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Implementation and Investigation of Improved 1×4 Linear Antenna Array Parameters Utilizing Parasite-Like Element Directors for LTE Applications

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ABSTRACT

This paper presents an implemented analysis of an improved rectangular 1x4 microstrip patch antenna array parameters utilizing parasite-like element directors. The proposed antenna array design methodology based on Yagi antenna theory. Three identical directors were loaded the proposed array to improve antenna array parameters such as maximum radiated power intensity (UMax), directivity (D), gain (G), radiated power (Prad) and the radiation efficiency (e0) while maintaining return loss (RL) and bandwidth (BW) at 2.4 GHz. The calculations and outcomes show how employing directors can enhance the proposed antenna parameters of microstrip antenna array. For an antenna array loaded with directors, UMax= 0.47 W/Str., D= 6.581 dB, G=6.073 dB, e0 =92 % and Prad= 0.9 W for one watt input power (Pin) were reported. The antenna's UMax, D, G, e0and Prad. improvement percentage compared with the array without directors reaches to (6, 80, 75.32 and 10) % respectively using three identical directors for the current mobile communication technology, known as Long Term Evolution (LTE) applications.

1. Introduction

Recent substantial advancements in wireless cellular network technology have made it possible to create a wide range of new applications beyond simple phone conversations [1]. With every new technological generation, mobile device functionality, data transfer rate, and connection quality have all improved [2]. The current mobile communication technology, known as LTE, is being employed in a substantial number of mobile devices, including smart phones, laptops, and tablets, due to its high spectrum efficiency, high-speed transmission, and high data rate capabilities [3]. An operational frequency range for LTE extends from 400 MHz to 4 GHz [4]. Microstrip and Yagi-Uda antennas have

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been integrated into numerous unidirectional designs to meet the demands of LTE applications [5-7].

In recent years, there has been a growing demand for creating and enhancing microwave system facilities across several areas. The majority of gadgets were created with their performance and structure in mind to satisfy the demands of the most recent applications such as LTE. For these applications, low profile, affordability, and ease of design and production are greatly desired. These requirements are satisfied by microstrip technology, such as low profiles and compact architectures. Patch antenna arrays are extensively utilized in contemporary microwave systems and applications. However, low radiating power and limited frequency ranges are problems with traditional microstrip devices, particularly antennas [8-10]. The most basic model, the transmission line model, as well as the cavity and full wave models, can all be used to analyze an antenna array. Typically; the microstrip patch is shaped like a square, rectangle, circle, triangle, or another popular form. Of all the microstrip antenna types, the rectangular microstrip patch antenna arrays are the most employed [2-4]. The antenna's performance is dependent on its substrate material, antenna dimensions, and feeding method. Using an array of patch elements rather than a single patch can improve antenna gain and directivity. To improve input impedance, the inset-fed technique is employed among other feeding strategies in the construction of rectangular patch antennae. Conventional microstrip antennas have a few drawbacks, such as a single operating frequency, low bandwidth impedance, a poor gain, a bigger dimension, and polarization issues [9-12].

The driven element is an isolated conductive element, and parasitic elements have been utilized to alter the radiation pattern of the radio waves it emits [13-15].In the microstrip antenna, a parasitic element functions as a convergent convex lens and passive resonator, amplifying antenna radiation in the desired direction and attenuating waves in the unwanted direction .In the design of the suggested antenna, the director length was assumed to be proportionate to the patch length, and the driven element is a linear array made up of four rectangular patches [16-19].A director and a single patch were created with precise geometrical specifications in order to illustrate the concept behind this work. In many researches, the designing formulas and associated antenna characteristic parameters, such as gain and directivity, were covered [16-32].

In this paper the proposed 1×4 antenna array models were designed as a linear microstrip patch antenna array based on Yagi-Uda antenna working at 2.40 GHz. The antenna consists of four patches as driven element and one, two and three directors with different lengths. The substrate material, dimension of antenna, feeding method will determine the overall performance of the antenna. For this reason, amongst distinctive feeding techniques; the inset fed approach is used for the design of rectangular patch antenna to enhance input impedance. To study the performance of antenna, the standard designation formulae were taken into considerations.

