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Design And Evaluation Of Cooperate-Series-Fed (Hybrid-Fed) 2 X 2 Microstrip Antenna Array At 2.4 GHz

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***Abstract*— In this work, the design and evaluation of cooperate-series-fed (hybrid-fed) 2 x 2 microstrip antenna array (MSA) at 2.4 GHz is presented. Notably, the computation of the dimensions of the patch and feed network of the cooperate-series-fed 2 x 2 microstrip antenna array (MSA) array are presented. Also, the designing of 1 x 2 MSA array and that of 1 x 4 cooperate-fed antenna array are presented as they serve as the building block for the 2 x 2 MSA. The antenna array are designed and simulated in Computer Simulation Technology (CST) Microwave Studio. The results show that the 1 x 4 arrays cooperate-fed achieved bandwidth of 44.33 MHz representing 1.85 % at Voltage Standing Wave Ratio (VSWR) of 1.1887; while bandwidths of 33.06 MHz and 50.41 MHz which represents 1.38 % and 2.26 % with VSWRs of 1.1543 and 1.5832 were achieved by the 1 x 2 cooperate-fed and 2 x 2 cooperate-series-fed array antennas respectively. It is observed from the results results that the 2 x 2 cooperate-series-fed RMSA array performance in terms of return loss, gain and bandwidth met the design objectives as it outperforms all the other designed antenna in terms of gain and directivity (in the H-field and in the E-field).**

Keywords*— *Microstrip Antenna, Cooperate-Series-Fed (Hybrid-Fed) Antenna, Microstrip Lines, Microstrip T-Junction, Mitred Bends

1.0 INTRODUCTION

Without doubt, antennas are indispensable element of any wireless communication system [1]. According to [1], whereas a transmission line requires a guiding structure (typically one conductor), antennas require no guiding structure. Also, [2] defined antenna as an electromagnetic transducer which is mainly used to convert, in transmit mode, guided waves within transmission lines to radiate free-space waves, or to convert, in receive mode, free-space wave to guided waves. The advent of advancement in the field of wireless communication made miniature antennas gain huge popularity. This popularity is partly due to sophistication required in modern communication gadgets which is evident in the rapid progress being made in various fields of technology [3]. Majority of these innovations are geared towards having a more efficient, compact, highly automated and reliable means of communication.

Nowadays, there are different types of antenna out of which microstrip patch antennas is gaining much market share; notably, microstrip patch antennas are increasingly getting popular for use in portable wireless system applications due to their light weight, low profile structure, low cost of production and robust nature is one of them [1]. A microstrip array antenna is a single microstrip antenna that has different patches etched on it that are connected in either a parallel or series form. The main advantage of an array antenna is that it yields a better gain than conventional microstrip antenna [4]. This study seeks to present the design and evaluation of cooperate-series-fed (hybrid-fed) 2 x 2 microstrip antenna array at 2.4 GHz [5]. Particularly, the computation of the dimensions of the patch and feed network of the cooperate-series-fed 2 x 2 microstrip antenna array (MSA) array are presented. Also, the designing of 1 x 2 MSA array [6] and that of 1 x 4 cooperate-fed antenna array [7] are presented as they serve as the building block for the 2 x 2 MSA. The antenna array are designed and simulated in Computer Simulation Technology (CST) Microwave Studio [8,9].

2. METHODOLOGY

2.1 The computation of the dimensions of the patch and feed network of the cooperate-series-fed 2 x 2 microstrip antenna array (MSA) array

The cooperate-series-fed 2 x 2 MSA antenna array presented in this study comprises of two primary patches and two secondary patches. The primary patches are patches that are directly linked to the feeding network, while the secondary patches are those that are fed from the primary patches. Notably, the cooperate-series-fed 2 x 2 MSA array configuration comprised of 4 rectangular microstrip patch antennas with two feeding patterns for the primary and secondary patches. To reduce the complexity of the feeding network of the cooperate-series-fed 2 x 2 MSA array, inset-fed technique is adopted for the primary patches. Specifically, available computational formulas are used to determine the dimensions of the feed network. The summary of the computed dimensions of the inset feed single band antenna used for the primary patches in the cooperate-series-fed 2 x 2 MSA array design is presented in Table 1.

Table 1: Feed dimensions of 2.4 GHz single band inset-fed RMSA

Microstrip line dimension Parameters:	Value (mm)
Width of transmission line, W_f	3.30
Inset fed gap, g	1.20
Inset fed distance, y_o	11.12
Length of 50 Ω line, L_f	4.80
Resonance Frequency, f_r	2.40 GHz

The corporate feed network is used for transmission and collection of power for the primary patches while series feed is employed for the secondary patches. Typical cooperate feed network is subdivided into three parts [10]:

i. Microstrip lines
ii. Microstrip T-Junction's power divider
iii. Mitred bends

i Microstrip Lines: A microstrip line feed of $Z_0 =$ 50 Ω branches off into two feed lines of $2Z_0$ ($Z_1 = 2 \times 50 = 100\,\Omega$) capacity which further branches into a $Z_2 = 70.7\,\Omega$ feed line as expressed in Equation 1 is used for in a parallel array feed network for antenna.

$$Z_2 = \sqrt{Z_0 \times Z_1} \qquad (1)$$

Hence, $Z_2 = \sqrt{50 \times 100} = 70.7\,\Omega$. All the elements of the array are to be matched to the standard 50 Ω impedance and hence the width of 50 Ω was calculated as $W_0 = 3.20$ mm. In this work, $\frac{W_Q}{h} < 2$, hence, the width of 70.7 Ω (W_3) and 100 Ω (W_2) lines are computed using Equation 2 and Equation 3 where Z = 70.7 or 100 Ω, $\varepsilon_r = 4.2$, h=1.6 mm.

$$\frac{W_Q}{h} = \begin{cases} \dfrac{8e^A}{e^{2A}-2} & \text{for } \dfrac{W_Q}{h} < 2 \\ \dfrac{2}{\pi}\left[B - 1 - \ln\left((2B-1) + \left(\dfrac{\varepsilon_r - 1}{2\varepsilon_r}\right)\left\{\ln(B-1) + 0.39 - \dfrac{0.61}{\varepsilon_r}\right\}\right)\right] & \text{for } \dfrac{W_Q}{h} > 2 \end{cases} \qquad (2)$$

Where;

$$A = \frac{Z}{60}\sqrt{\frac{\varepsilon_r + 1}{2}} + \frac{\varepsilon_r - 1}{\varepsilon_r + 1}\left(0.23 + \frac{0.11}{\varepsilon_r}\right) \qquad (3)$$

$$B = \frac{377\pi}{2Z\sqrt{\varepsilon_r}} \qquad (4)$$

Width of 70.7 Ω therefore is computed as:

$$A = \frac{70.7}{60}\sqrt{\frac{4.2 + 1}{2}} + \frac{4.2 - 1}{4.2 + 1}\left(0.23 + \frac{0.11}{4.2}\right) = 2.06$$

$$W_3 = \frac{8 \times e^{2.06}}{e^{(2\times 2.06)} - 2} = 1.05 \text{ mm}$$

Width of 100 Ω therefore is computed thus:

$$A = \frac{100}{60}\sqrt{\frac{4.2 + 1}{2}} + \frac{4.2 - 1}{4.2 + 1}\left(0.23 + \frac{0.11}{4.2}\right) = 2.85$$

$$W_2 = \frac{8 \times e^{2.85}}{e^{(2\times 2.85)} - 2} = 0.50 \text{ mm}$$

Therefore, the width of 70.7 Ω, $W_3 = 1.05$ mm and that of 100 Ω, $W_2 = 0.50$ mm. The lengths of the quarter-wave lines is calculated from Equation 5 as;

$$L_Q = \frac{\lambda}{4} = \frac{\lambda_0}{4\sqrt{\varepsilon_{reff}}} \qquad (5)$$

