = 1.6$
		$\epsilon r = 4.3$
		$\tan\delta = 0.025$
	Cut in FR-4	Length, $L_{fr} = 3$
		Width, $W_{fr} = 4.25$
Horn	Horn dimensions	Horn length, $L_h = 7.14$
		Horn width, $W_h = 7.14$
		Waveguide length, $L_g = 3$
		Waveguide width, $W_g = 4.25$
		Thickness of metal horn, $t = 2$
Full structure	Total height	4

rectangular waveguide were optimized as given in Table 1. The initial length of the rectangular waveguide was chosen to be $L_g = \lambda_0/2$, which is a half wavelength at 60 GHz. The rectangular waveguide length has an effect on the reflection coefficient, which is minimum when L_g is around $\lambda_0/2$.

Figures 3(a) and 3(b) show the E-plane and H-plane radiation patterns, simulated in CST and HFSS, of the proposed antenna, for the frequencies at 59, 62, and 65 GHz, respectively. Thus for the multilayer structure at 62 GHz, the E-plane has side lobe of level −5 dB, half-power beamwidth of 31°, and a back radiation of −18.3 dB. The H-plane radiation pattern at 62 GHz has a side lobe of −13.2, half-power beamwidth of 69.8°, back radiation of −17 dB, and cross polarization level of > −30 dB.

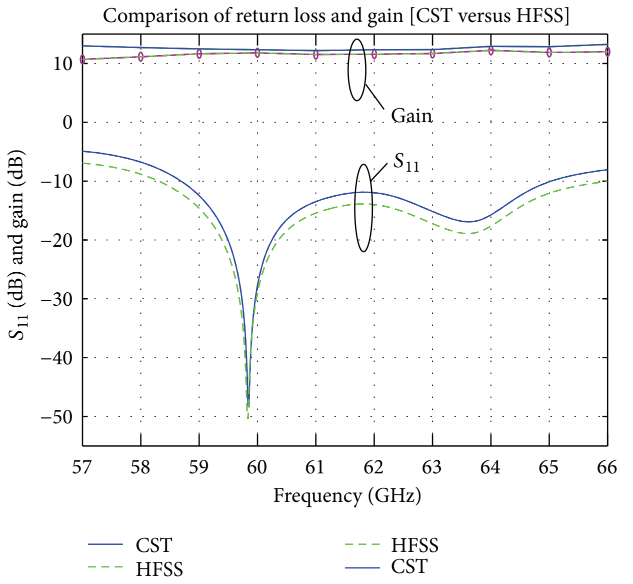


Figure 2: Comparison of return loss and gain.

3. Design of Antenna Array

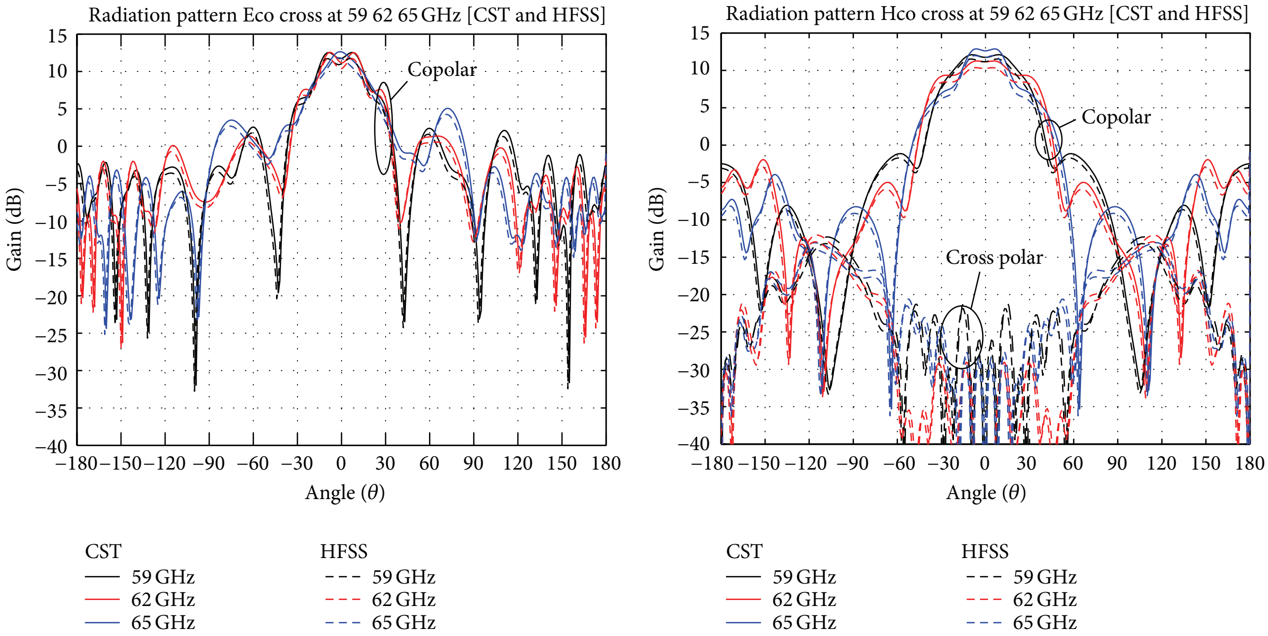
Limited methods exist in analyzing the antenna arrays. In the existing methods, arrays factor is the easiest one among others [6]. In simplest terms, array theory works on the principle that each antenna element is treated as an individual isotropic point source. Energy contributions from each point source are derived in the far field expressed as array factor (AF). The method of array factor is based on the theorem of orientation multiplying [6]:

$$\mathrm{AF}(f,\theta) = \sum_{n=1}^{4} e^{jnkd\sin\theta}. \qquad (1)$$

The array factor depends only on the geometry of the array and the phase between each element. The actual radiator then replaces each point and the far field radiation pattern is determined by pattern multiplying the array factor with the pattern of the radiator. Mutual coupling is ignored in the process since the radiators are treated separately; also their influences on each other are not considered. Since we are working on improving the gain of the antenna, therefore, the mutual coupling cannot be ignored and the results deduced by array factor must be modified.

3.1. 2 × 2 Array.

3.1. 2 × 2 Array. The next step is to improve the gain by making use of 2 × 2 and 4 × 4 arrays. The 3D exploded view of the 2 × 2 arrays structure is shown in Figure 4, where a copper reflector element of distance $\lambda/4$ has been introduced below layer I to suppress the back radiations of the array. An important aspect in designing an array is the optimal distance between the patches or antenna elements to reduce mutual coupling among them. Mutual coupling has a noteworthy influence on the performance of antenna array. Mutual coupling affects several factors such as inputting resistance, orientation pattern of array, gain of the array, and



(a)

(b)

FIGURE 3: (a) Simulated E-plane radiation pattern at 59, 62, and 65 GHz and (b) simulated H-plane radiation pattern at 59, 62, and 65 GHz.