This study provides a better antenna array that uses a FR4 dielectric material with ε_r=4.5, and height of the substrate h_s =1.6mm and has been simulated using HFSS simulator.

The paper is organized as follows:

i. Section 2 introduces an analysis and the design procedure methodology for the antenna array without and with directors.
ii. In Section 3, presents the single element patch antenna design methodology, calculations and simulation results for antenna element.
iii. Section 4, introduces analysis of improved antenna array utilizing parasite-like element directors including the single director design, antenna array without directors, antenna array with directors' design and simulation results.

iv. Section 5, introduces analysis and comparison between simulation and implementation results for the proposed arrays. The comparison with recent related works, and finally concludes the research work is presented in section 6.

2. Methodology

This section introduces the Yagi antenna's geometry, the suggested antenna and the block diagram of procedures methodology processes as shown in Figure 1. The methodology is divided into two main parts:

i. First part is the antenna design and fabrication.
ii. Second part is the antenna analysis.

The director length is shorter than patch length (LD< LP); the director length equals patch length (LD = LP=28.5 mm) and the director length longer than patch length (LD> LP).

An explanation of the examined and fabricated antenna parameters is used to compare these characteristics in different scenarios to make sense of the impact of the director on antenna performance.

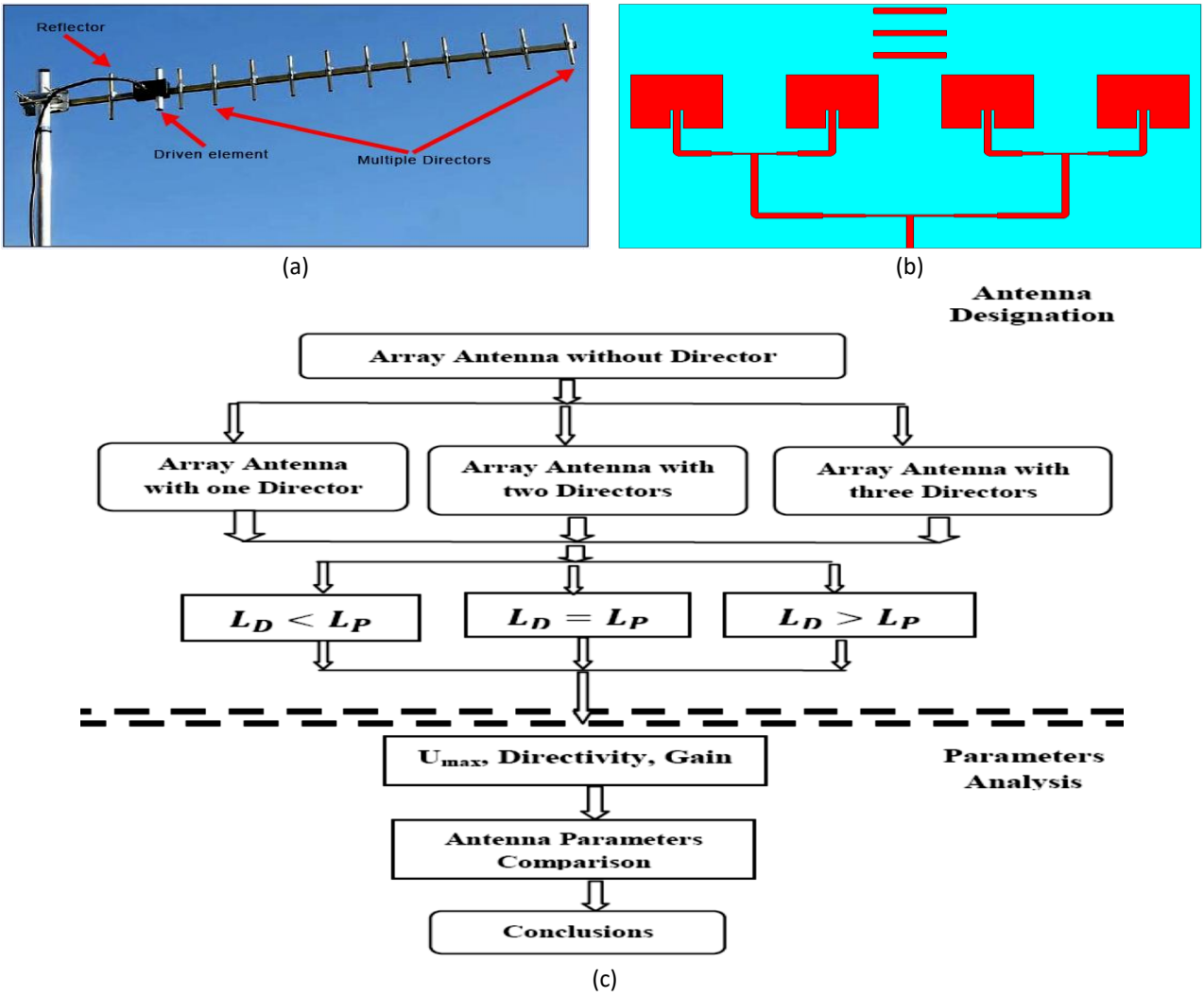