Now, $\lambda_0 = 0.122$ m and $\varepsilon_{reff} = 3.9$ then , $L_Q = \frac{0.122}{4\sqrt{3.9}}$ which gives $L_Q =$ 0.0154 m = 15.40 mm.

ii Microstrip T- junction power divider: The T-Junction power divider/splitter is a three port network similar to Wilkinson 3 port power divider but it does not have any isolation between the output ports [11]. In Wilkinson power divider, the output ports 2 and 3 have an isolation from each other. The resistance applied between port 2 and 3 is used to stop the power from transmitting in the backward direction towards the source. Usually the reflection affects the VSWR, but in case of T-Junction, it is still acceptable because of the quarter wavelength length between the two output ports, which somehow cancel the reflection at the input as illustrated in Figure 1

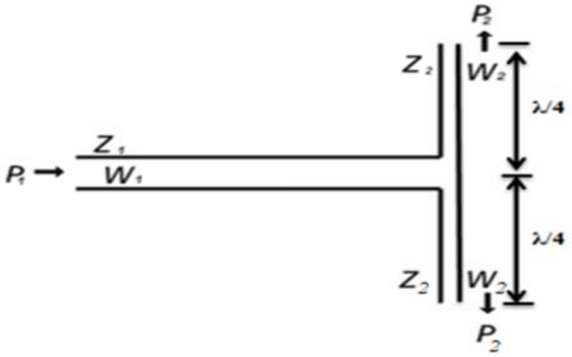

Figure 1: Microstrip T-junction.

Where P_1 is the input port with an impedance of $Z_1 = Z_0$ and a width of $W_1 = W_f$. The power at P_1 is split into two outputs, $2P_2$. T-junction strongly depends upon the quarter wavelength of the output port, for the smooth transition of power from high impedance to low impedance microstrip lines. Z_1 is the impedance of the common port, while Z_2 is the impedance of split ports. Mathematically Z_2 is given by Equation 3.23;

$$Z_2 = 2 \times Z_1 \quad (6)$$

iii Mitred Bend: In notable cases of the parallel feed networks, unlike array series feed networks, the transmission lines are not always in a straight line, they are made to bend up to certain degrees. For instance, if a horizontal transmission line has to be bent to a vertical transmission line by a 90^0 change in direction, [12] stated that this results in most of the power from the input being reflected back at the discontinuity towards the source, which reduces the performance of the system. A 90^0 bend in transmission line causes a change in capacitance of the line, which in turn changes the impedance of the line. The change in impedance causes a mismatch with the input port impedance. To resolve this problem, microstrip mitred bends are introduced. The purpose of the mitred bend is to chop that little amount of capacitance to bring back the impedance of the line to the matching impedance. A mitred bend is illustrated in Figure 2.

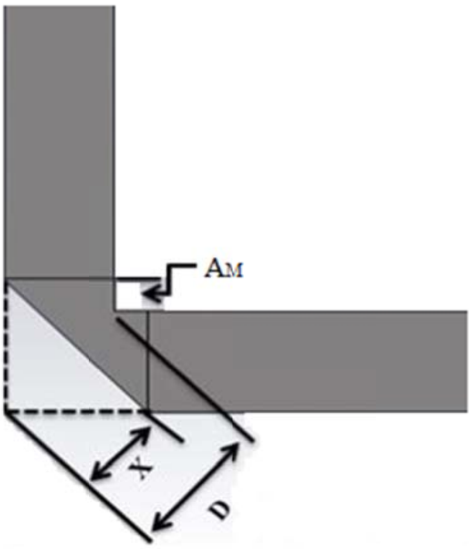

Figure 2: Microstrip mitred bend.

The expressions for A_M, X and D are given by Equation 7, Equation 8 and Equation 9 as:

$$D = W \times \sqrt{2} \quad (7)$$

Where W is the width of the transmission line and h is the height of the substrate. Only the input 50 Ω line will incorporates the bend in the 1× 4 array antenna design, W = 3.30 mm.

Hence; D = 3.30 × $\sqrt{2}$ = 4.67 mm

$$X = D \times \left[0.52 + 0.65 e^{\left(-1.35\frac{W}{h}\right)}\right] \quad (8)$$

Hence, $X = 4.67 \times \left[0.52 + 0.65 \times e^{\left(-1.35\times\frac{3.30}{1.6}\right)}\right] =$ 2.62 mm

$$A_m = \left(X - \frac{D}{2}\right) \times \sqrt{2} \quad (9)$$

Hence, $A_m = \left(2.62 - \frac{4.67}{2}\right) \times \sqrt{2} =$ 0.40 mm

The summary of the computed dimensions of the patch and feed network of the array antennas is given in Table 2.

Table 2 Summary of the computed dimensions of the patch and feed network of the array antennas.

Parameter	Value (mm)
Patch dimensions:	
Length of patch, L_p	27.52
Width of patch, W_p	39.97
Dielectric constant, ε_r	4.2
Height of substrate, h	1.60
Feed dimensions:	
Width of 50 Ω transmission line, W_f	3.30
Width of 70.7 Ω transmission line, W_3	1.05
Width of 100 Ω transmission line, W_2	0.50
Inset distance, y_o	11.12
Inset gap, g	1.20
Length of transmission line, L_f	4.80
Length of quarter wave, L_q	14.90
Resonance Frequency, f_r	2.4 GHz
Ground plain dimensions:	
Length of ground plain, L_g	70
Width of ground plan, W_g	160
Mitred bend dimensions:	
A_m	0.40
X	2.62
D	4.67
Distance between Patches, d	61.00

2.2 Designing of the 1 x 2 MSA array and that of 1 x 4 cooperate-fed antenna array

To make for a more detailed design and analysis thereafter, it is important to start by first designing a 1 x 2 MSA array at 2.4 GHz which will serve as a building block for both the 1 x 4 cooperate-fed antenna array and the 2 x 2 cooperate-series-fed antenna array. The feed network design for the 1 x 2 array antenna starts with a 50 Ω line branching off to a 100 Ω feed that is further transformed to a 70.71 Ω before the final branch that feeds the patch with suitable impedance match as illustrated in the sketch showing the width corresponding to each impedance in Figure 3.

