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Single Ported Pharaonic Ankh-Key Antenna Array for Millimeter-Wave, 5G, 6G and Beyond Technologies Applications: Design, Simulation and Fabrication.

Noha Moustafa Rashad[1,2*], Ashraf A. M. Khalaf [2]

[1] *Communications and Electronics Engineering Department, Faculty of Engineering, October University for Modern Sciences and Arts (MSA), Giza Egypt.*

[2] *Electrical Engineering Department, Faculty of Engineering, Minia University, Minia, Egypt.*

* *corresponding author E-mail: noha-moustafa@live.com , nrashad@msa.edu.eg*

ABSTRACT

In this paper, a single layer multi-resonating frequency two-element Pharaonic Ankh-Key array antenna with length of 35 mm, width of 18.5 mm and height of 0.787mm Rogers/Duroid RT 5880 (ε_r = 2.2 and tanδ = 0.0009) fed with one port is proposed. The two elements are fed with a feeding network which is connected with a 50 Ω line of width 2.21 mm and length 8.8 mm. This antenna operates in all bands between 23.2 GHz to beyond 140 GHz with a band notch between 27.9 GHz to 30.4 GHz. It supports many bands such as 24 GHz, 28 GHz, 37 GHz, 39 GHz, 47 GHz, E-band, W-band, and D-band enhancing the use of 5G and advanced technologies applications. The antenna has a maximum gain between 8 dBi and 15.5 dBi along the operating spectrum. For performance verification, it has been simulated using three different simulators (HFSS, CST, and IE3D) each with a different simulation technique (FEM, FIT, and MOM, respectively). The fabrication of the proposed antenna was done at a very low cost compared to the existing ones and the measuring results were compared to the simulated results showing a very good agreement.

Keywords: Millimeter-Wave, Antenna Array, Multi-band, Ankh-Key, 5G, 6G, 7G.

I. INTRODUCTION

Wireless technologies are booming now a days challenging researchers to find advanced solutions that cope with the developed technologies. Millimeter-wave applications are getting more used these days due its large bandwidth that extends from 30 – 300 GHz and its high data rate of transfer for short-range applications. 5G and 6G technologies are also spreading in this era and Federal Communications Commission (FCC) encourages engineers to search more in this area by expanding the use of more spectrum each year. In October 2015, FCC agreed for using 24 GHz, 28 GHz, 37 GHz, 39 GHz, 47 GHz, and 64-71 GHz bands for wireless broadband applications (FCC 15-138), and the auction was completed in March 2020 [1]. Then it allowed the use of 21.2 GHz of the Spectrum Horizons bands that extends from 95 GHz to 3 THz (or Terahertz Spectrum) for unlicensed devices using: the 116-123 GHz band, the 174.8-182 GHz band, the 185-190 GHz band, and 244-246 GHz band in March 2019 (FCC 19-44) [2]. And it decided to free up 2.75 GHz of the 5G spectrum in 26 GHz and 42 GHz bands and began to add more millimeter band spectrum in 70/80/90 GHz band for use in 5G applications in February 2021 [1].

