*Progress In Electromagnetics Research Letters, Vol. 53, 71–76, 2015*

# Electromagnetically-Coupled Millimeter-wave Antenna Array with Non-Uniform Distribution for 60 GHz ISM Applications

**Osama M. Haraz**[1, 2, *]

**Abstract**—In this article, the design of an electromagnetically-coupled millimeter-wave elliptical patch array antenna prepared to work in the 56–65 GHz (14.8%) frequency band is presented. The introduced antenna array is designed for low-loss, high-gain and low cross-polarization levels. The proposed antenna exhibits a measured gain of 8 dBi and good linear polarization across the desired frequency range. It has a good side lobe suppression better than 17 dB in both $E$- and $H$-planes. Measured and simulated results confirm that this antenna is a good candidate for short-range wireless communication applications at millimeter-wave frequencies.

## 1. INTRODUCTION

There is a great opportunity for ultra-high speed short-range wireless communications by using the unlicensed 60-GHz millimeter-wave (mmW) ISM band [1]. Researchers have shown big interest in developing the electromagnetically (EM) coupled patch antennas, which can fulfil the above mentioned requirements [2–10]. This kind of antennas is useful in many applications requiring a wide range of frequencies to be covered. Achieving high gain becomes very important especially for mmW communication applications.

The end-fire antennas with directional radiation pattern can be used for some applications at 60 GHz such as the wireless file-transfer on computer desktops [4]. However, one challenge for an end-fire antenna design is the limitation of the antenna aperture by the substrate thickness which may prevent achieving high gains. Another reported design is a traveling-wave antenna with an antipodal Fermi profile that can achieve a high gain of 15 dBi over 57–66 GHz [5]. An alternative solution to achieve the high gain is to employ an antenna array configuration.

In this letter, the design of an electromagnetically coupled millimeter-wave elliptical patch array antenna is introduced. All calculations were carried out with the help of two different electromagnetic simulators based on different numerical techniques, Ansys HFSS, and CST Microwave Studio. The proposed antenna is capable of covering the whole 56–65 GHz band with a broad input impedance matching band of 14.8%. The optimized array antenna is composed of five electromagnetically-coupled patches (ECP) driven by a microstrip line. It is observed that the measured and simulated results using both HFSS and CST are in good agreement with each other. The proposed array antenna has also a broadside radiation pattern and good gain of 8 dBi at 60 GHz with variation of less than 0.5 dBi across the desired frequency band. From these results, the antenna is suitable for short range wireless communication applications at millimeter-wave frequencies.

*Received 17 March 2015, Accepted 15 May 2015, Scheduled 19 May 2015*
* Corresponding author: Osama Mohamed Haraz (osama_m_h@yahoo.com).
[1] KACST Technology Innovation Center in Radiofrequency and Photonics for the e-Society (RFTONICS), King Saud University, Riyadh 11451, Saudi Arabia. [2] Electrical Engineering Department, Faculty of Engineering, Assiut University, Assiut 71515, Egypt.

## 2. ANTENNA GEOMETRY AND DESIGN

### 2.1. Antenna Geometry

The geometrical configuration of the proposed mmW array antenna is shown in Figure 1. It consists of five elliptical patches ($EP1$ to $EP5$) of different sizes, but symmetric with respect to the central patch ($EP3$). All parameters are optimized using parametric studies and optimization techniques in the full-wave EM simulator. The central patch has major radius $a_3$ and minor radius $b_3$. The other four patches have major radii of $a_1$ & $a_2$ and minor radii of $b_1$ & $b_2$. Those patches are fed through electromagnetic (EM) coupling to their corresponding microstrip lines of length $L_S$ and width $W_T$ interspaced a distance $d$ apart. Those microstrip lines are held together through a common line of length $L_T$ and width $W_T$, fed by a $50\,\Omega$ microstrip line of length $L_F$ and width $W_F$, respectively. A rectangular ground plane of length $L$ and width $W$ is located underneath the lower substrate. The optimized antenna parameters have been calculated and summarized in Table 1.