The only difference between 1 x 2 feed network and that of 1 x 4 cooperate feed is that in the cooperate-fed 1 x 4, the final feed stage of the cooperate feed (50 Ω) is repeated to achieve a 4-element configuration as given in the schematic diagram of Figure 4. The images in Figures 5 and Figures 6 are the pictorial views of the 1 x 2 and 1 x 4

MSA antenna array designed in Computer Simulation Technology (CST) Microwave Studio.

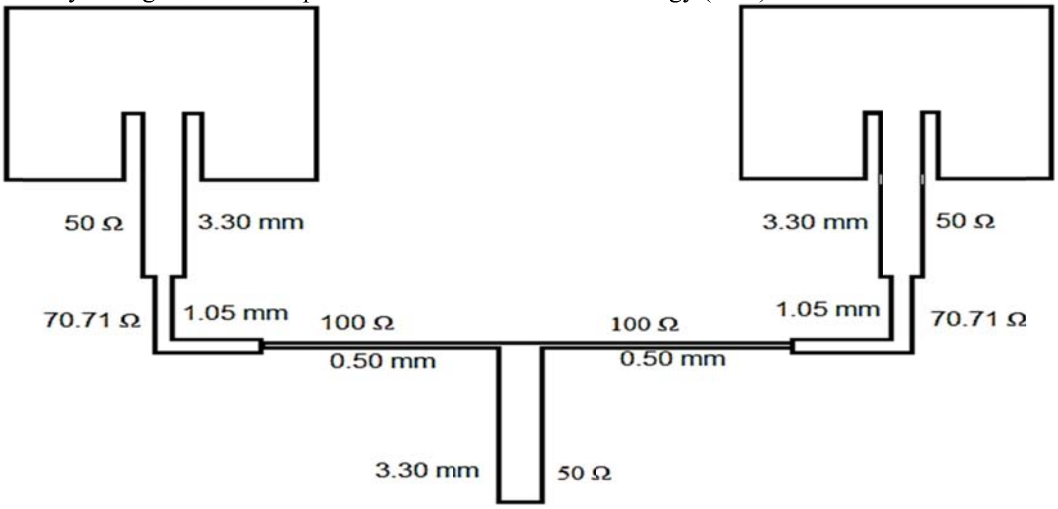

Figure 3: Schematic diagram of cooperate-fed 1 x 2 antenna array.

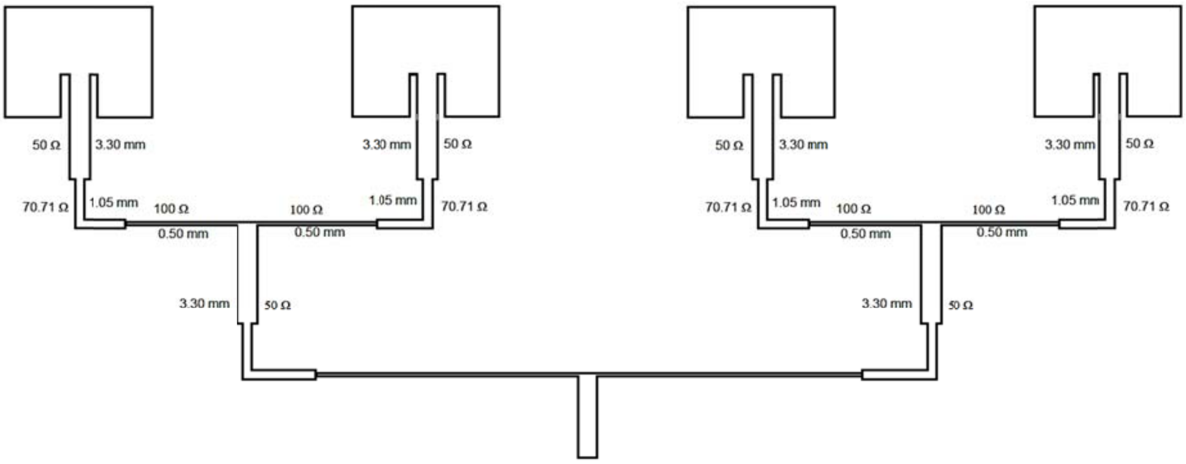

Figure 4: Schematic diagram of cooperate-fed 1 x 4 antenna array.

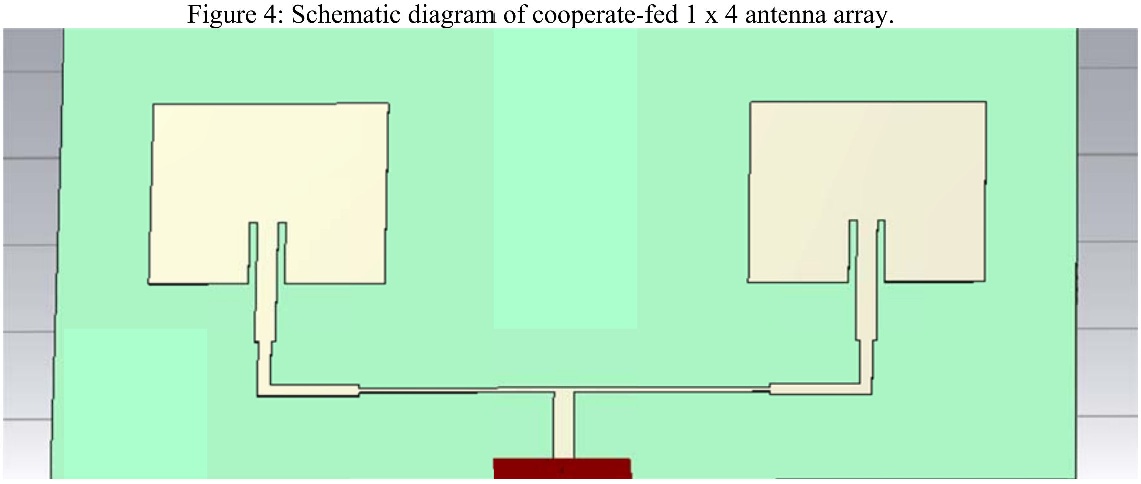

Figure 5: 1 x 2 cooperate-fed MSA array designed in CST studio.

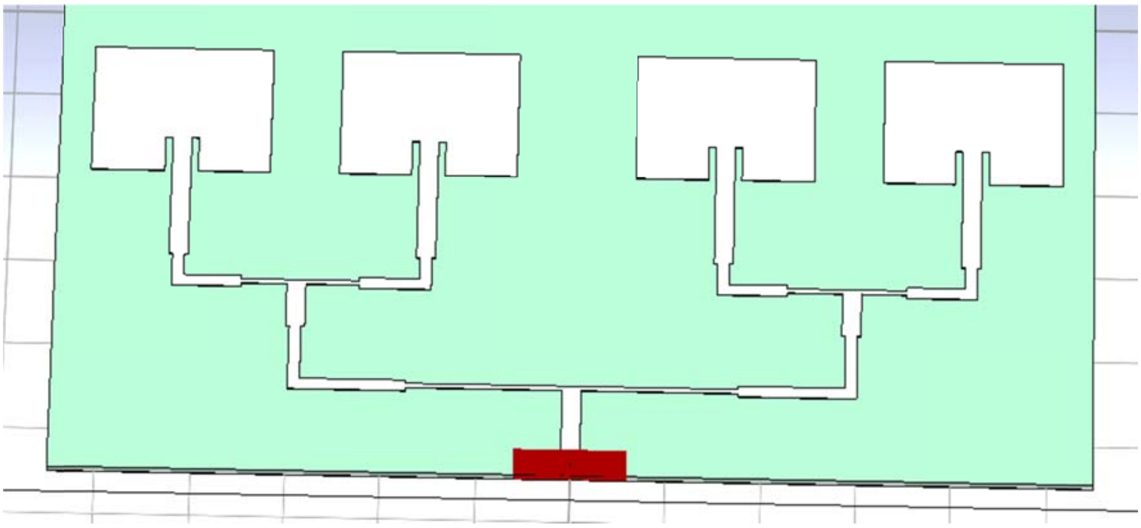

Figure 6: 1 x 4 cooperate-fed MSA array designed in CST studio.