In this article, a two-element Pharaonic Ankh-Key array antenna fed with one port is proposed enhancing the use of different types of applications in 5G, 6G and beyond technologies. The two radiating elements are separated with distances between, D1 and D2, which were designed and optimized to be between λ/4 and λ/2 to achieve the best antenna performance for wide bandwidth and S12 below -20 dB all over the operating bandwidth [3]. The main radiating Pharaonic Ankh-Key antenna was designed to achieve a huge bandwidth with many resonating frequencies using many microstrip antenna characteristics such as; sharp edges, bow-tie, tapering, and round slots [11,12]. The proposed antenna is designed from the Pharaonic Ankh-Key with the large bow-tie as it has better gain and more resonating frequencies all over the desired bandwidth [11]. The proposed antenna's overall dimensions are length, L, 35 mm, and width, W, 18.5 mm of copper and dielectric substrate of height 0.787 mm Rogers/Duroid RT5880 with εr = 2.2 and tanδ = 0.0009 between the patch and the ground. The antenna can operate within a huge bandwidth extending from below 23.2 GHz to beyond 140 GHz with a band notches between 27.9 GHz and 30.4 GHz band having a peak gain between 8 dBi and 15.5 dBi along the operating spectrum. Each Ankh-Key element has an overall dimensions of length 16.8 mm and width 5.7 mm. The two elements are fed with a feeding network that is connected to a 50Ω microstrip line of width 2.21 mm. Due to the large bandwidth and irregular antenna geometry, most of the antenna parameters are conducted using optimization techniques and many trials to obtain the desired frequency range. As the operating bandwidth is very large, the antenna was simulated using three different simulators with different techniques to validate their results; Ansys HFSS (FEM technique), CST Microwave Suite (FIT technique), and IE3D Mentor Graphics (MOM technique), and then fabricated using the Photolithographic technique showing a very good agreement between the simulated and the measured results. The new design supports very large bandwidth and very high peak gain enhancing the use of many wireless applications. The

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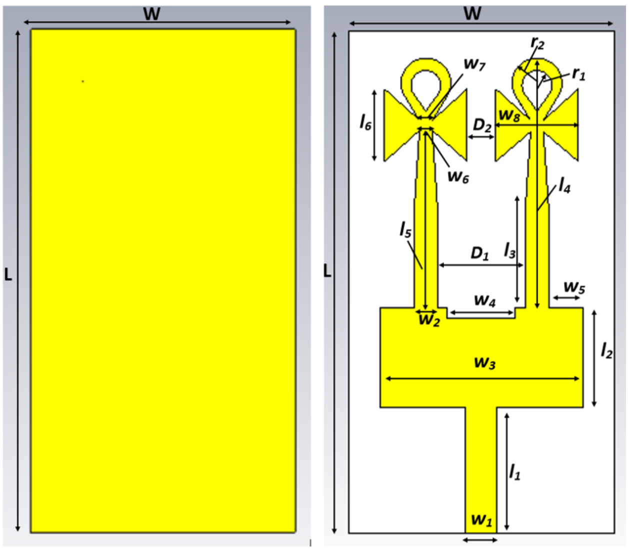
following section discusses the newly proposed design and all its related results.

II. Antenna Geometry

The proposed array antenna is designed to operate in large bandwidth with high gain compared to the existing antennas in the market. The new antenna can operate in all bands between 23.2 GHz and beyond 140 GHz with one band notch between 27.9 – 30.4 GHz. The antenna is a single layer two-element array with overall dimensions of 35 mm x 18.5 mm and a height of 0.787 mm of dielectric substrate material Rogers/Duroid RT5880 with of ε_r = 2.2 and $tan\delta$ = 0.0009. The two elements are connected with one 50Ω microstrip line by a feeding network with optimized dimensions to achieve the best performance and gain of a one-port-fed antenna supporting its related applications in 5G and advanced millimeter-wave technologies. Figure 1 below shows the antenna geometry of the proposed design.



(a) (b)

Figure 1. Proposed two-element array antenna; (a) Ground Plane and (b) Radiating Element.

The top part of the antenna, the main two elements, has the same structure each with overall dimensions of 16.8 mm x 5.7 mm. The two elements are designed and optimized with separating distances, D_1 and D_2, between $\lambda/4$ and $\lambda/2$ achieving the best performance where S_{12} is below -20 dB all over the operating bandwidth as shown in figure 2 below. The figure shows the simulated S_{11} and S_{12} when each element is separately fed. The simulations were done using FIT and FEM techniques where the results showed good agreement as the bandwidth extends from 24 GHz to beyond 140 GHz with two band notches between 33.5 GHz to 36 GHz and 39.3 GHz to 42.8 GHz achieving S_{12} below -20 dB along the operating spectrum. The other part is considered as a feeding network to the two-element arrays enhancing the antenna to be fed with one port instead of two ports permitting the use of different wireless applications.