All the five elliptical patches are etched on Rogers Duroid RT 5880 dielectric substrate with thickness of $H_1$ and relative permittivity $\varepsilon_r = 2.2$ and loss tangent $\tan\delta = 0.0009$ (typical values at 10 GHz and 23°C). The feeding network is built on another 5880 dielectric substrate with thickness

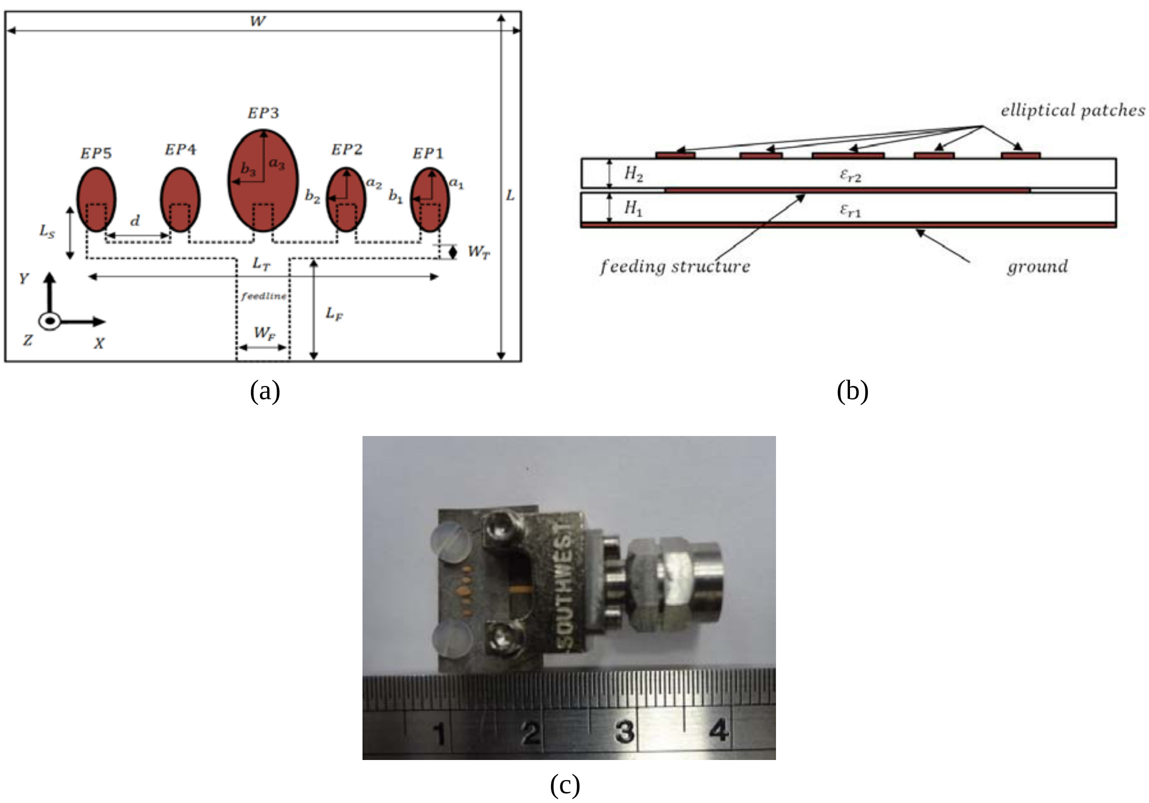


**Figure 1.** Geometry of proposed millimeter-wave antenna array, (a) top view, (b) side view, (c) photographs of the fabricated array antenna prototype.

**Table 1.** Optimized dimensions of the proposed millimeter-wave antenna array (Units are in mm).

| Parameter | $L\,(=W)$ | $a_1\,(=a_2)$ | $a_3$ | $L_S$ | $L_T$ | $L_F$ |
|---|---|---|---|---|---|---|
| Value | 7.5 | 0.5 | 0.8 | 0.85 | 4.65 | 3.625 |
| Parameter | $H_1\,(=H_2)$ | $b_1\,(=b_2)$ | $b_3$ | $W_T$ | $W_F$ | $d$ |
| Value | 0.254 | 0.25 | 0.45 | 0.25 | 0.7 | 1.1 |

of $H_2$. The reason behind choosing two substrates is to feed those elliptical patches through non-direct coupling or electromagnetic coupling. This is to improve the antenna bandwidth to cover the entire 60-GHz ISM band compared to other feeding techniques such as microstrip line or coplanar waveguide (CPW) feed. In that case, the feeding network will be separated from the radiating patch elements. This will give more degree of freedom in controlling the signal excitation to the antenna elements. The substrate types which are Rogers® Duroid™ 5880 with relative permittivity $\varepsilon_r = 2.2$ and thickness $H_1 = H_2 = 0.254$ mm, have been chosen because of their low loss and good characteristics for antenna design.