2.3 The Cooperate-Series-Fed 2 x 2 MSA Array Design

The array antenna presented in Figure 6 is further redesigned using a 50 Ω series feed to add a secondary patch at the top of each primary patch as illustrated in Figure 7. The distance between the primary and secondary patches is about half wavelength. The cooperate-series-fed 2 x 2 MSA designed in CST Studio is presented in Figure 8.

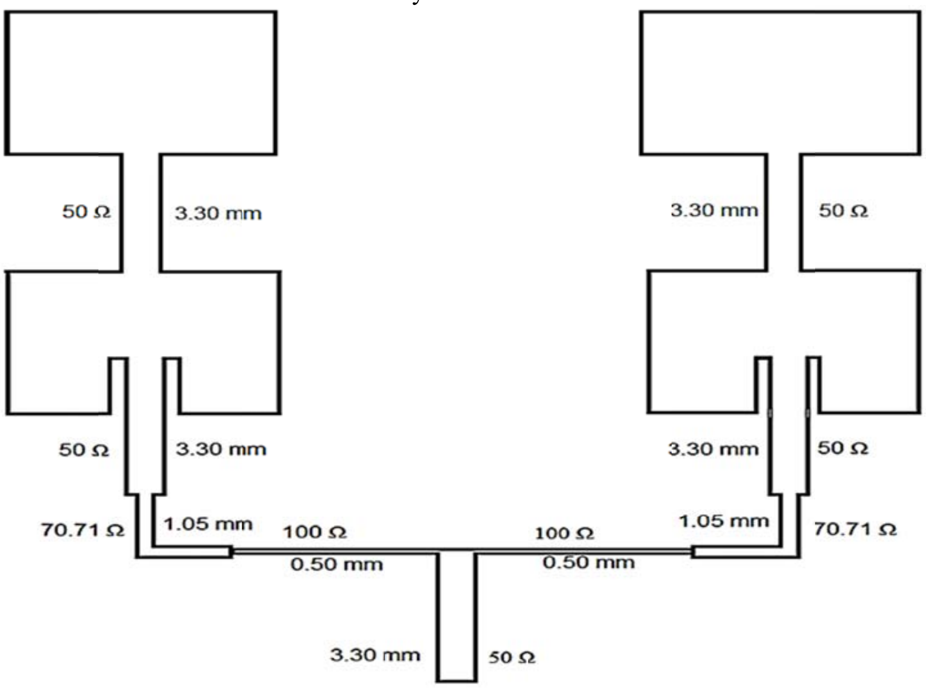

Figure 7: Schematic diagram of cooperate-series-fed 2 x 2 antenna array.

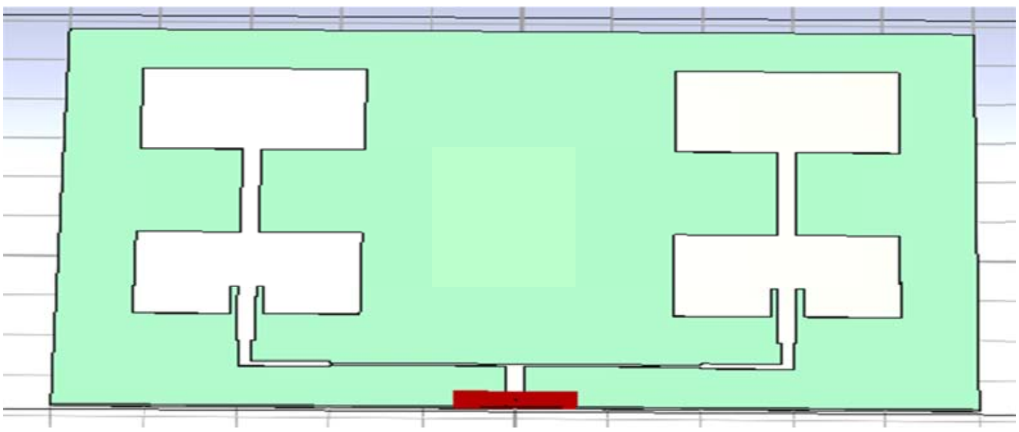

Figure 8: 2 x 2 cooperate-series-fed 2 x 2 MSA array designed in CST studio.

3. RESULT AND DISCUSSION

3.1 The Return Loss Plots and Impedance Bandwidth of the 1 x 2 cooperate-fed antenna, the 1 x 4 cooperate-fed antenna array and cooperate-series-fed 2 x 2 MSA array

The return loss plot of the 1 x 2 cooperate-fed antenna, the 1 x 4 cooperate-fed antenna array cooperate-series-fed 2 x 2 MSA antenna array at 2.4 GHz are measured at the points of minimum return loss are shown in Figures 9 , Figures 10 and Figure 11 respectively.

