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Two-Element Pharaonic Ankh-Key Array Antenna Design, Simulation, and Fabrication for 5G and Millimeter-Wave Broadband Applications

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ABSTRACT In this paper, a two-element Pharaonic Ankh-Key array antenna is proposed. The array antenna is designed, simulated and fabricated to enhance the new technologies upcoming in the market. The multiband array antenna can operate in 24 GHz band, 28 GHz band, 37 GHz band, 39 GHz band, 47 GHz band, E-band, W-band, and D-band with peak gain between 7.8 dBi to 12.3 dBi along the resonating spectrum. The array antenna is a single layer of two-element antenna separately fed by 50Ω microstrip line with dimensions 18.7 mm × 18.5 mm and a height of 0.787mm Rogers/Duroid RT 5880 of $\varepsilon_r = 2.2$ and $tan\delta = 0.0009$ which was easily fabricated with a very low cost compared to the existing antennas in the market making it a very promising candidate for 5G and beyond technologies MIMO applications as it operates in almost all band between 23 GHz and 140 GHz. The antenna is designed and simulated using CST Suite, Ansys HFSS, and IE3D Mentor Graphics simulators then the simulated results where compared to the measured results achieving a very good agreement.

INDEX TERMS Millimeter-wave, array antenna, multi-band, Ankh-Key, broadband, MIMO, 5G, 6G, 7G, HFSS, CST, IE3D.

I. INTRODUCTION

New technologies are spreading widely in the market challenging the researchers to find better solutions and seek better performance to meet the market needs. Wireless technologies are booming in this era operating in too many bands in different areas and applications. Many of the advanced-technology use the Millimeter-wave band which extend from 30-300 GHz providing multigigabytes of data transfer for short range applications. In October 2015, Federal Communications Commission (FCC) proposed the use of 24 GHz, 28 GHz, 37 GHz, 39 GHz, 47 GHz and 64-71 GHz band for wireless broadband applications (FCC 15-138) and the auction was completed by March 2020 [1]. In March 2019, FCC allowed the use of Terahertz spectrum or 6G spectrum, 95 GHz – 3 THz, unlicensed for experimental use to allow engineers focusing on the next generation start their work (FCC 19-44) [2]. In February 2021, FCC decided to work on freeing up 2.75 gigahertz of the 5G spectrum in 26 and 42 GHz band and initiated to add more millimeter band spectrum in 70/80/90 GHz band for use in 5G services [1].

The proposed design is a two-element Pharaonic Ankh-Key array antenna operating from below 23 GHz to beyond 140 GHz with some band notches between 30-35 GHz and 40 GHz band having a peak gain between 7.8 dBi and 12.3 dBi and coupling coefficient (S_{12}) below −20 dB all over the operating spectrum. Each element of the array is separately fed with a 50Ω microstrip line and separating distance, D, between λ/4 and λ/2 allowing the use of MIMO (Multi-Input-Multi-Output) applications. The single layer array antenna has a full ground structure of length, L, 18.7 mm and width, W, 18.5 mm of copper and dielectric substrate of height 0.787 mm Rogers/Duroid RT5880 with of $\varepsilon_r = 2.2$ and $\tan\delta = 0.0009$ between the radiator and the ground. The antenna is simulated using three different simulators with different techniques; CST Microwave Suite using Finite Integration Technique (FIT) technique, Ansys HFSS using Finite Element Method (FEM) technique and IE3D Mentor Graphics using Method of Moments (MOM) technique, then fabricated using Photolithographic technique

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showing a very good agreement between the simulated and the measured results. The design showed better performance than the single element design as it increased the operating spectrum as well as the peak gain, as stated in [3].

II. RELATED WORK

The main goal for using millimeter wave technology is the capability of using wideband spectrum with high data rate transmission and reception operating in low and very high frequencies with high gain and compact antenna sizes. This challenges researchers to contribute more in this field and find better solutions capable for 5G and beyond technologies applications.

In [3], N. M. Rashad and *et al.* designed a modified single element Pharaonic Ankh-Key microstrip antenna with dimensions 12.75mm × 18.7 mm and height of 0.787 mm of Rogers/Duroid RT 5880 ($\varepsilon_r = 2.2$ and $\tan\delta = 0.0009$) to work in 28 GHz band, 37 GHz band and all bands between 49 GHz and beyond 140 GHz with peak gain between 6.9 dBi and 10.2 dBi along the operating spectrum.

In [4], Amjad Omar and et. al presented two MIMO two-element array antenna designs from a single element of dimensions 4.4mm × 4.1 mm and height of 0.635 mm of RT/Duroid 6010LM ($\varepsilon_r = 10.7$) to operate in 28 GHz and 38 GHz bands only.