## 2.2. Parametric Studies

Figure 2(a) shows the effect of varying the inter-element spacing distance $d$ on the antenna array performance. During this study, all other parameters are kept unchanged while varying the parameter $d$. It can be noticed that by increasing the inter-element spacing distance $d$, the resonant frequency decreases accordingly. To maintain the antenna functionality in the entire 60-GHz ISM band, the optimum value of $d$ should be 1.0 mm. Another parametric study has been carried out to investigate the effect of varying the length of microstrip feedline is $L_S$. Figure 2(b) presents the variation of antenna return loss $|S_{11}|$ versus frequency for different values of microstrip feedline $L_S$. It can be seen from results that the parameter $L_S$ strongly affect the coupling between the feeding structure and the radiating antenna patch elements. The best values for parameter $L_S$ is found to be 1.0 mm to achieve the desired bandwidth.

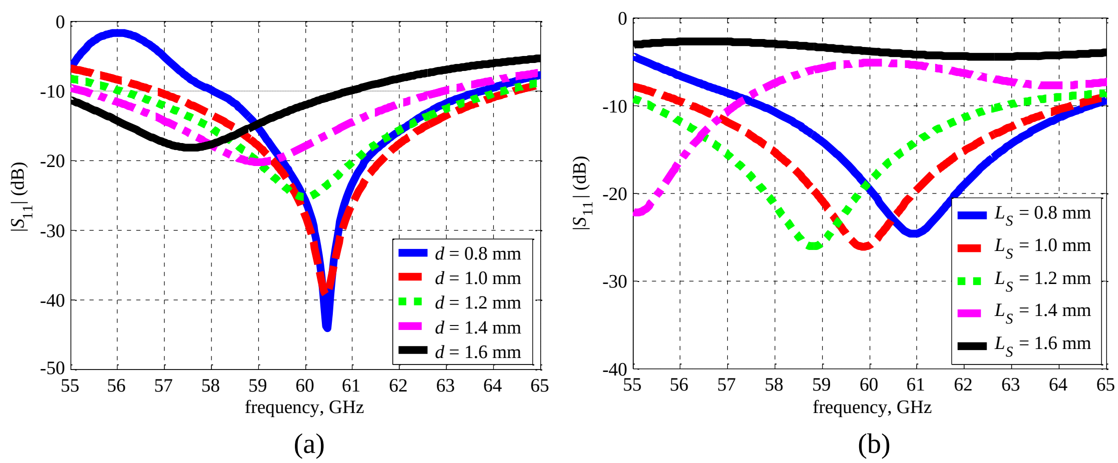


**Figure 2.** Effect of varying (a) the inter-element spacing parameter $d$, (b) feedline length parameter $L_S$ on the antenna return loss $|S_{11}|$.

## 3. EXPERIMENTAL AND SIMULATION RESULTS

### 3.1. Impedance Bandwidth

The scattering parameters of the fabricated mmW array antenna prototype were measured using Agilent Vector Network Analyzer PNA N5250C with port impedance of 50 Ω. Figure 3 shows the measured and simulated return loss $|S_{11}|$ of proposed array antenna versus frequency. All the following experimental results include the losses of 50 Ω microstrip feeding line, and the 1.85 mm connectors. The overall bandwidth remains unchanged. In addition, a shift in the measured curve towards higher frequencies has been occurred. This may be due to the fabrication errors, and the dispersive behavior of the frequency-dependent permittivity of the substrate material at high frequencies that could not be correctly modeled during simulations. It is worthy to mention that the connectors used are special types of connectors called 1.85 mm end-lunch connector for frequencies up to 67 GHz. There is may be some errors due to connector losses during measurement. The antenna exhibits a measured 10 dB bandwidth ranges from