Fig. 1. Procedure methodology (a) Yagi Array Antenna, (b) The proposed 1x4 Antenna Array, (c) Methodology

3. Single Element Patch Antenna Design Methodology

A rectangular patch is used as the essential radiator. The patch is usually made of conducting material such as copper or gold and can take any possible shape. For precise antenna performance, a low dielectric constant (εr) typically in the range 2.2< εr <12 with thick dielectric. The rectangular patch is analysed using both the transmission-line and cavity models; hence it was proposed to design the antenna working at the resonant frequency f = 2.40 GHz. The substrate material is Rogers TMM4 with εr=4.5, and height of the substrate hs =1.6mm. The main dimensions of patch calculating using Eq. (1), Eq. (2) and Eq. (3) [24,25].

$$W = \frac{1}{2f_r\sqrt{\mu_0\varepsilon_0}}\sqrt{\frac{2}{\varepsilon_r+1}} = \frac{v_0}{2f_r}\sqrt{\frac{2}{\varepsilon_r+1}} \tag{1}$$

$$\frac{\Delta L}{d} = 0.412\frac{(\varepsilon_{reff}+0.3)\left(\frac{W}{d}+0.264\right)}{(\varepsilon_{reff}-0.258)\left(\frac{W}{d}+0.8\right)} \tag{2}$$

$$L = \frac{1}{2f_r\sqrt{\varepsilon_{reff}}\sqrt{\mu_0\varepsilon_0}} - 2\Delta L = \frac{\lambda}{2} - 2\Delta L \tag{3}$$

The transmission line model is one of the simplest models for antenna feeding. For Z_0=50Ω, ε_r=4.5 and thickness h_s of 1.6 mm, then the width of transmission line W_0 and length L_t are calculated using Eq. (4) to Eq. (8) [26,27].

$$\frac{W_0}{h_s} = \begin{cases} \frac{8e^A}{e^{2A}-2} & \text{for } \frac{W_0}{h_s} < 2 \\ \frac{2}{\pi}\left[B - 1 - \ln(2B-1) + \frac{\varepsilon_r-1}{2\varepsilon_r}\left(\ln(B-1) + 0.39 - \frac{0.61}{\varepsilon_r}\right)\right] & \text{for } \frac{W_0}{h_s} > 2 \end{cases} \tag{4}$$