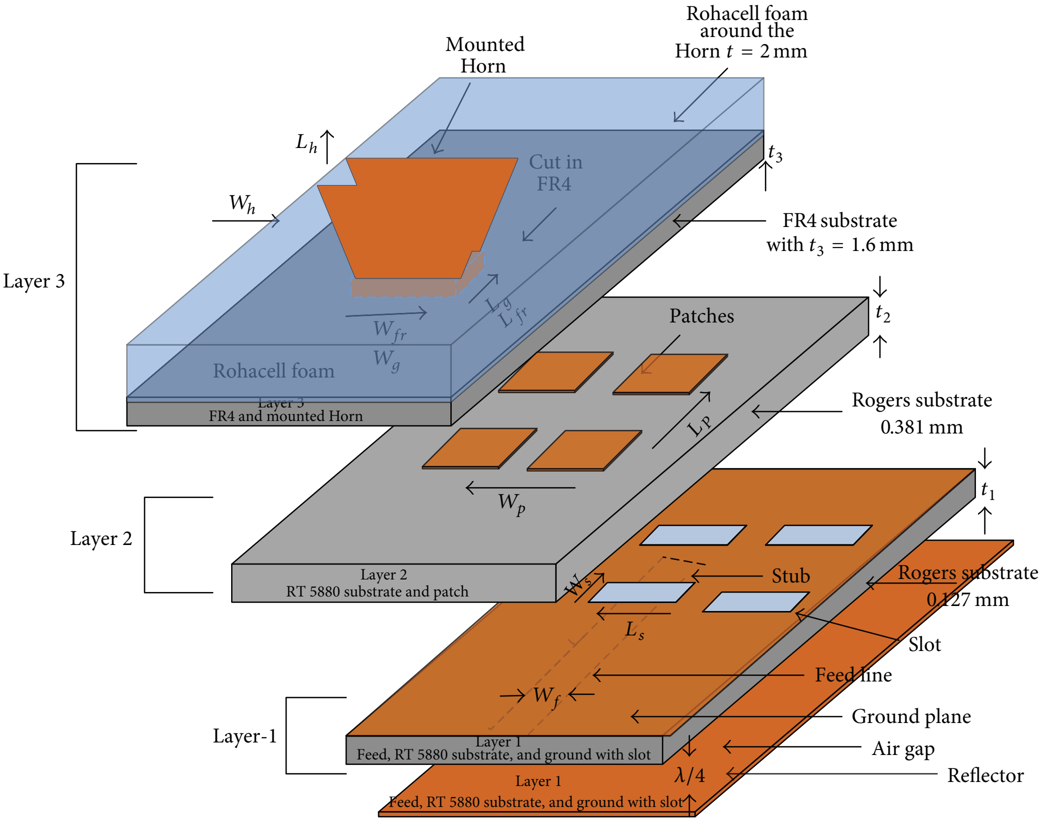


FIGURE 4: Exploded view of 2 × 2 multilayer array with $\lambda/4$ reflector.

its polarization [24–27]. In our proposed array design, center-to-center distances between patches were optimized from 0.5λ to 1λ that gave minimum coupling and maximum gain. The element spacing was selected to be $0.82\lambda_o$ in the x-y direction for both 2 × 2 and 4 × 4 arrays.

A corporate feed network connected to a 50 Ω line was used as power division between antenna elements. Corporate feed networks are in general very versatile as they offer power splits of 2^n (i.e., $n = 2, 4, 8, 16, 32$, etc.) and control to the designer in terms of amplitude and phase selection of individual feed element and its power division among the transmission lines. It is ideal for scanning phased arrays, shaped-beam arrays, and multibeam arrays [6]. The length and width of the transmission lines can be varied as per requirement of power division. The feed network consists of 50 Ω transmission line and 70.7 Ω quarter-wavelength transformers matched to primary 50 Ω feeding line. The corporate feed network for 2 × 2 arrays is shown in Figure 5.

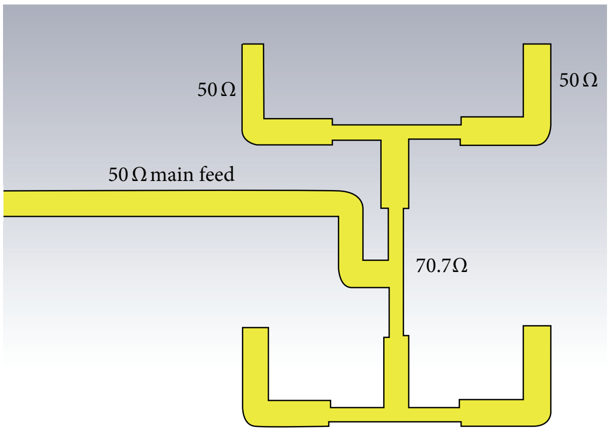


Figure 5: Corporate-feed network for 2 × 2 array.

Analyzing the top half of feed network shown in Figure 5 and because of symmetry, two 50 Ω lines coming from each antenna are connected to two 70.7 Ω lines where each of them is a quarter wave transformer. This transforms each line into a 100 Ω line. Now we have two 100 Ω lines in parallel resulting in 50 Ω line. This 50 Ω is again connected to quarter wave transformer resulting in 100 Ω line. Similarly, another 100 Ω is available from the bottom half of the circuit resulting in a final 50 Ω line connected and matched to the main 50 Ω feed. The lengths and widths of 50 Ω and 70.7 Ω used in this feed network are shown in Table 2.

The proposed antenna of 2 × 2 array was simulated via simulation tools. Figure 6 shows the comparison between simulators on the simulated return loss and gain for 2 × 2 arrays. Impedance bandwidth remains the same as 10.58% (58.9–65.25 GHz). The gain and efficiency are 15.3 dB and 88%, respectively. Due to the introduction of 0.381 mm substrate as compared to previous work [21], some parameters of the multilayer antenna design were optimized for the array structures to achieve wide bandwidth and impedance matching. The rest of the parameters were kept the same as presented in Table 1. The modified parameters are shown in Table 3.