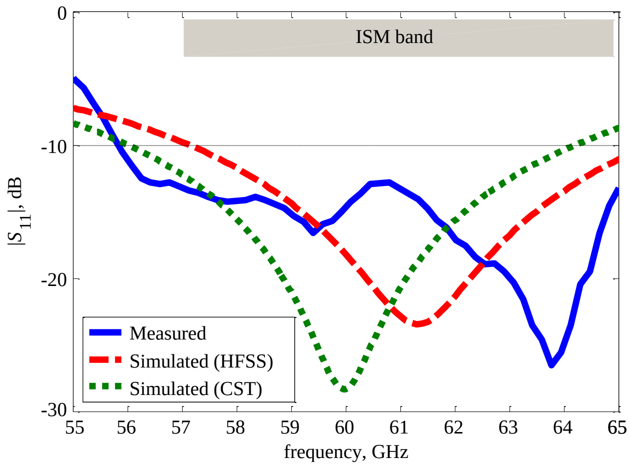


**Figure 3.** Measured and simulated return losses $|S_{11}|$ of proposed millimeter wave array antenna versus frequency.

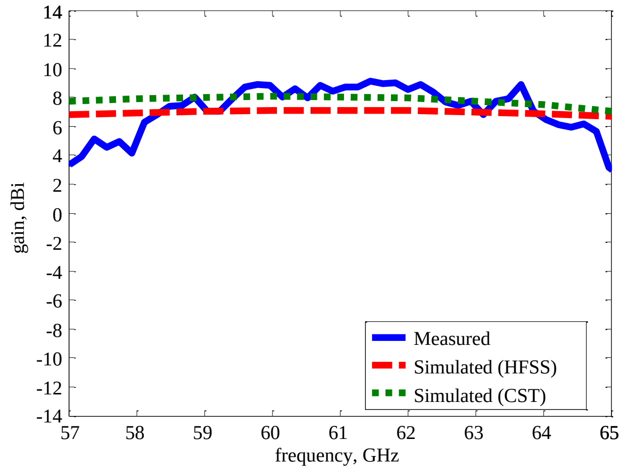


**Figure 4.** Measured and simulated maximum realized gain versus frequency of the proposed millimeter wave array antenna.