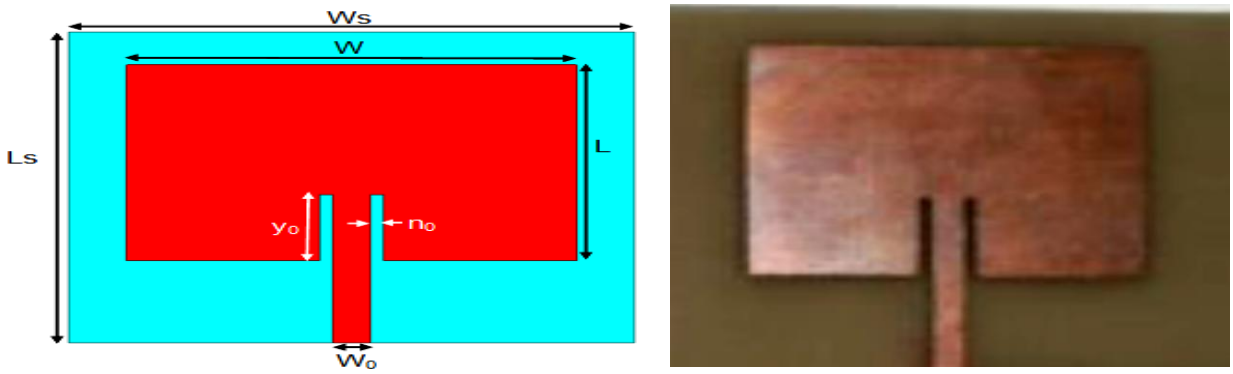
$$A = \frac{Z_0}{60}\sqrt{\frac{\varepsilon_r+1}{2}} + \frac{\varepsilon_r-1}{\varepsilon_r+1}\left(0.23 + \frac{0.11}{\varepsilon_r}\right) \tag{5}$$

$$B = \frac{377\pi}{2Z_0\sqrt{\varepsilon_r}} \tag{6}$$

$$\varepsilon_e = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2}\frac{1}{\sqrt{1+12h_R/w_{T1}}} \tag{7}$$

$$\lambda_g = \left(3\times10^8/f\sqrt{\varepsilon_e}\right) \tag{8}$$

The main dimensions of feeding line, patch antenna element design and fabricated element are illustrated and tabulated in Figure 2 and Table 1 respectively.



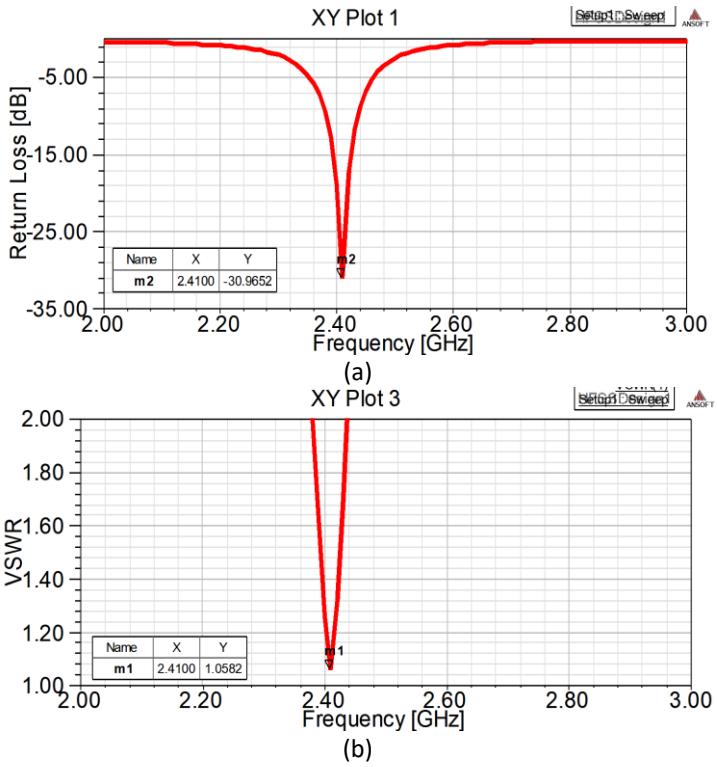
(a) (b)

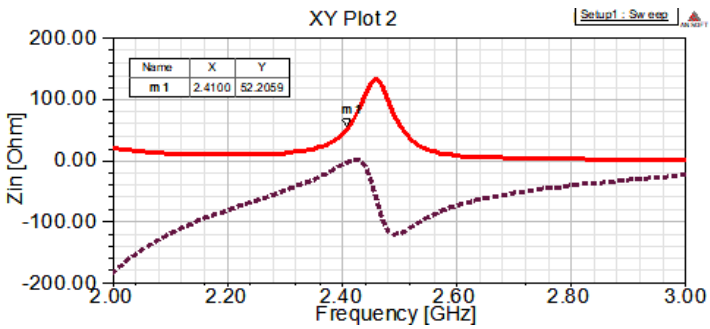
Fig. 2. Single Patch Antenna element (a) Patch dimensions (b) Fabricated element