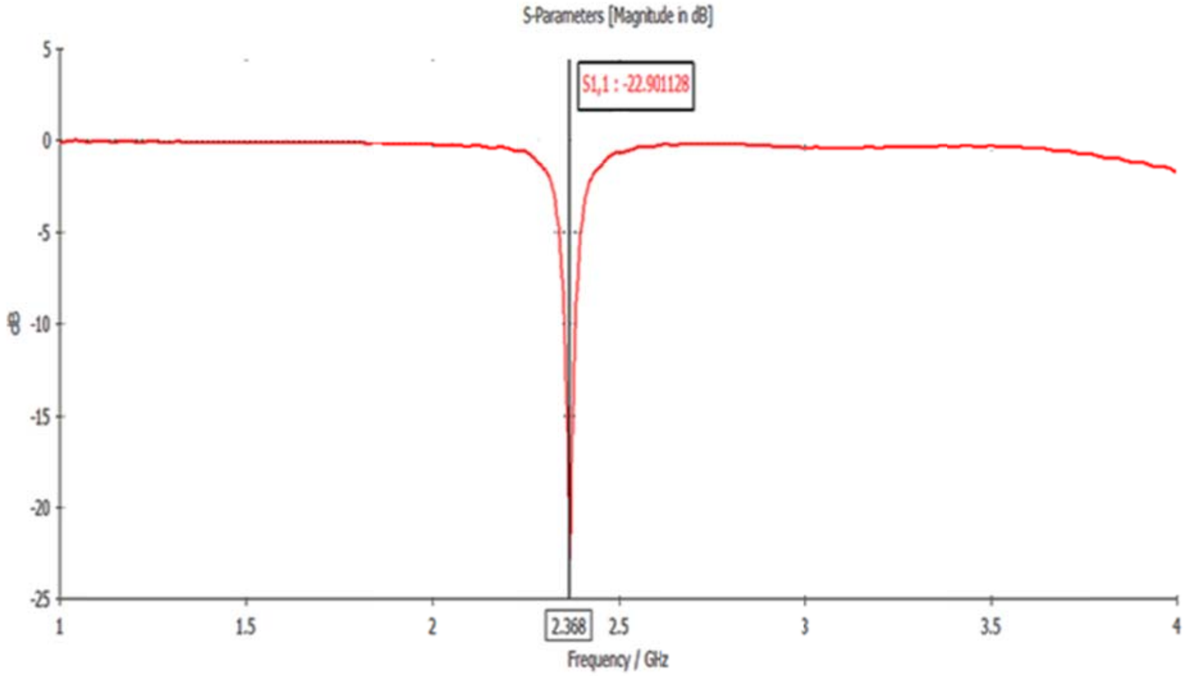

Figure 9: Return loss plot of the 1 x 2 cooperate-fed antenna array.

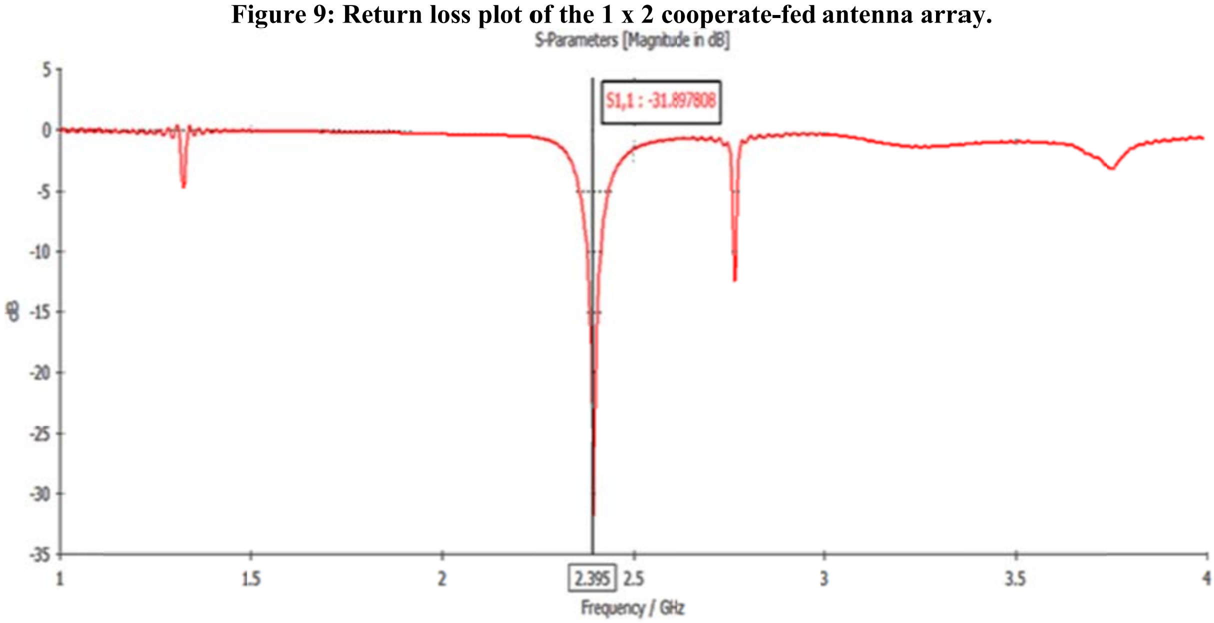

Figure 10: Return loss plot of the 1 x 4 cooperate-fed antenna array.

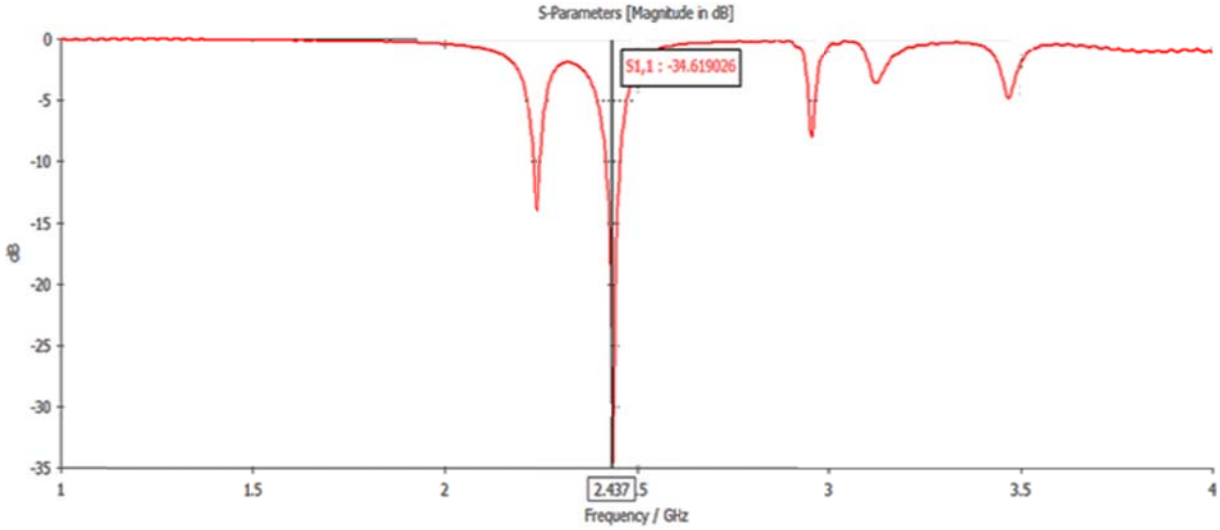

Figure 11: Return loss plot of the 2 x 2 cooperate-series-fed antenna array.

3.2 Voltage Standing Wave Ratio (VSWR) of the 1 x 2 cooperate-fed antenna, the 1 x 4 cooperate-fed antenna array and cooperate-series-fed 2 x 2 MSA array

The VSWR plot of the 1 x 2 cooperate-fed antenna, the 1 x 4 cooperate-fed antenna array cooperate-series-fed 2 x 2 MSA array at 2.4 GHz are shown in Figures 12, Figures 13 and Figure 14 respectively.