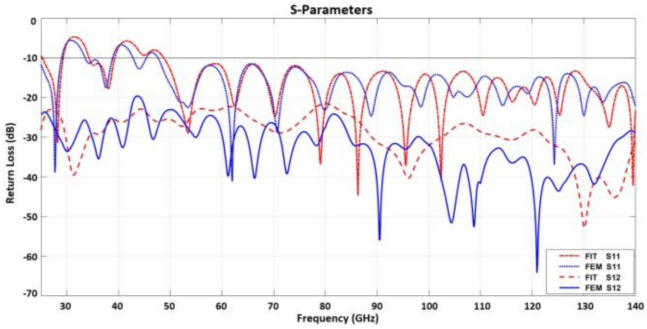


Figure 2. Simulated S_{11} and S_{12} of the separately fed two-element array antenna.

Table I below shows the dimensions of the proposed structure.

TABLE I. Dimensions of the new proposed two-element ankh-key array antenna

Parameter	l_1	l_2	l_3	l_4	l_5	r_1	r_2
Dimension (mm)	8.8	6.95	7.01	17.34	12.22	1.04	1.73
Parameter	w_1	w_2	w_3	w_4	w_5	w_6	w_7
Dimension (mm)	2.21	1.61	14.15	4.75	2.39	0.89	1.91

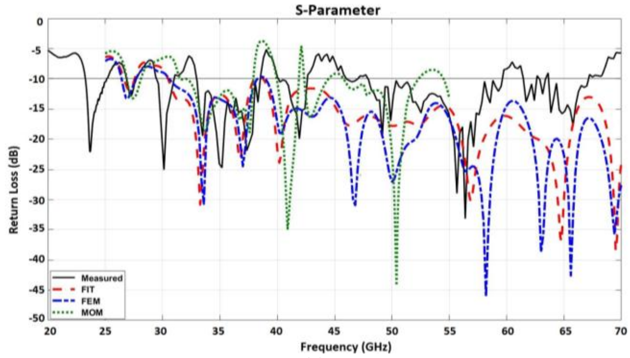
The dimensions of the feeding network and its feeding line are optimized to reach the best performance achieving wider bandwidth and higher gain compared to the separately fed two-element array antenna. The simulated and measured results are discussed in the next section.

III. Simulation and Fabrication Results

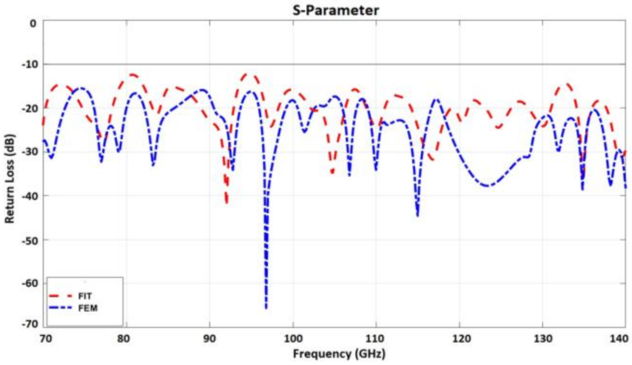
The array antenna was simulated using three different simulators each with a different solving technique; Ansys HFSS (FEM technique), CST Microwave Suite (FIT technique), and IE3D Mentor Graphics (MOM technique) and their results showed very good agreement. Then the antenna is fabricated using Photolithographic technique and connected to an SMA connector with a maximum frequency of 40 GHz. The return loss was then measured using ZVA 67 Vector Network Analyzer of range from 10 MHz to 67 GHz at the Electronics Research Institute (ERI), Cairo, Egypt.

a. S-Parameters

Figure 3 shows a comparison result between the return losses (S_{11}) of the three simulators and the measured results.