In [5], Kifayat Ullah and *et al.* presented a single element defected ground structure patch antenna with dimensions 8 × 8 mm^2 and height 0.8 mm of Rogers Ro4350 ($\varepsilon_r = 3.66$) operating in both 28GHz and 42 GHz with peak gain 6.2 dBi and efficiency above 96%.

In [6], Jianxing Li and *et al.* designed an eight-element slotted antenna array for MIMO applications with dimensions 140mm × 70 mm and 1mm height of FR4 ($\varepsilon_r = 4.4$ and $\tan\delta = 0.025$) operating in 3500 MHz and 5500 MHz bands with total efficiency above 51% and channel capacity more than 36.9 bps/Hz.

In [7], B. V. Naik and *et al.* presented a rectangular slot patch antenna with dimensions 21.37mm × 5mm and 1.59 mm thickness of FR4 substrate ($\varepsilon_r = 4.4$ and $\tan\delta = 0.017$) operating in 28 GHz band with peak gain 3.9 dBi.

In [8], Ikhlas Ahmad and *et al.* designed a frequency reconfigurable antenna which can operate in frequency range between 240 to 8510 MHz based on switches. The antenna dimensions are 30mm × 20 mm and height 1.6 mm of FR4 substrate ($\varepsilon_r = 4.3$ and $\tan\delta = 0.025$) achieving a peak gain of 2.05 dBi and radiation efficiency of 84%.

In [9], Muhammad Waqas and *et al.* designed a 4 × 4 MIMO antenna to work in the 39 GHz band with overall dimension 35.2 × 43 mm^2 and height 0.508 mm of Rogers RT5880 (lossy) with gain of 5.002 dBi and total efficiency of 92%.

In [10], Muhammas zahid and *et al.* presented an Ultra wideband antenna of dimensions 16.5 × 10 mm^2 and height 0.787 of Rogers RT5880 operating in 15.6 GHz, 24.7 GHz and 41.4 GHz bands with maximum gain 7.77 dBi and maximum efficiency 95.5%.

In [11], Naser and *et al.* presented a 1 × 8 phased array antenna with dimensions 75 × 150 mm^2 and height 0.5 mm of Rogers RT5880 covering all bands from 26 GHz to 43 GHz with gain more than 10 dBi and total efficiency more than 70%.

In [12], Gynougdeuk kim and Sangkil Kim presented a 1 × 4 antenna array with dimensions $2.78\lambda_o \times 0.14\lambda_o \times 0.1\lambda_o$ using substrate thickness FR4 ($\varepsilon_r = 4.1 \sim 4.2$ and $\tan\delta = 0.03$) operating in all bands between 23 GHz and 29 GHz with gain 11 dBi and maximum radiation efficiency 84%.

In [13], Kamil Trezebiatowski and *et al.* proposed an antenna with overall dimensions of 14.7 mm × 11.9 mm and height 0.254 mm of Rogers CuClad 217 ($\varepsilon_r = 2.2$ and $\tan\delta = 0.001$) operating in the band from 55GHz to 65 GHz with gain above 3 dBi.

Referring to all the above proposed antennas, a new design of 2 element array antenna is proposed in this paper with simple and smaller dimensions achieving better performance with very large bandwidth exceeding 100 GHz.

III. ARRAY ANTENNA GEOMETRY

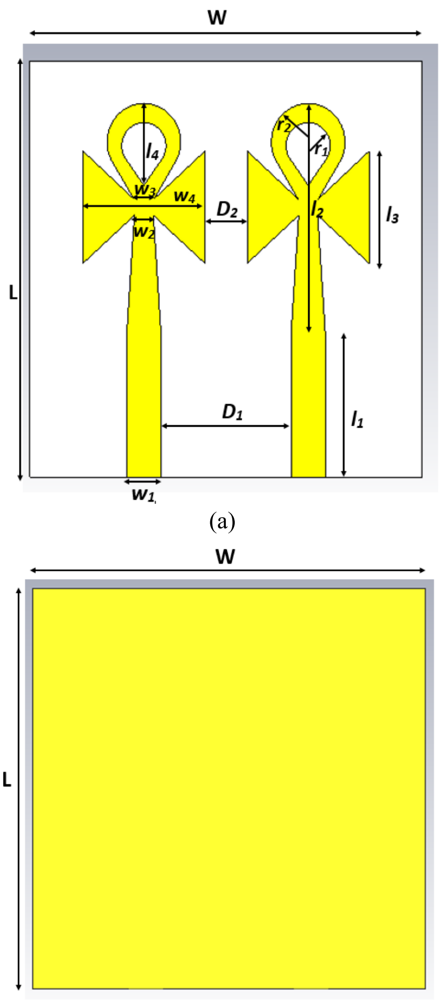
The two element array antenna is designed to operate in all bands from 23 GHz to beyond 140 GHz with overall dimensions 18.7 mm × 18.5 mm × 0.787 mm. Figure 1 shows the array antenna geometry of the microstrip patch antenna, (a), and the ground plane, (b).