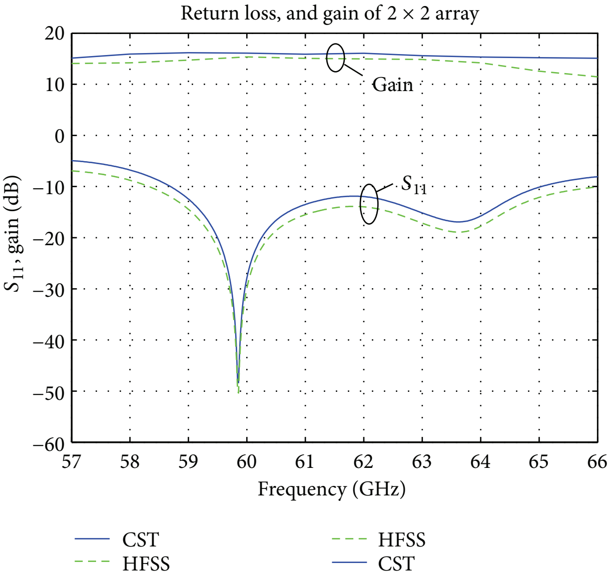


Figure 6: Return loss and gain of 2 × 2 array.

The E-plane and H-plane radiation patterns, simulated in CST and HFSS, for 2 × 2 array structure at frequencies 59, 62, and 65 GHz are shown in Figures 7(a) and 7(b), respectively. It is observed that the E-plane at 62 GHz has a side lobe of level −13.7 dB, half-power beamwidth of 22.1°, and a back radiation of −25.3 dB. The H-plane radiation pattern at 62 GHz has a side lobe of −9.1 dB, half-power beamwidth of 22.2°, back radiation of −21.8 dB, and cross polarization level of > −30 dB.

Table 2: Lengths and widths of 50 Ω and 70.7 Ω feeds.

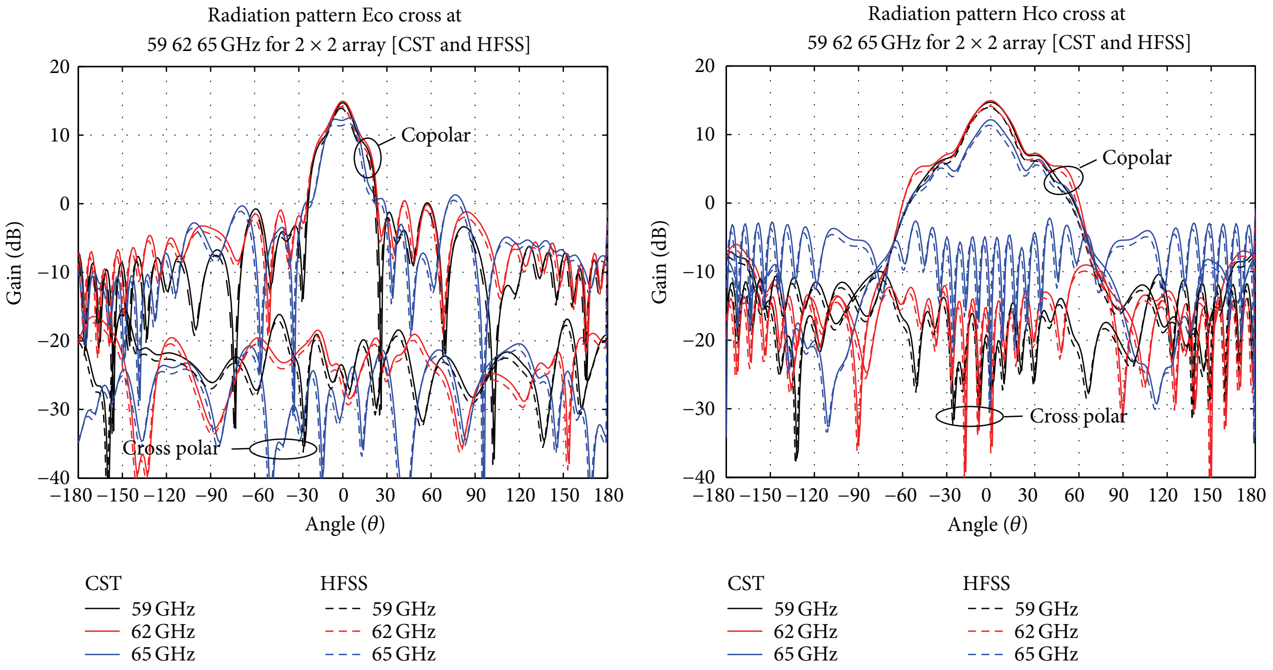
Transmission line	Width (mm)	Length (mm)
50 Ω	0.386	1.07
70.7 Ω	0.2262	0.93

3.2. 4 × 4 Array.