(a)



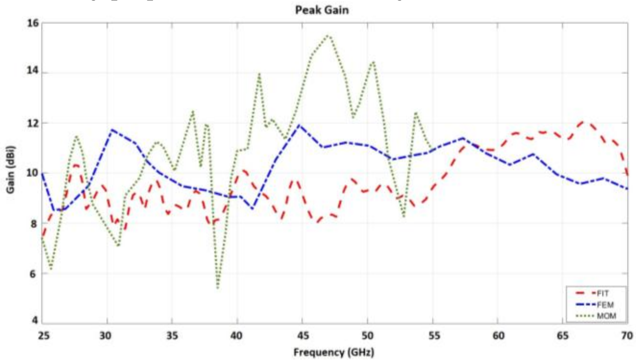
(b)

Figure 3. Simulated and Measured S_{11}; (a) Frequency range 20 – 70 GHz, (b)) Frequency range 70 – 140 GHz.

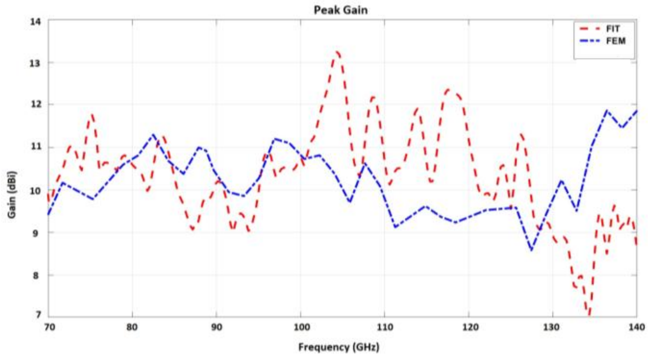
Figure 3 (a) and (b) show the simulated and measured S_{11} results for the proposed antenna where figure 3(a) shows the frequency range between 20 – 70 GHz and figure 3(b) shows the frequency range between 70 – 140 GHz. As shown in figure 3(a), the antenna is simulated using IE3D Mentor Graphics (MOM technique) until 55 GHz as this solver shows better results in the low frequencies than in high frequencies. This technique showed that the antenna can operate in the ranges of; 26.8 – 28.3 GHz, 31.4 – 38 GHz, 39.9 – 41.9 GHz, and 42.3 – 55 GHz. Whereas CST Microwave Studio (FIT technique) and Ansys HFSS (FEM technique) showed the same operating bandwidth ranges and almost the same resonating frequencies where the antenna can operate in all the ranges between 26.4 GHz to beyond 140 GHz with a band notch between 27.9 GHz to 30.4 GHz. All the simulated and measured results showed convenient agreement with measured results which showed that antenna can operate in the ranges of; 23.2 – 25.2 GHz, 26.8 – 27.9 GHz, 29.4 – 31.1 GHz, 32.8 – 38.6 GHz, 40 – 42.7 GHz, 45.8 – 59.7 GHz, and 61.4 – 68.4 GHz with multi-resonating frequencies supporting all applications that work in ranges between 23.2 GHz to beyond 140 GHz.

b. Peak Gain

Figure 4 (a) and (b) below show the simulated peak gain for the three simulators used where figure 4 (a) shows frequency range of 20 – 70 GHz and figure 4 (b) shows frequency range of 70 – 140 GHz. The MOM technique showed a peak gain between 6 dBi and 15.5 dBi, the FIT technique showed a peak gain between 8 – 12 dBi in the low frequencies, and about 13.2 dBi in the high frequencies, and FEM technique showed peak gain 8.8 – 11.9 dBi all over the operating spectrum which is comparatively higher than the previously proposed two-element array antenna.