The two elements are designed to meet the required criterion according to the dimensions in table 1 below.

TABLE 1. Dimensions of the two-element Ankh-Key array antenna.

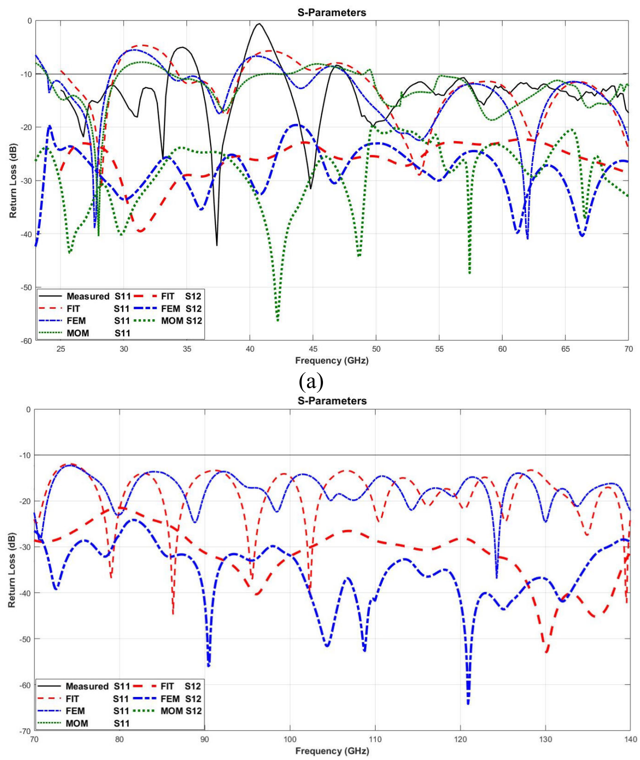
Parameter	Dimension (mm)	Parameter	Dimension (mm)
l_1	6.46	w_1	1.6138
l_2	10.3343	w_2	0.8936
l_3	5.034	w_3	0.9549
l_4	3.6761	w_4	5.736
r_1	1.0404	D_1	6.1362
r_2	1.734	D_2	2.014

Each element is separately fed with a 50Ω microstrip line and the separating distances, D_1 and D_2, are designed between $\lambda/4$ and $\lambda/2$ to maintain the coupling coefficient (S_{12}) along the operating band thus increase the bandwidth and peak gain of the operating spectrum in comparison with the single element antenna, where the operating bandwidth of the single element was from 26.6 GHz to beyond 140 GHz [3] while the two-element array works from below 25 GHz to beyond 140 GHz with less band notches compared to the single element band, and the peak gain of the single element is



(b)

FIGURE 1. **(a) Microstrip patch, (b) Ground plane.**



(b)

FIGURE 2. **Simulated and measured S_{11} and S_{12} (a) 20 GHz to 70 GHz band, (b) 70 GHz to 140 GHz band.**

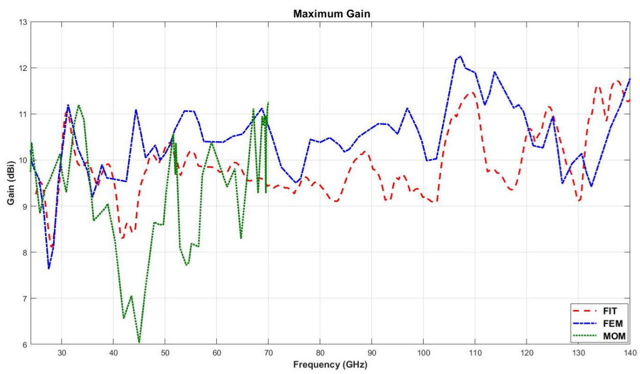


FIGURE 3. **Simulated peak gain.**

between 6.9 dBi and 10.2 dBi whereas the two-element array peak gain is between 7.8 dBi and 12.3 dBi along the operating frequency [3].

IV. RESULTS AND DISCUSSION

The array antenna was designed and simulated using three different simulating techniques with different simulators; CST Microwave Suite (FIT technique), Ansys HFSS (FEM technique) and IE3D Mentor Graphics (MOM technique), and the results were compared to show a very good agreement. The antenna is then fabricated using Photolithographic technique, but was connected to an SMA (SubMiniature Version A) connector with maximum frequency 40 GHz as some products were not available in the market due to Corona Pandemic and that's why we used three different simulators with different techniques to prove the results. 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 RESULTS

Figure 2 shows a comparison result between the return losses (S_{11}) of the three simulators and the measured results, and the coupling coefficient (S_{12}).