3.2. 4 × 4 Array. Similarly, the 4 × 4 array was simulated and the comparison of results in terms of return loss and gain is shown in Figure 8. Impedance bandwidth achieved is 10.58% (58.9–65.25 GHz) at 60 GHz. The gain and efficiency are 18.07 dB and 68.3%, respectively. Figures 9(a) and 9(b) show radiation patterns at 59, 62, and 65 GHz for 4 × 4 array. The E-plane at 62 GHz has a side lobe of level −11.8 dB, half-power beamwidth of 13.6°, and a back radiation of −23.07 dB. The H-plane radiation pattern at 62 GHz has a side lobe of −12.4, half-power beamwidth of 16.1°, and a back radiation of −23.07 dB. Table 4 shows the comparison of improved gain from single element to 2 × 2 and 4 × 4 arrays.

4. Conclusion

A high gain and wide band multilayer antenna for 60 GHz are proposed in this paper. Stacked structure technique



(a)

(b)

FIGURE 7: (a) E-plane radiation pattern at 59, 62, and 65 GHz for 2 × 2 array and (b) H-plane radiation pattern at 59, 62, and 65 GHz for 2 × 2 array.

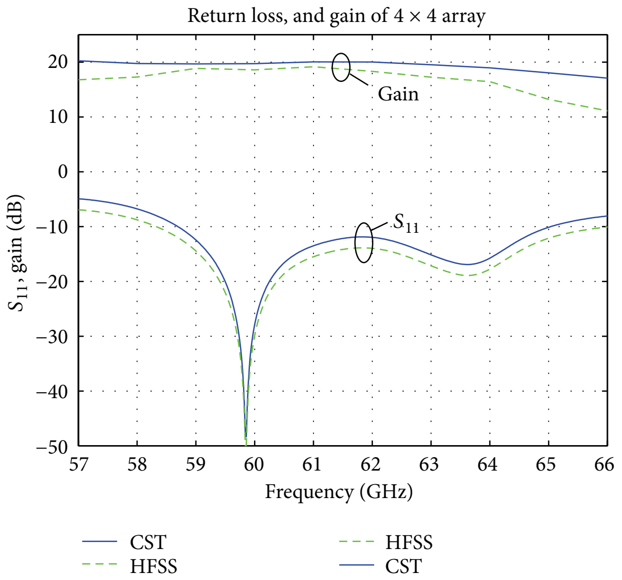


FIGURE 8: Return loss and gain of 4 × 4 array.

TABLE 3: Modified antenna parameters.

Parameters	2 × 2 array	4 × 4 array
Patch length, L_p	1.25	1.25
Patch width, W_p	1.25	1.25
Stub length, L_{fs}	0.45	0.45
Horn length, L_{hr}	12	12
Horn width, W_{hr}	18	20

