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 two-element antenna separately fed by 50Ω microstrip line with dimensions 18.7 mm x 18.5 mm and a height of 0.787mm Rogers/Duroid RT5880 with εr = 2.2 and tanδ = 0.0009 which was easily fabricated with a very low cost comparing 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 were 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, 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 (S12) 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 εr = 2.2 and tanδ = 0.0009 between the radiator and the ground. The antenna is simulated using three different simulators with different techniques: CST Microwave Suite using FIT (Finite Integration Technique) technique, Ansys HFSS using FEM (Finite Element Method) technique and IE3D Mentor Graphics using MOM (Method of Moments) technique, then fabricated using Photolithographic technique 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 $12.75\text{mm} \times 18.7\text{mm}$ and height of $0.787\text{mm}$ of Rogers/Duroid RT 5880 ($\varepsilon_r = 2.2$ and tan$\delta = 0.0009$) to work in $28\text{GHz}$ band, $37\text{GHz}$ band and all bands between $49\text{GHz}$ and beyond $140\text{GHz}$ with peak gain between $6.9\text{dBi}$ and $10.2\text{dBi}$ 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 $4.4\text{mm} \times 4.1\text{mm}$ and height of $0.635\text{mm}$ of RT/Duroid 6010LM ($\varepsilon_r = 10.7$) to operate in $28\text{GHz}$ and $38\text{GHz}$ bands only.

In [5], Kifayat Ullah and et al. presented a single element defected ground structure patch antenna with dimensions $8x8\text{mm}$ and height $0.8\text{mm}$ of Rogers Ro4350 ($\varepsilon_r = 3.66$) operating in both $28\text{GHz}$ and $42\text{GHz}$ with peak gain $6.2\text{dBi}$ and efficiency above $96\%$.

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

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

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

In [9], Muhammad Waqas and et al. designed a $4\times4$ MIMO antenna to work in the $39\text{GHz}$ band with overall dimension $35.2 \times 43\text{mm}^2$ and height $0.508\text{mm}$ of Rogers RT5880 (lossy) with gain of $5.002\text{dBi}$ and total efficiency of $92\%$.

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

In [11], Naser and et al. presented a $1\times8$ phased array antenna with dimensions $75 \times 150\text{mm}^2$ and height $0.5\text{mm}$ of Rogers RT5880 covering all bands from $26\text{GHz}$ to $43\text{GHz}$ with gain more than $10\text{dBi}$ and total efficiency more than $70\%$.

In [12], Gynougdeuk kim and Sangkil Kim presented a $1\times4$ antenna array with dimensions $2.78\lambda_0 \times 0.14\lambda_0 x 0.1\lambda_0$ using substrate thickness FR4 ($\varepsilon_r = 4.1 \sim 4.2$ and tan$\delta = 0.03$) operating in all bands between $23\text{GHz}$ and $29\text{GHz}$ with gain $11\text{dBi}$ and maximum radiation efficiency $84\%$.

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

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 $100\text{GHz}$.

III. ARRAY ANTENNA GEOMETRY

The two element array antenna is designed to operate in all bands from $23\text{GHz}$ to beyond $140\text{GHz}$ with overall dimensions $18.7\text{mm} \times 18.5\text{mm} \times 0.787\text{mm}$. 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) |
|-----------|----------------|-----------|----------------|
| l₁        | 6.46           | w₁        | 1.6138         |
| l₂        | 10.3343        | w₂        | 0.8936         |
| l₃        | 5.034          | w₃        | 0.9549         |
| l₄        | 3.6761         | w₄        | 5.736          |
| r₁        | 1.0404         | D₁        | 6.1362         |
| r₂        | 1.734          | D₂        | 2.014          |

Each element is separately fed with a 50Ω microstrip line and the separating distances, D₁ and D₂, are designed between λ/4 and λ/2 to maintain the coupling coefficient (S₁₂) 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 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].

**III. 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 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. Figure 2 shows a comparison result between the return losses (S₁₁) of the three simulators and the measured results, and the coupling coefficient (S₁₂).

Figure 2 shows the simulated and measured S₁₁ and simulated S₁₂ 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 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 (S₁₂) 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.

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 3. Simulated Peak Gain

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 4. Simulated VSWR

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 5. Fabricated Array Antenna

Figure 6 below shows the simulated radiation pattern in E-plane and H-plane compared to the 3D pattern at different frequencies. The results show a very good and directed pattern at the 5G frequencies and omnidirectional pattern in most of the frequency bands.

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25 GHz

27.7 GHz

34.4 GHz

37.6 GHz

44 GHz

51.8 GHz
Figure 6. Simulated Radiation Pattern E-Plane and H-Plane on the left, and 3D Pattern on the right at different frequencies.

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

**FIGURE 7.** Simulated Current Distribution at different Frequencies.
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  |
|------------|----------------|-----------------------------|----------------|-------------------|-----------------|-------------------|-------------|
|            |                |                             |                | 28 / 38           | 26.6 - 28.6 / 36 - 38.3 / 49 - 140 | 10.25 | 90%          |
| [3]        | 12.75 x 18.7 x 0.787 | 1                           | Rogers RT 5880 | e_r = 2.2 and tanδ = 0.0009 | 28 / all bands between 49 - 140 | N/A   | N/A          |
| [4]        | 4.4 x 4.1 x 0.635 | 2                           | RT 6010LM      | e_r = 10.7        | 28 / 38 | N/A   | N/A          |
| [5]        | 8 x 8 x 0.8    | 1                           | Rogers RO4350  | e_r = 3.66        | 28.2 / 42 | 2 / 9.2 | 6.12 / 6.21 | 90%          |
| [6]        | 140 x 70 x 1   | 8                           | FR4            | e_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            | e_r = 4.4 and tanδ = 0.017 | 28 | 7%   | 3.9 | N/A          |
| [8]        | 30 x 20 x 1.6  | 1                           | FR4            | e_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 | 3.5 - 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 | 8                           | 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]       | 2.78x x 0.14x x 0.12x | 3                           | Rogers CuClad 217 | e_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 RT 5880 | e_r = 2.2 and tanδ = 0.001 | All bands between 23 - 140 | 23.2 - 33.5 / 36 - 39.3 / 42.8 - 140 | 7.8 - 12.3 | 98%          |

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

IV. 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 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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