Table 1
Single element Patch Antenna Dimensions (mm)

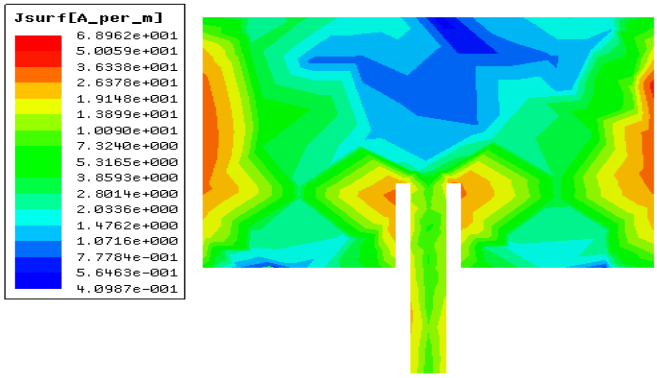
Ws	Ls	hs	W	L	y_0	W_0	n_0
46.6	45.28	1.6	37	28.5	9.65	3	1.15

Figure 3 shows the simulation results for the suggested single element patch antenna, including the RL, VSWR, Js, Zin, and radiation pattern, which are introduced to determine the performance of antennas.





(c)



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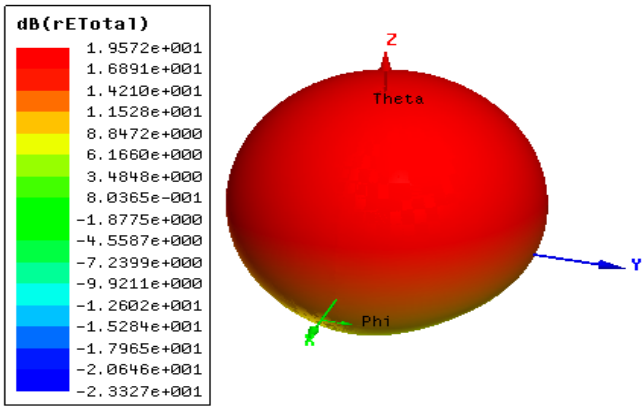
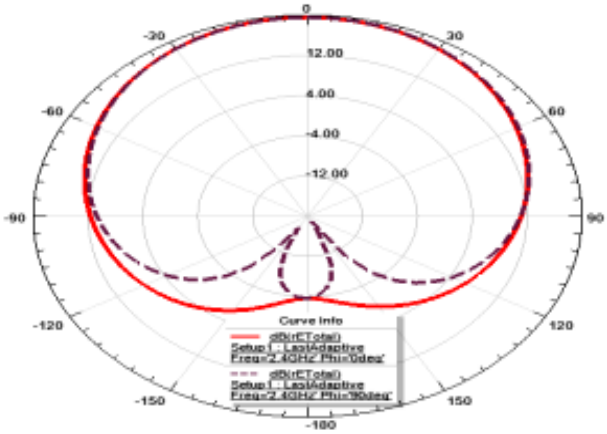


(e)



(f)