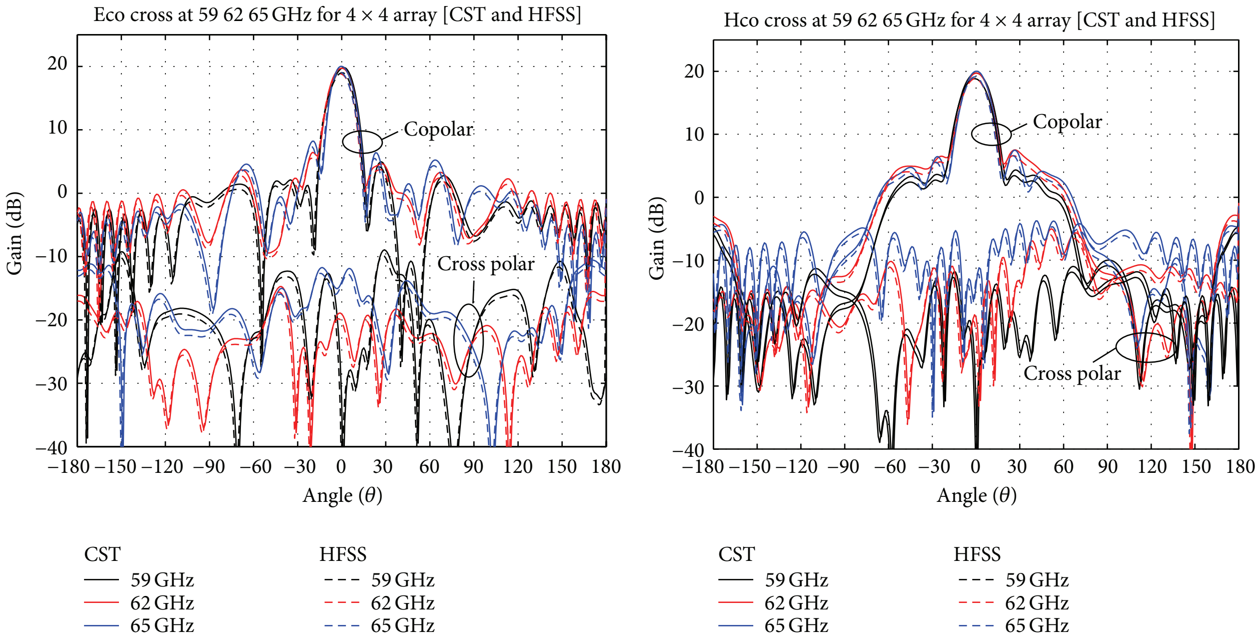
TABLE 4: Simulated results of single element and 2 × 2 and 4 × 4 arrays.

Array/parameters	Single element	2 × 2 array	4 × 4 array
Bandwidth	10.58%	10.55%	10.51%
Gain	11.78 dB	15.3 dB	18.07 dB
Efficiency	88%	83%	68.3%

employing aperture coupled feeding with mounted Horn antenna is employed as the radiator for the single element, 2 × 2 and 4 × 4 arrays. The proposed antenna exhibits a broad impedance bandwidth of about 10.5% (58.9–65.25 GHz). Comprised by the proposed antenna element, an antenna array is investigated. Simulated results in CST and HFSS show that the antenna array realized provides a maximum gain and efficiency of 18.07 dB and 68.3%, respectively. The proposed antenna finds application in V-band communication systems.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.



(a)

(b)

Figure 9: (a) E-plane radiation pattern at 59, 62, and 65 GHz for 4 × 4 array and (b) H-plane radiation pattern at 59, 62, and 65 GHz for 4 × 4 array.

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References

[1] IEEE.802.15.WPANTG3c, 2009, http://www.ieee802.org/15/pub/TG3c.html.

[2] "Standard ECMA: High Rate 60 GHz PHY, MAC & HDMI PAL," 2008, http://www.ecmainternational.org/publications/files/ECMAST/Ecma-387.pdf.

[3] C. Kärnfelt, P. Hallbjörner, H. Zirath, and A. Alping, "High gain active microstrip antenna for 60-GHz WLAN/WPAN applications," *IEEE Transactions on Microwave Theory and Techniques*, vol. 54, no. 6, pp. 2593–2603, 2006.

[4] I.-S. Chen, H.-K. Chiou, and N.-W. Chen, "V-band on-chip dipole-based antenna," *IEEE Transactions on Antennas and Propagation*, vol. 57, no. 10, pp. 2853–2861, 2009.

[5] Y. P. Zhang, M. Sun, K. M. Chua, L. L. Wai, and L. Duixian, "Antenna-in-package design for wirebond interconnection to highly integrated 60-GHz radios," *IEEE Transactions on Antennas and Propagation*, vol. 57, no. 10, pp. 2842–2852, 2009.

[6] C. A. Balanis, *Antenna Theory: Analysis and Design*, John Wiley and Sons, New York, NY, USA, 2nd edition, 1997.

[7] Y. Kim and D. L. Jaggard, "The fractal random array," *Proceedings of the IEEE*, vol. 74, pp. 1278–1280, 1986.

[8] C. Puente-Baliarda and R. Pous, "Fractal design of multiband and low side-lobe arrays," *IEEE Transactions on Antennas and Propagation*, vol. 44, no. 5, pp. 730–739, 1996.