Figure 2 shows the simulated and measured S_{11} and simulated S_{12} from 20 GHz to 140 GHz. CST Microwave Studio (FIT technique) shows an open bandwidth from 25-29.3 GHz, 34.2-39.3 GHz and 49 GHz to beyond 140 GHz, whereas Ansys HFSS (FEM technique) shows an open bandwidth from 23.2- 29 GHz, 33.5-38.8 GHz, 42.8-45.8 GHz and 47.8 GHz to beyond 140 GHz. In IE3D Mentor Graphics (MOM technique), the simulation was carried out to 70 GHz

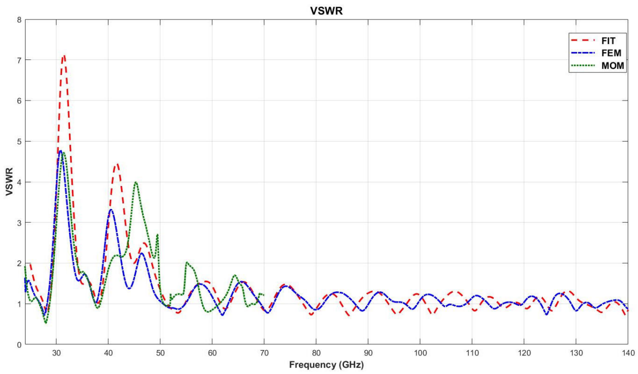


FIGURE 4. Simulated VSWR.

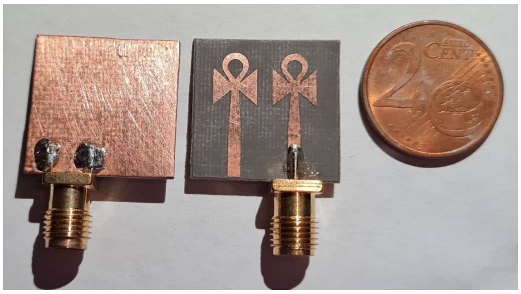


FIGURE 5. Fabricated array antenna.

only as this simulator shows very good results in low frequencies only, thus the return loss shows 23.2-29.5 GHz, 33.5-43 GHz and 49-70 GHz open bands, while the measured results show 23.2-33.5 GHz, 36-39.3 GHz and 42.8-70 GHz working bands. It is clearly observed that the simulated and measured results showed perfect agreement in the range from 20 GHz to 40 GHz (maximum frequency of the SMA connector) and this can prove the agreement of the whole band. All simulators show the results of the coupling coefficient (S_{12}) below -20 dB along the operating spectrum from 20 GHz to beyond 140 GHz as shown in the bottom curves in figure 2 making the design a very good candidate for MIMO 5G applications.

B. MAXIMUM GAIN AND VSWR RESULTS

Figure 3 below shows the simulated maximum gain all over the operating spectrum. CST and HFSS simulators show peak gain between 7.8 dBi and 11.2 dBi in the low frequencies and between 9.5 dBi and 12.3 dBi in the high frequencies, whereas IE3D simulator shows peak gain between 6 dBi and 11.2 dBi in the low frequencies, thus all simulators results show very good agreement along the operating spectrum.

Figure 4 shows the VSWR simulated by the three techniques where all the band is below 2 except for the notch bands in 30 GHz and 40 GHz bands.

Figure 5 shows the fabricated array antenna, front view and ground view, with one element connected to an SMA connector beside a 2-cent coin to indicate its real dimensions.