(a)



(b)

Figure 4. Simulated Peak Gain.

c. VSWR

Figure 5 below shows simulated VSWR for the three simulators. As observed, the FIT and FEM techniques showed almost the same VSWR where the antenna operates in all frequency range between 26.5 GHz to beyond 140 GHz with band notch between 27.9 GHz to 30.4 GHz. Whereas the MOM technique showed that the antenna can operate in almost the same ranges but with more band notches which are between 28.3 – 31.4 GHz, 38 – 39.9 GHz, and 41.9 – 42.3 GHz.

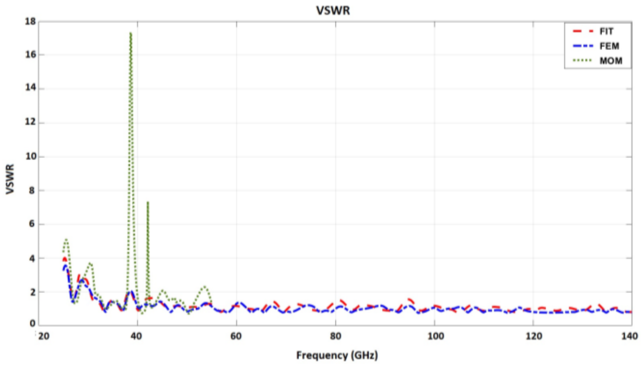


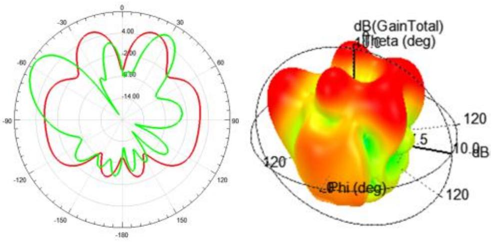
Figure 5. Simulated VSWR.

d. Radiation Pattern

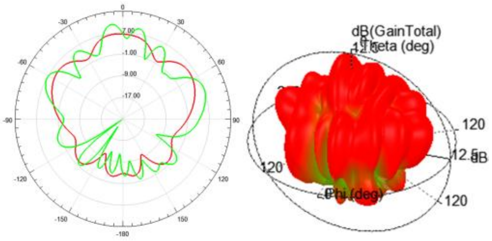
Figure 6 below shows the simulated radiation pattern in E-plane and H-plane compared to the 3D pattern at different frequencies. For each mentioned frequency, a polar plot figure (on the left) with E-plane compared to H-plane and a 3D figure (on the right) for the 3D-radiation pattern are presented. The difference in the radiation pattern is due to the change in wave-lengths along the operating spectrum and this is clear according to the following fundamental equation of the directivity gain is;

$$G(\theta,\varphi) = \frac{4\pi A(\theta,\varphi)}{\lambda^2} \quad [16]$$

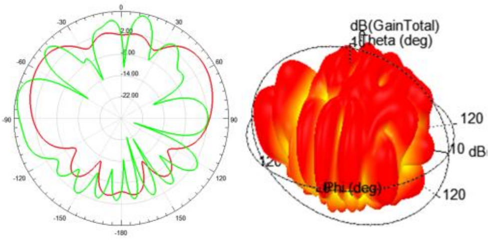
Where $A(\theta,\varphi)$ is the antenna Effective aperture and λ is the wave-length. It can be observed from the equation that the directivity gain changes when the frequency changes and thus the radiation pattern. The figures show high gain and directed patterns at the 5G frequencies and omnidirectional patterns in most of the frequency bands Most of these radiation patterns are at resonating frequencies.