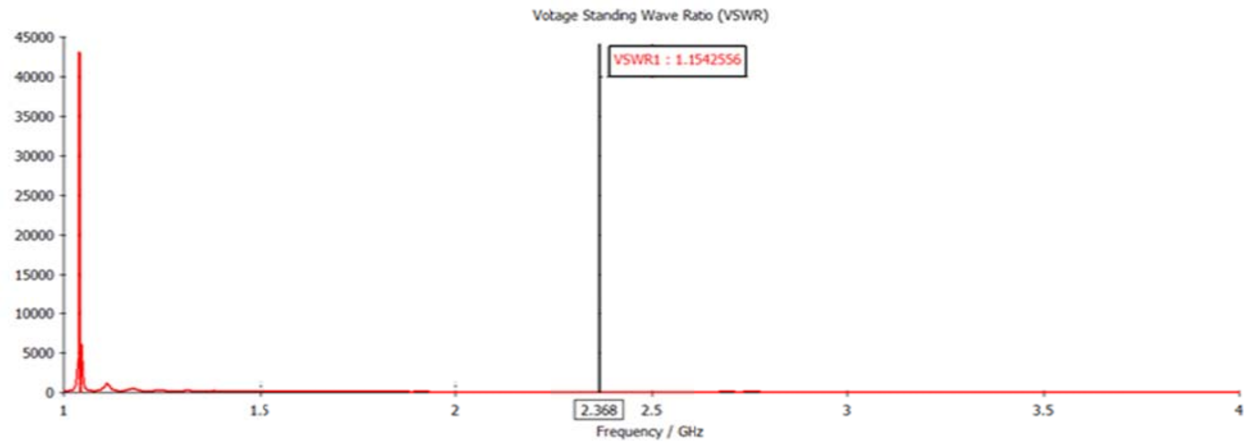

Figure 12: VSWR of 1 x 2 cooperate antenna array at 2.4 GHz.

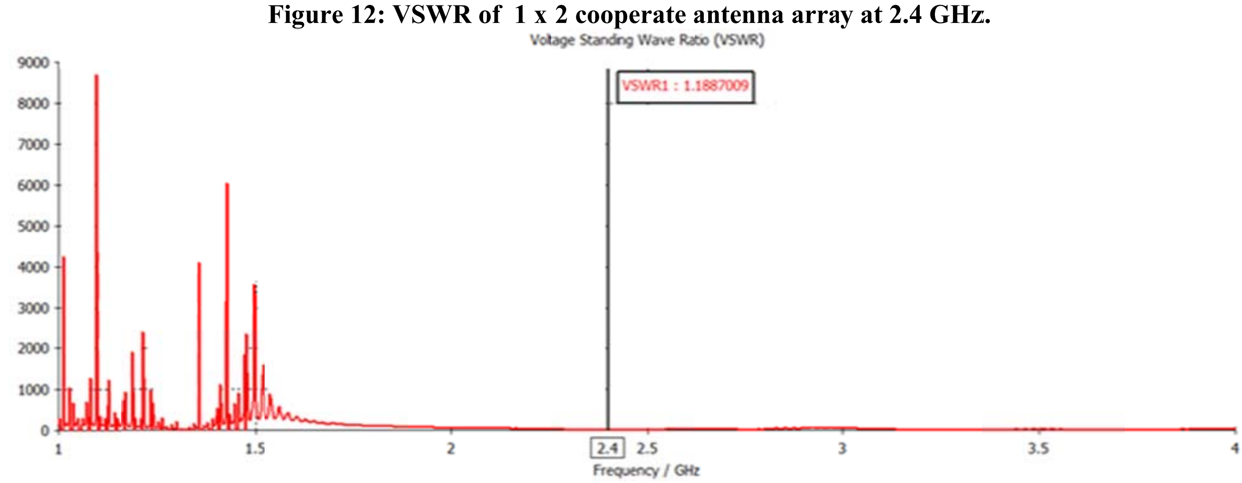

Figure 13: VSWR of 1 x 4 cooperate antenna array at 2.4 GHz.

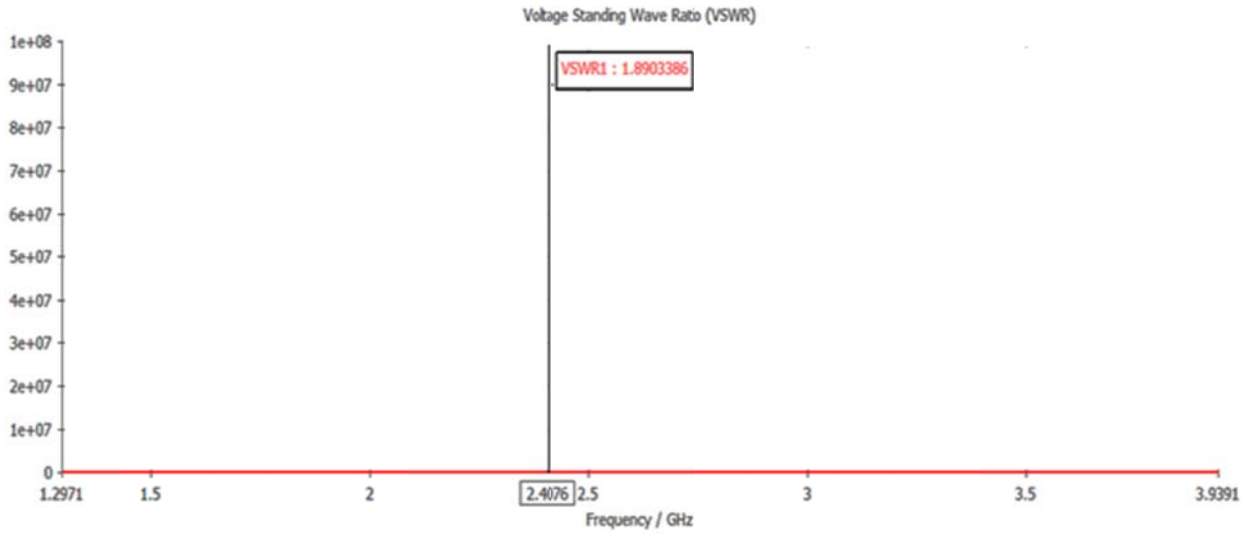

Figure 14: VSWR of 2 x 2 cooperate-series-fed antenna array at 2.4 GHz.

3.3 Directivity of the 1 x 2 cooperate-fed antenna, the 1 x 4 cooperate-fed antenna array and cooperate-series-fed 2 x 2 MSA array

The radiation patterns of the various antennas are presented, namely; the 1 x 4 cooperate-fed antenna arrays at 2.4 GHz in the H-plane (φ = 90°), as well as the 1 x 2 cooperate-fed and 2x2 cooperate-series-fed RMSA array at 2.4 GHz in the H-plane (φ = 90°) . Notably, the radiation patterns are in the broadside as shown in Figures 15 and Figure 16 respectively. Again, the radiation patterns of the various antennas; the 1 x 4 series-fed and 1 x 4 cooperate-fed antenna arrays at 2.4 GHz in the E-plane (φ = 0°), as well as the 1 x 2 cooperate-fed and 2x2 cooperate-series-fed RMSA array at 2.4 GHz in the E-plane (φ = 0°) are in the broadside as shown in Figures 17 and Figure 18 respectively.