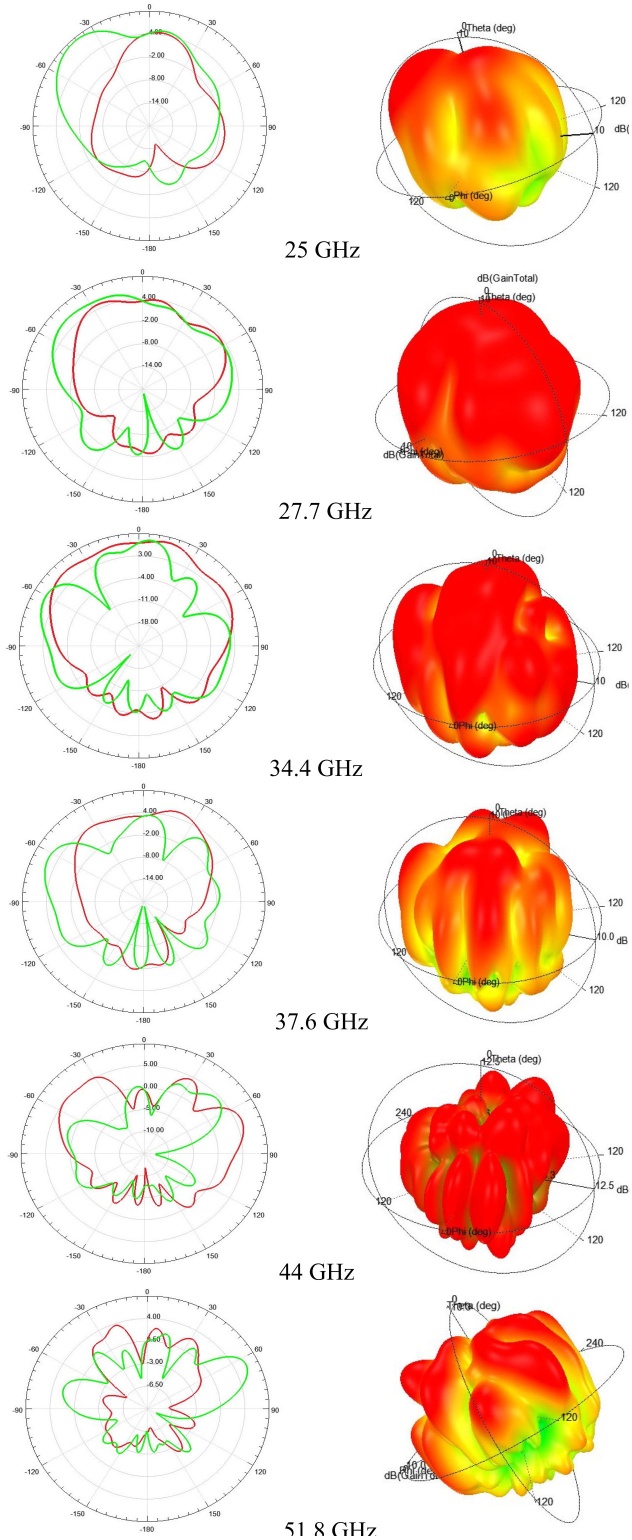


FIGURE 6. Simulated radiation pattern E-plane and H-plane on the left, and 3D pattern on the right at different frequencies.

C. SIMULATED RADIATION PATTERN

Figure 6 below shows the simulated radiation pattern in E-plane and H-plane compared to the 3D pattern at