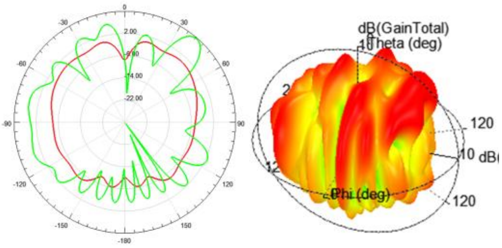
27 GHz



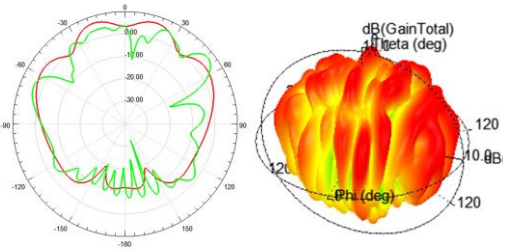
33.6 GHz



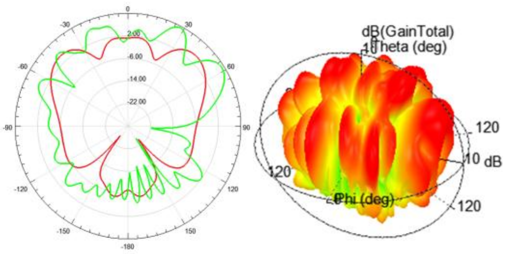
37 GHz



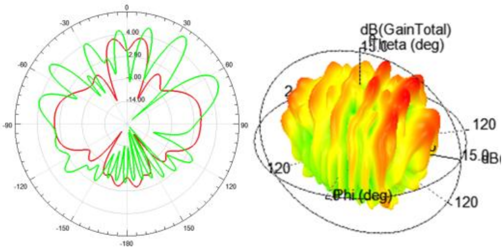
40.2 GHz



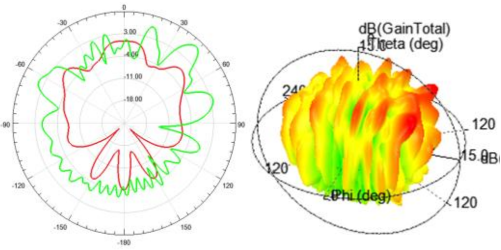
46.8 GHz



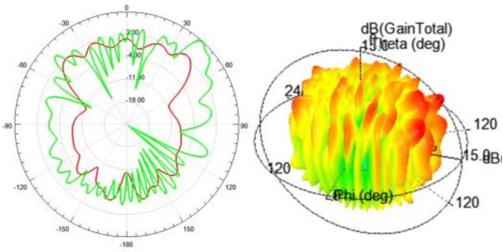
50 GHz



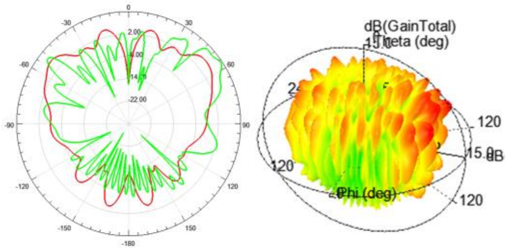
56.4 GHz



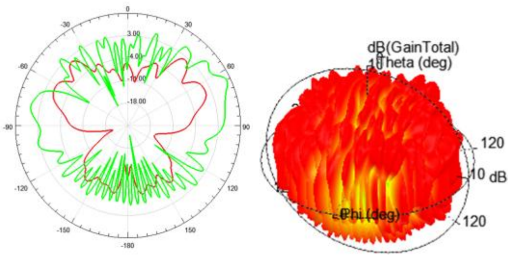
69.4 GHz



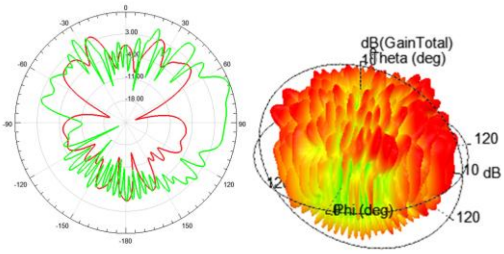
77 GHz



83.2 GHz



92.8 GHz



96.8 GHz

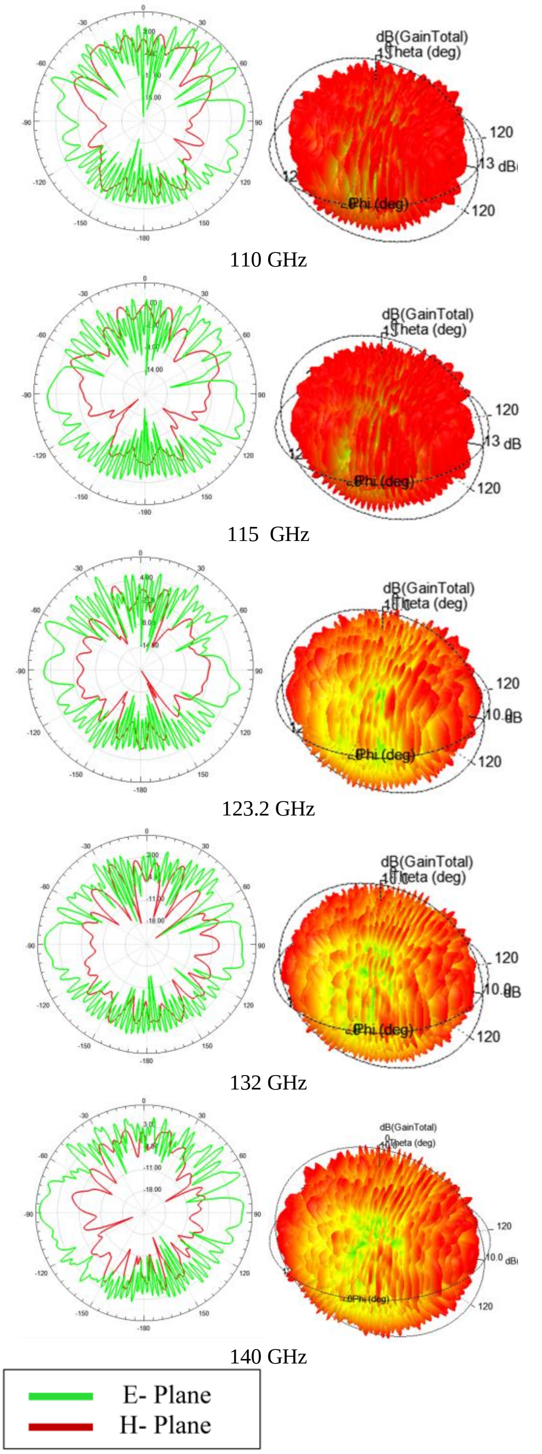


Figure 6. Simulated Radiation Pattern (E-Plane and H-Plane) verses 3D Pattern at different frequencies.

e. Radiation Efficiency

Figure 7 below shows a simulated radiation efficiency between 97.5 % and 100% along the operating spectrum and these results were obtained from the CST simulator. The radiation efficiency (e_{cd}) can be calculated using the following formula:

$$e_{cd} = \frac{P_{rad}}{P_{rad} + P_{ohmic}} \qquad [16]$$

where P_{rad} is the total power radiated by the antenna and P_{ohmic} is the total power dissipated by the antenna in the form of ohmic losses. So it can be calculated from figure 7 and the above equation that the ohmic losses in the proposed is less than 2.5% of the radiated power showing that the proposed antenna is very effective along the operating spectrum.

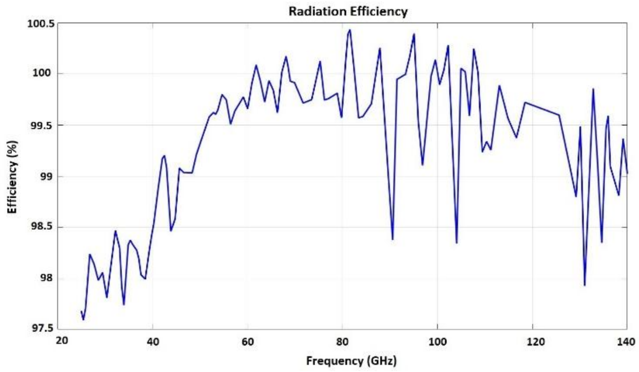


Figure 7. Simulated Radiation Efficiency.

f. Fabrication

Figure 8 below shows the fabricated array antenna, using Photolithographic technique, connected to an SMA connector with a maximum frequency of 40 GHz as the measuring process was carried out to 67 GHz. The fabricated antenna in the figure is connected to a two-cent coin to show its real dimensions.