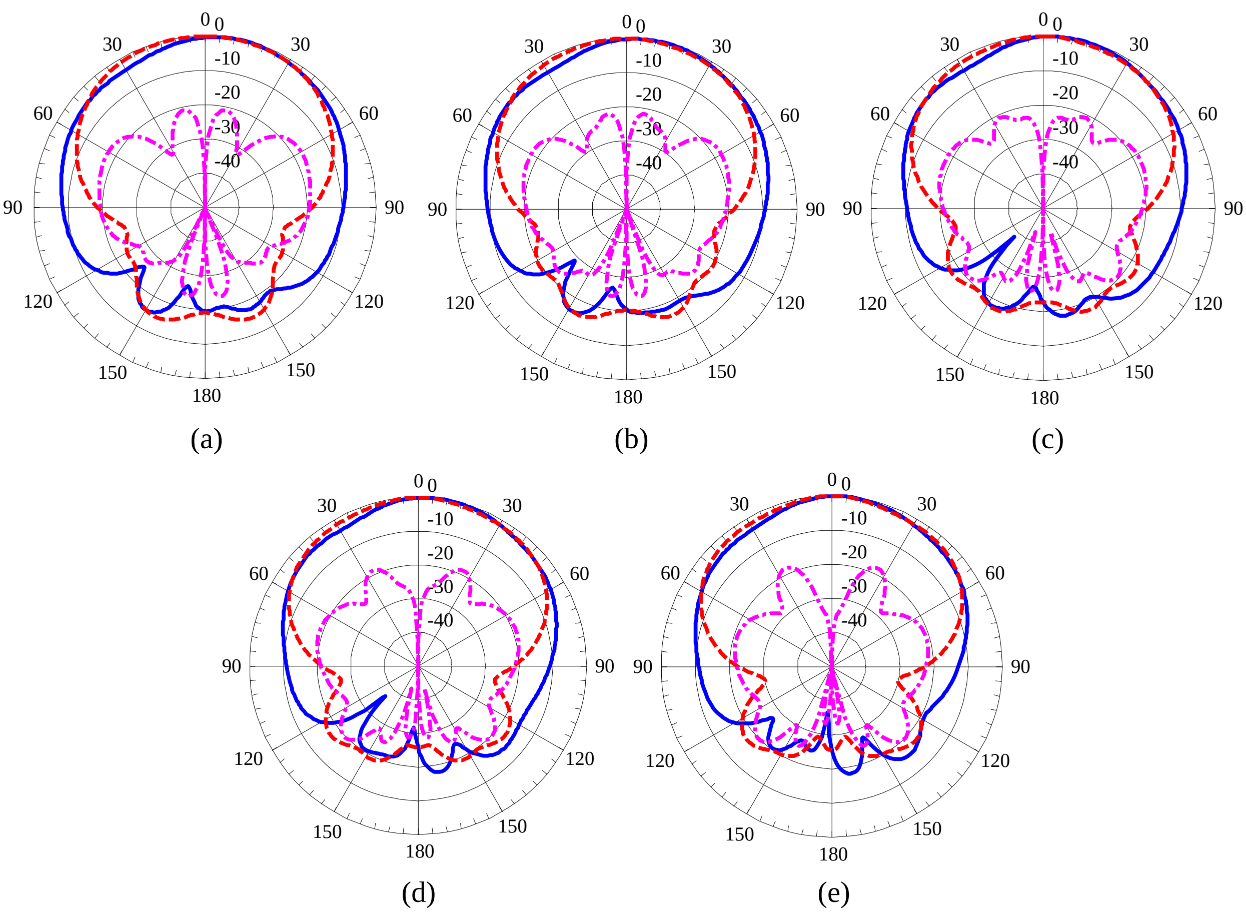


**Figure 5.** Simulated co- and cross-polarization radiation patterns in both $E$- and $H$-planes at: (a) 56 GHz, (b) 58 GHz, (c) 60 GHz, (d) 62 GHz, and (e) 64 GHz. (blue solid line for $E$-co-pol, red dashed line for $H$-co-pol, magenta dash-dotted line for cross-pol).

56 to beyond 65 GHz (> 14.8%) and simulated bandwidth from 56 to 64.2 GHz (13.6%) with CST and from 57.1 to beyond 65 GHz (> 13.8%) with HFSS.

### 3.2. Antenna Gain

The antenna gain in the bore-sight direction versus frequency has been measured and plotted in Figure 4. The calculated gains using both HFSS and CST programs are also presented for comparison purposes. It can be seen that the maximum achievable gain is 8 dBi at 60 GHz with less than 0.5 dBi gain variation across the frequency range of interest with good agreement between the two simulators. A noticeable measured gain drop has been occurred especially in the 55–58 GHz range while simulations show a stable gain. This may be due to errors in gain measurements at that range. This is because we have used a customized radiation pattern measurement setup for measuring the radiation patterns and gain at mm-wave frequencies. No absorbing material have been used inside the chamber and this may cause errors during measurement.

### 3.3. Radiation Patterns

The simulated co-polarization and cross-polarization radiation patterns in both $E$- and $H$-planes at different frequencies 56 GHz, 58 GHz, 60 GHz and 64 GHz are introduced in Figure 5. A noticeable low cross-polarization level has been achieved at all frequencies of interest. The measured and simulated co-polarization radiation patterns in the $H$-plane at different frequencies 56 GHz, 58 GHz, 60 GHz and 64 GHz are introduced in Figure 6. It can be noticed that the proposed array antenna has good broadside radiation patterns in the $H$-plane through the desired frequency range.