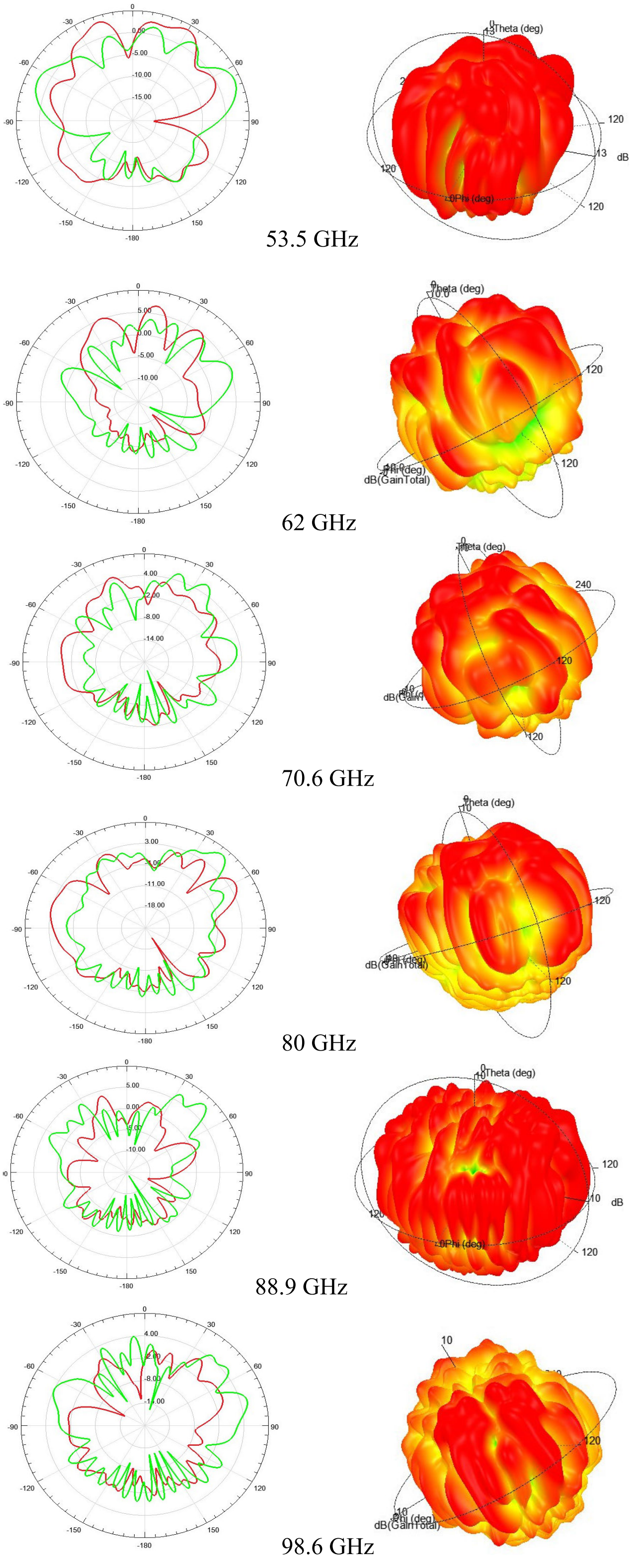


FIGURE 6. ***(Continued.)*** **Simulated radiation pattern E-plane and H-plane on the left, and 3D pattern on the right at different frequencies.**

different frequencies. The results show a very good and directed pattern at the 5G frequencies and omnidirectional pattern in most of the frequency bands.

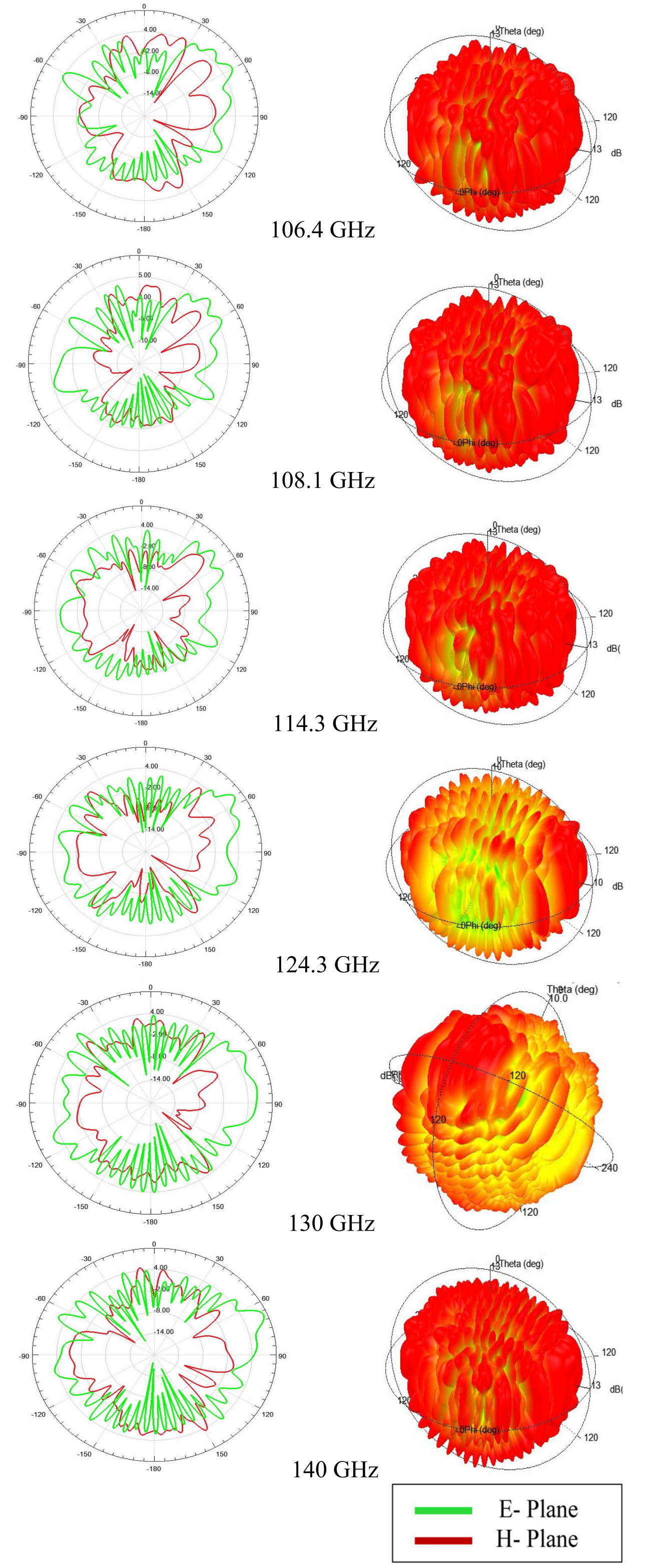


FIGURE 6. ***(Continued.)*** **Simulated radiation pattern E-plane and H-plane on the left, and 3D pattern on the right at different frequencies.**

D. SIMULATED CURRENT DISTRIBUTION AND EFFICIENCY

Figure 7 below shows the simulated current distribution of the array antenna when each element is separately fed at