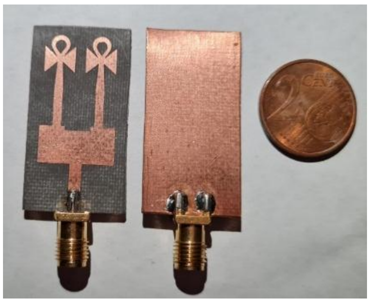


Figure 8. Fabricated Array Antenna.

Last but not least, from all the obtained results we can say that the proposed antenna is very efficient with large bandwidth and high gain. Table 2 shows a comparison between the performance of the proposed antenna and some related recent researches. It is observed that the proposed antenna has many pros compared to other antennas that work in similar bands or with the same design technology. The proposed antenna has a simple and small structure with a very large bandwidth and high gain with the best radiation efficiency compared to the other antennas making it a very good candidate for 5G and advanced technology wireless applications.

TABLE II. **Performance Comparison between the Proposed array antenna and the related work.**

References	Dimensions (mm)	# of Antenna Elements	Frequencies (GHz)	Bandwidth (GHz)	Maximum Gain (dBi)	Efficiency
N.M. Rashad et al., (2022) [3]	18.7 x 18.5 x 0.787	2	All bands between 23 - 140	23.2 - 33.5 / 36 - 39.3 / 42.8 - 140	7.8 - 12.3	98%
N.A. Eltersy et al., (2021) [4]	21.5 x 21.5 x 0.8	2	5.8	4.8 – 6.8	5	70.8
Y. Zhang et al., (2020) [5]	1 x 470 x 104	16	2.6	N/A	13	N/A
P. Liu et al., (2021) [6]	32 x 32 x 7	64	N/A	71 – 86	22.1	70%
F. Sun et al., (2021) [7]	76 x 76 x 23	64	37	30%	28.5	90%
Ikhlas Ahmad et al., (2021) [8]	30 x 20 x 1.6	1	4.5/4.8/5.5 or 3.5 or 2.6 /6.2 or 2.1/5/6.5	3.51 - 8.51 or 3.1 - 4.11 or 2.41 - 2.81 / 5.47 - 7.18 or 2.03 - 2.27 / 4.61 -5.35 / 5.87 - 7.22	2.5 or 1.95 or 1.54 or 1.64	84% or 82% or 83% or 80%
Mohammad Wagas et al., (2021) [9]	35.2 x 73 x 0.508	16	39	1.01	5.002	92%
Mohammad Zahid et al., (2020) [10]	16.5 x 10 x 0.787	N/A	15.6 / 24.7 / 41.4	3.1 / 1.1 / 31.7	4.6 / 6.95 / 7.77	95.5%
Proposed Antenna	35 x 18.5 x 0.787	2	All bands between 23.2 - 140	23.2 – 27.9 / 30.4 – 140	8 – 15.5	100%

IV. Conclusion

In this paper, a two-element Pharaonic Ankh-Key array antenna with single port is designed, simulated, and fabricated to meet the requirements of 5G and beyond technologies applications with promising peak gain and radiation pattern as it is a very good candidate to work in all bands from 23.2 GHz to beyond 140 GHz with a band notch between 27.9 GHz to 30.4 having peak gain between 8 dBi to 15.5 dBi all over the operating bandwidth with radiation efficiency reaching 100%. The two-element array is fed with a feeding network, thus the number of elements can be increased, in future work, using the same technique to achieve higher gain and better performance.

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