[9] D. M. Pozar and D. H. Schaubert, *Microstrip Antennas, the Analysis and Design of Microstrip Antennas and Arrays*, IEEE Press, New York, NY, USA, 1995.

[10] L. Stark, "Microwave theory of phased-array antennas–a review," *Proceedings of the IEEE*, vol. 62, no. 12, pp. 1661–1701, 1974.

[11] A. A. Efanov and H. W. Thim, "Corporate-fed 2 × 2 planar microstrip patch sub-array for the 35 GHz band," *Antennas and Propagation Magazine*, vol. 37, no. 5, pp. 49–51, 1995.

[12] K. F. Lee, R. Q. Lee, and T. Talty, "Microstrip subarray with coplanar and stacked parasitic elements," *Electronics Letters*, vol. 26, no. 10, pp. 668–669, 1990.

[13] D. Pozar, *A Review of Aperture Coupled Microstrip Antennas: History, Operation, Development, and Applications*, Lecture Note, 1996.

[14] H. Vettikalladi and M. A. S. Alkanhal, "BCB-Si based wide band millimeter wave antenna fed by substrate integrated waveguide," *International Journal of Antennas and Propagation*, vol. 2013, Article ID 816050, 4 pages, 2013.

[15] O. Lafond, M. Himdi, and J. P. Daniel, "Thick slot-coupled printed antenna arrays for a 60 GHz indoor communication system," *Microwave and Optical Technology Letters*, vol. 28, pp. 105–108, 2001.

[16] H. Vettikalladi, O. Lafond, and M. Himdi, "High-efficient and high-gain superstrate antenna for 60-GHz indoor communication," *IEEE Antennas and Wireless Propagation Letters*, vol. 8, pp. 1422–1425, 2009.

[17] H. Vettikalladi, L. le Coq, O. Lafond, and M. Himdi, "Efficient and high-gain aperture coupled superstrate antenna arrays for 60 GHz indoor communication systems," *Microwave and Optical Technology Letters*, vol. 52, no. 10, pp. 2352–2356, 2010.

[18] H. Vettikalladi, L. le Coq, O. Lafond, and M. Himdi, "Wideband and high efficient aperture antenna with superstrate for 60 GHz

indoor communication systems," in *Proceedings of the IEEE International Symposium on Antennas and Propagation and CNC-USNC/URSI Radio Science Meeting—Leading the Wave (AP-S/URSI '10)*, Toronto, Canada, July 2010.

[19] H. Vettikalladi, L. le Coq, O. Lafond, and M. Himdi, "Broadband superstrate aperture antenna for 60 GHz applications," in *Proceedings of the 13th European Microwave Week (EuMW '10)*, pp. 687–690, Paris, France, September 2010.

[20] N. Ashraf, H. Vettikalladi, and M. A. Alkanhal, "Substrate integrated waveguide antennas/array for 60 GHz wireless communication systems," in *Proceedings of the IEEE International RF and Microwave Conference (RFM '13)*, 2013.

[21] W. T. Sethi, H. Vettikalladi, and M. A. Alkanhal, "Millimeter wave antenna with mounted horn integrated on FR4 for 60 GHz Gbps communication systems," *International Journal of Antennas and Propagation*, vol. 2013, Article ID 834314, 5 pages, 2013.

[22] V. Rathi, G. Kumar, and K. P. Ray, "Improved coupling for aperture coupled microstrip antennas," *IEEE Transactions on Antennas and Propagation*, vol. 44, no. 8, pp. 1196–1198, 1996.

[23] "Ansoft designer version 4".

[24] R. P. Jedlicka, M. T. Poe, and K. R. Carver, "Measure mutual coupling between microstrip antennas," *IEEE Transactions on Antennas and Propagation*, vol. 29, no. 1, pp. 147–149, 1981.

[25] M. Malkomes, "Mutual coupling between microstrip patch antennas," *Electronics Letters*, vol. 18, no. 12, pp. 520–522, 1982.

[26] E. Penard and J. P. Daniel, "Mutual coupling between microstrip antennas," *Electronics Letters*, vol. 18, no. 14, pp. 605–607, 1982.

[27] E. H. van Lil and A. R. van de Capelle, "Transmission line model for mutual coupling between microstrip antennas," *IEEE Transactions on Antennas and Propagation*, vol. 32, no. 8, pp. 816–821, 1984.


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