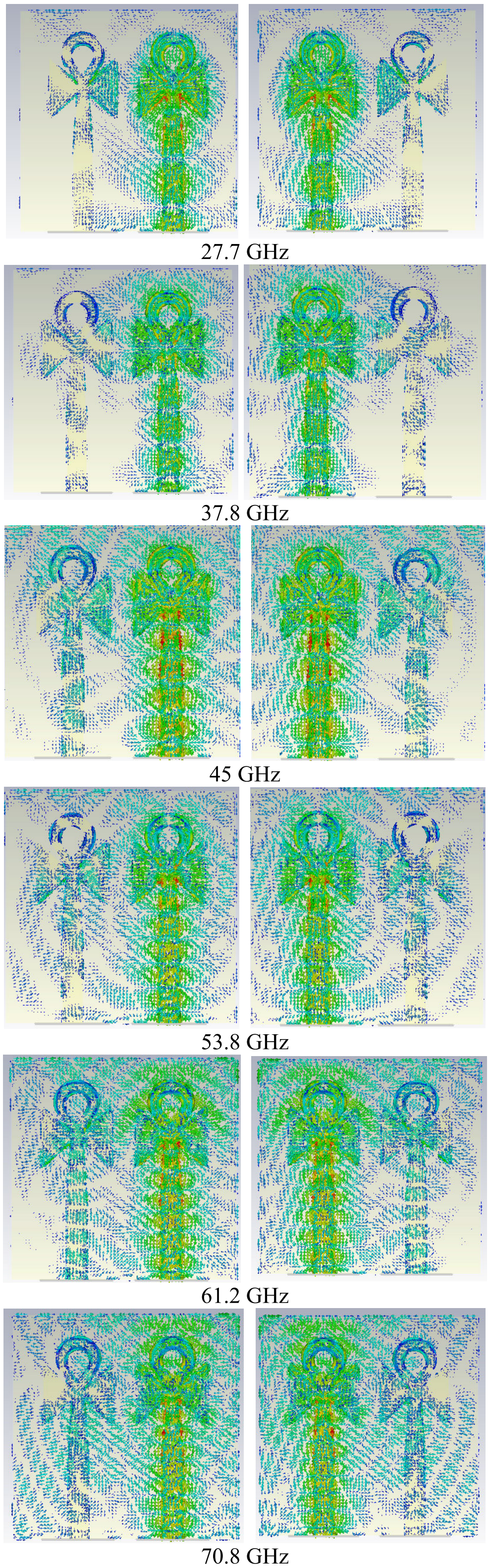


FIGURE 7. Simulated current distribution at different frequencies.

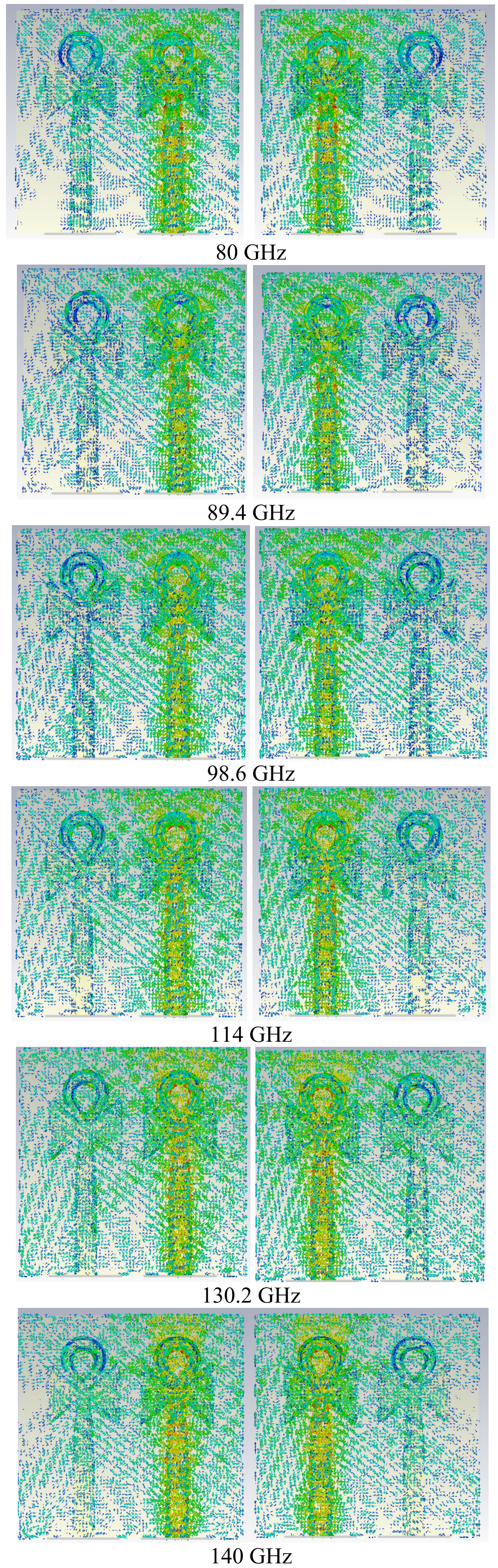


FIGURE 7. *(Continued.)* Simulated current distribution at different frequencies.

different frequencies. The current is equally distributed on each antenna which indicate that the elements are matched perfectly resulting in better radiation pattern and better gain.