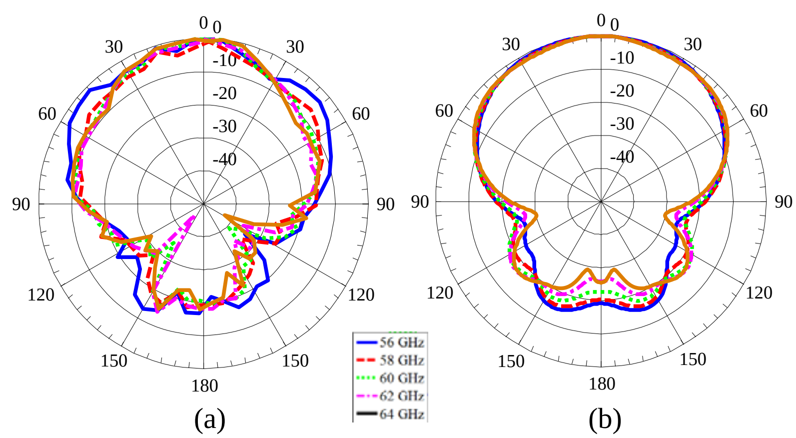


**Figure 6.** (a) Measured, (b) simulated radiation patterns in $H$-plane at 56 GHz, 58 GHz, 60 GHz, 62 GHz, and 64 GHz.

## 4. CONCLUSION

This paper proposes both numerical and experimental investigations for an electromagnetically coupled millimeter-wave antenna array operating at 60 GHz ISM-band frequency range. The array antenna consists of five elliptical patches with different sizes fed by electromagnetic coupling feeding technique from a microstrip-feeding network existing underneath the radiating patch elements. Results show that the proposed antenna is a good candidate for 60 GHz ISM-band applications.

## ACKNOWLEDGMENT

This research is supported by King Abdul-Aziz City for Science and Technology (KACST) Technology Innovation Center in radiofrequency and photonics (RFTONICS) in the e-society hosted at King Saud University.

## REFERENCES


1. Fisher, R., "60 GHz WPAN standardization within IEEE 802.15.3c," *Proc. Int. Symp. on Signals, Systems and Electronics*, 103–105, 2007.
2. Br'egains, J. C., L. Castedo, and F. Ares, "A WiMAX conformal broad-beam antenna," *IEEE Antennas and Propagation Magazine*, Vol. 52, 106–109, 2011.
3. Haraz, O., S. Almorqi, A.-R. Sebak, and S. A. Alshebeili, "High-gain broadband antennas for 60-GHz short-range wireless communications," *Wideband, Multiband, and Smart Reconfigurable Antennas for Modern Wireless Communications*, M. A. Matin (ed.), in Press.
4. Nakano, S. H., Y. Hirachi, J. Hirokawa, and M. Ando, "Cost-effective 60-GHz antenna-package with end-fire radiation from open-ended post-wall waveguide for wireless file-transfer system," *Proc. IEEE MTT-S Int. Microwave Symp. Digest (MTT)*, 449–452, May 23–28, 2010.
5. Sun, M., X. Qing, and Z. N. Chen, "60-GHz antipodal Fermi antennas on PCB," *Proc. Eur. Conf. on Antennas and Propagation*, 11–15, Rome, Italy, Apr. 2011.
6. Elboushi, A. M., O. Ahmed, A. Sebak, and T. Denidni, "A new circularly polarized high gain DRA millimeter-wave antenna," *IEEE International Symposium on Antennas and Propagation and CNC/USNC/URSI Radio Science Meeting (AP-S/URSI)*, 1–4, Toronto, Canada, Jul. 11–17, 2010.
7. Haraz, O. M., A.-R. Sebak, and S. A. Alshebeili, "Study the effect of using low-cost dielectric lenses with printed log-periodic dipole antennas for millimeter-wave applications," *International Journal of Antennas and Propagation*, Vol. 2015, Article ID 209430, 7 Pages, 2015, Doi: 10.1155/2015/209430.
8. Haraz, O. M., A.-R. Sebak, and S. A. Alshebeili, "Performance investigation of V-band PLPDA antenna loaded with a hemispherical dielectric lens for millimeter-wave applications," *Microwave and Optical Technology Letters*, Vol. 57, No. 3, 630–634, Mar. 2015.
9. Haraz, O. M., A.-R. Sebak, and S. A. Alshebeili, "Low-cost high gain printed log-periodic dipole array antenna with dielectric lenses for V-band applications," *IET Microwaves, Antennas and Propagation*, Vol. 9, No. 6, 541–552, Nov. 24, 2014, Doi: 10.1049/iet-map.2014.0319.
10. Haraz, O. M., A.-R. Sebak, and S. A. Alshebeili, "Design of a printed log-periodic dipole array antenna with high gain for millimeter-wave applications," *International Journal of RF and Microwave Computer-Aided Engineering*, Vol. 25, No. 3, 185–193, 2015, Doi: 10.1002/mmce.20848.