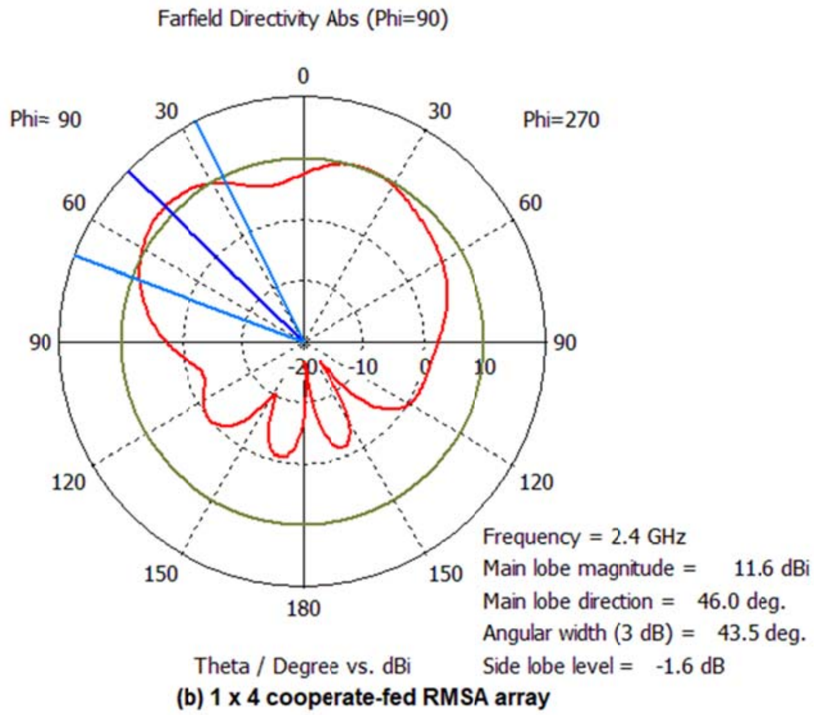

Figure 15: Directivity of the 1 x 4 cooperate-fed antenna arrays at 2.4 GHz in H-plane (φ = 90°).

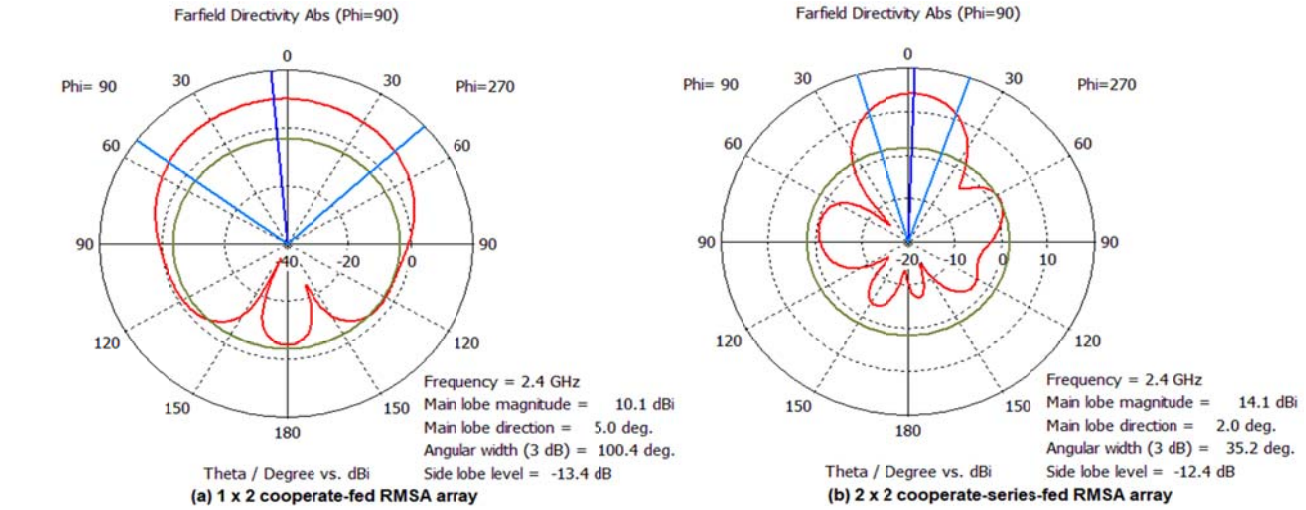

Figure 16: Directivity of antenna arrays 1 x 2 cooperate-fed and 2x2 cooperate-series-fed RMSA array at 2.4 GHz in H-plane (φ = 90°).

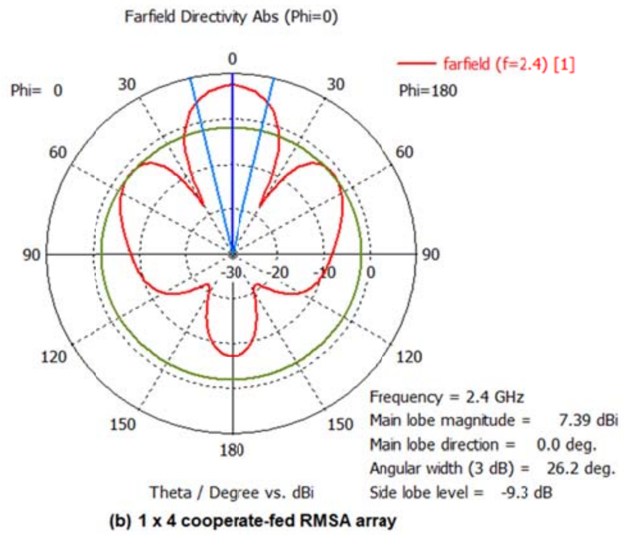

Figure 17: Directivity of array antennas at 2.4 GHz in E-plane (φ = 0°).

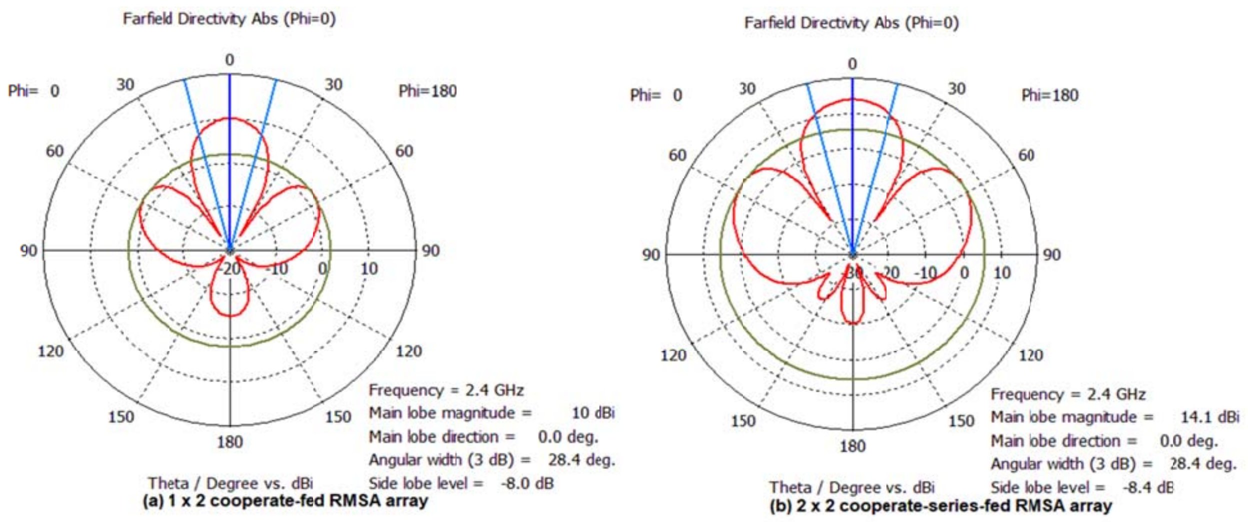

Figure 18: Directivity of array antennas at 2.4 GHz in E-plane (φ = 0°).