As shown in table 2, the proposed antenna performance shows the best compared to the other previously proposed ones as it is relatively small and simple in designing with

TABLE 2. Performance comparison between the proposed array antenna and the related work.

References	Dimension (mm)	Number of Antenna Elements	Substrate Used	Frequencies (GHz)	Bandwidth (GHz)	Maximum Gain (dBi)	Efficiency
[3]	12.75 x 18.7 x 0.787	1	Rogers RT 5880 ε_r = 2.2 and tanδ = 0.0009	28 / 38 / all bands between 49 - 140	26.6 - 28.6 / 36 - 38.3 / 49 - 140	10.25	90%
[4]	4.4 x 4.1 x 0.635(single element dimension)	2	RT 6010LM ε_r = 10.7	28 / 38	N/A	N/A	N/A
[5]	8 x 8 x 0.8	1	Rogers RO4350 ε_r = 3.66	28.2 / 42	2 / 9.2	6.12 / 6.21	90%
[6]	140 x 70 x 1	8	FR4 ε_r = 4.4 and tanδ = 0.025	3.5 /5.5	3.4 - 3.6 / 5.150 - 5.925	N/A	51%
[7]	21.37 x 5 x 1.59	1	FR4 ε_r = 4.4 and tanδ = 0.017	28	7%	3.9	N/A
[8]	30 x 20 x 1.6	1	FR4 ε_r = 4.3 and tanδ = 0.025	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%
[9]	35.2 x 73 x 0.508	16	Rogers RT 5880 (lossy)	39	1.01	5.002	92%
[10]	16.5 x 10 x 0.787		Rogers RT 5880	15.6 / 24.7 / 41.4	3.1 / 1.1 / 31.7	4.6 / 6.95 / 7.77	95.5%
[11]	75 x 150 x 0.5	8	Rogers RT 5880	26/ 28/ 36 / 38 / 40	26 - 43	10	70%
[12]	$2.78\lambda_o$ x $0.14\lambda_o$ x$0.1\lambda_o$	4	FR4 ε_r = 4. ~ 4.2 and tanδ = 0.03	24.5 / 26 / 28	23 - 29	11	84%
[13]	14.7 x 11.9 x 0.254	1	Rogers CuClad 217 ε_r = 2.2 and tanδ = 0.001	N/A	55 - 65	3	80%
Proposed Antenna	18.7 x 18.5 x 0.787	2	Rogers RT 5880 ε_r = 2.2 and tanδ = 0.0009	All bands between 23 - 140	23.2 - 33.5 / 36 - 39.3 / 42.8 - 140	7.8 - 12.3	98%

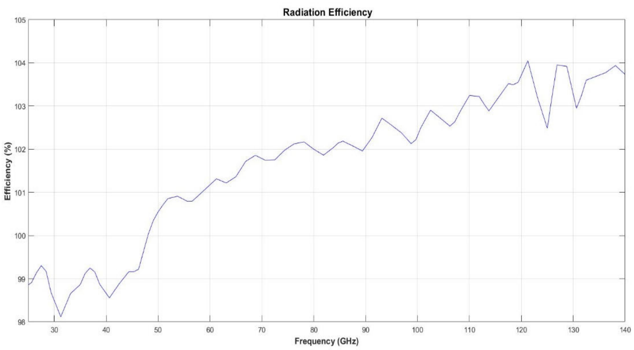


FIGURE 8. Simulated radiation efficiency.

very low cost supporting a huge bandwidth with high gain and very high radiation efficiency exceeding 98% as shown in figure 8.

V. CONCLUSION

In this paper, a two-element array antenna of Modified Pharaonic Ankh-Key antenna is designed, simulated and fabricated to meet the requirements of 5G, 6G and beyond technologies applications as well as MIMO applications with promising peak gain and radiation pattern as it is a very good candidate to work in all bands from 23 GHz to beyond 140 GHz with band notches in the 30 GHz and 40 GHz bands having peak gain between 7.8 dBi to 11.2 dBi in the low frequencies and 9.5 dBi to 12.3 dBi in the high frequencies with radiation efficiency over 98%.

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