3.4 The Gain of the Antenna

The standard IEEE gain of the 1 x 4 cooperate-fed RMSA arrays are shown in Figures 19. Gain of 11.50 dB is achieved at 2.4 GHz. Also, the gains of the 1 x 2 cooperate-fed and the 2 x 2 cooperate-series-fed RMSA arrays are presented in Figure 20.

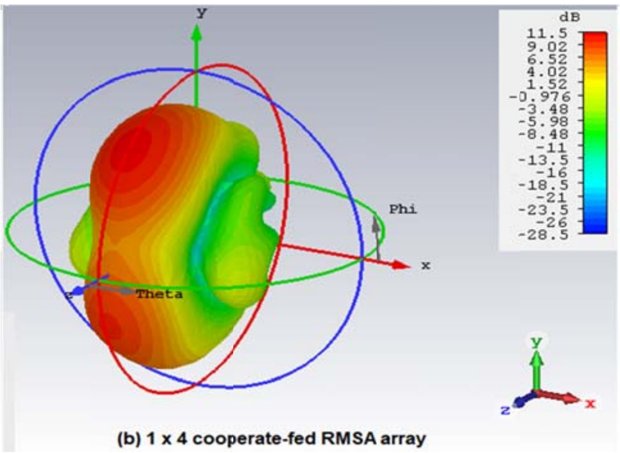

Figure 19: The 3-D gain of the 1 x 4 cooperate-fed RMSA array at 2.4 GHz.

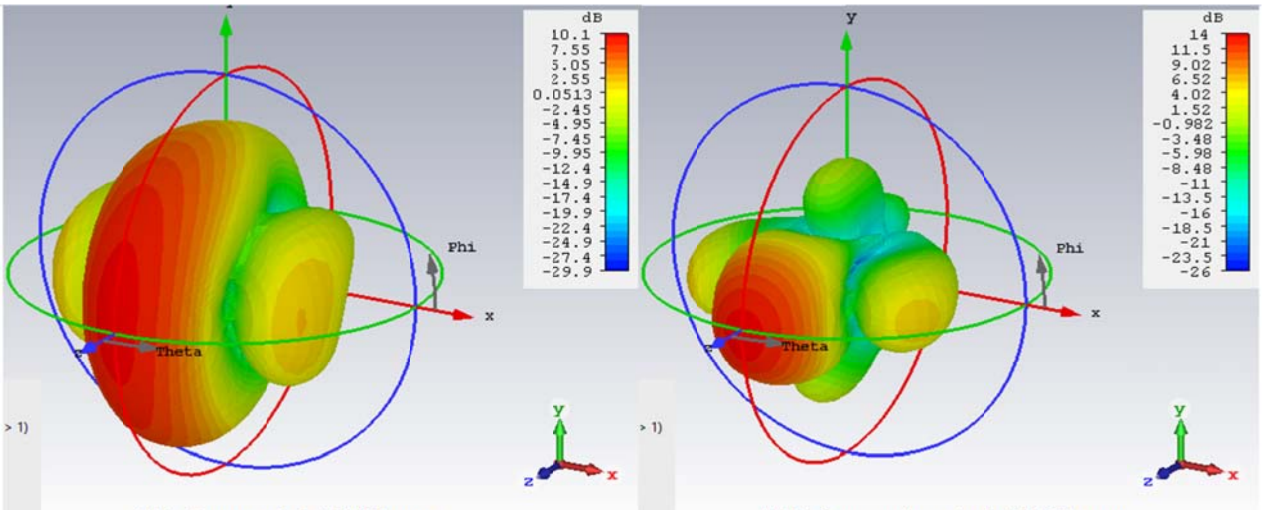

Figure 20: The 3-D gain of the 1 x 2 cooperate-fed and the 2 x 2 cooperate-series-fed RMSA array at 2.4 GHz.

4.2.1 Discussion and comparison of RMSA Array Design Results

The array antennas design results are compared as presented in Table 3. It is observed from the results results in in Table 3 that the 2 x 2 cooperate-series-fed RMSA array performance in terms of return loss, gain and bandwidth met the design objectives as it outperforms all the other designed antenna in terms of gain and directivity (in the H-field and in the E-field).

Table 3: Comparison of the array antennas design results

Configuration	Min. S_{11} (dB)	Bandwidth (MHz)	Gain (dB)	Directivity, $\varphi = 90^0$ (dBi)	Directivity, $\varphi = 0^0$ (dBi)
1 x 4 cooperate-fed array	-31.90	44.33	11.50	11.60	7.39
1 x 2 cooperate-fed array	-22.90	33.06	10.10	10.10	10.00
2 x 2 cooperate- and series-fed array	-34.62	50.41	14.00	14.10	14.10

Also, the array antenna presented by Obot *et al* in [14] is compared with 1 x 4 cooperate-fed MSA array as summarised in Table 5. The results of the 2 x 2 array antenna are also compared with those of some related antennas presented in some published works , as whon in Table 4. From the results in Table 4, it is evident that all the reviewed works performed well but none matched the performance of the 2 x 2 RMSA array in terms of gain. Sizes of the different antennas would have been used as a yardstick for comparison only if they were all operating at the same frequency. Also, unlike bandwidth, combined gain performance is not an important measure used for antenna parametric comparison hence the exclusion of dual band antenna arrays in the comparison.

Table 4: Comparison of 2 x 2 antenna array with some selected published works

Antenna	Gain (dBi)	f_r (GHz)	Bandwidth (MHz)
Obot *et al* in [14]	10.29	2.4	-
Designed 1 x 4 series-fed in this work	5.08	2.4	152.07
Designed 1 x 4 cooperate-fed in this work	11.50	2.4	44.33
Designed 2x2 RMSA in this work	14	2.4	50.41

4. CONCLUSION

In this work, the design of 1 x 2 cooperate-fed antenna, 1 x 4 cooperate-fed antenna array and cooperate-series-fed 2 x 2 MSA array at 2.4 GHz is presented. The antenna array are designed and simulated in Computer Simulation Technology (CST) Microwave Studio. Details of the computation of several parameters such as return loss, impedance, bandwidth, gain, directivity and VSWR are presented. From the computed and simulated results, it has been observed that the major parameters that determine the behavioural characteristics of the antenna are the relative permittivity (ε_r) of the dielectric material under the patch, the width (Wf) of the microstrip line and the height of the substrate (h). Results obtained show that the 2 x 2 cooperate-series-fed antenna outclassed all designed and reviewed works by previous authors in terms of gain performance hence satisfying the objective of the study.

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