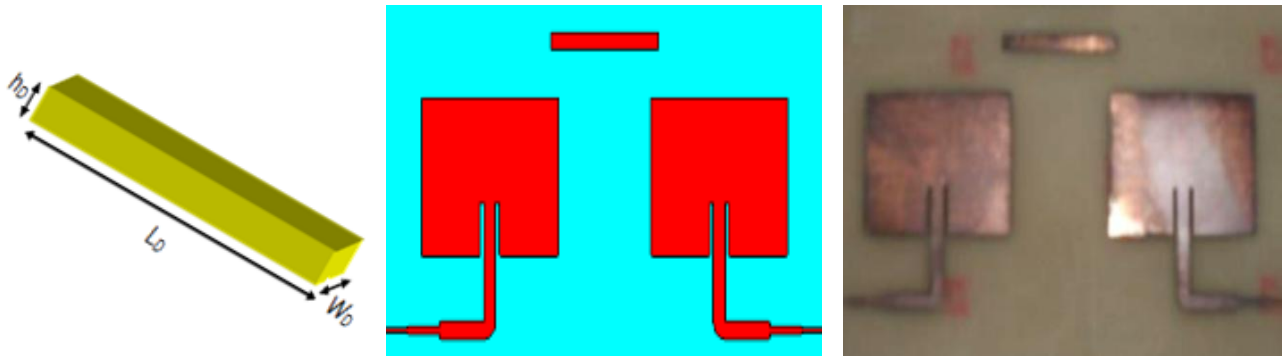
Fig. 3. Single Patch results (a) RL [dB] (b) VSWR (c) Zin [Ω] (d) Js [A/m] (e) 3D Radiation [dB] (f) 2D Radiation [dB]

Based on the simulation findings displayed in Figure 3, the suggested structure adds a matching antenna parameter of -30.9 dB return loss with 1.05 VSWR at the 52.2-ohm real component of the input impedance with a bandwidth of 0.08 GHz. The radiation pattern and current distributions over the antenna surface indicates a good performance of the patch antenna as shown in results.

4. Improved Antenna Array Utilizing Parasite-Like Element Directors

4.1 Single Director Design

The director changes the radiation of the electromagnetic waves emitted by element, directing them in a beam in specific direction and increasing the directivity. A director does this by acting as a passive resonator, the waves from the different antenna elements interfere, strengthening the antenna radiation in the desired direction, and cancelling out the waves in undesired directions. Figure 4 shows the shape of a single director; width W_D = 3mm, the various director length can be L_D = 25, 28.535 and 29.15 mm and height of the director (h_D =0.1mm).



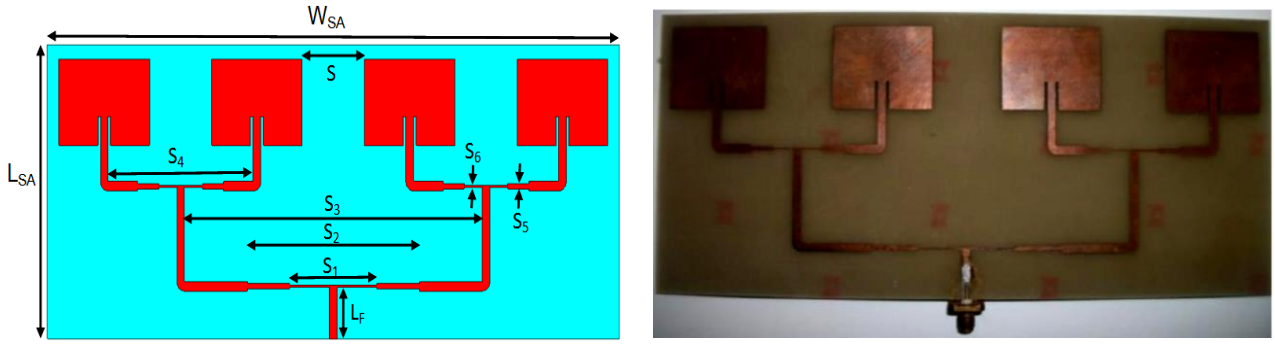
(a) (b) (c)

Fig. 4. Single Director Design (a) Dimensions (b) Director Loaded Patch (c) Fabricated Director Loaded Patch

4.2 Antenna Array without Directors

Four elements 1x4 linear array patch antenna without directors is constructed using four ways microstrip divider as shown in Figure 5. Copper is used for the patch materials and Rogger is used for the substrate material. By sweeping the parameters to achieve the required parameters such as return loss, VSWR, gain, bandwidth, and directivity, the value of the initial antenna parameters will be optimized. To avoid the grating lobes, we kept λ/2inter-element spacing.

The main dimensions of divider, antenna array and fabricated array are illustrated and tabulated in Figure 5 and Table 2 respectively.



(a) (b)

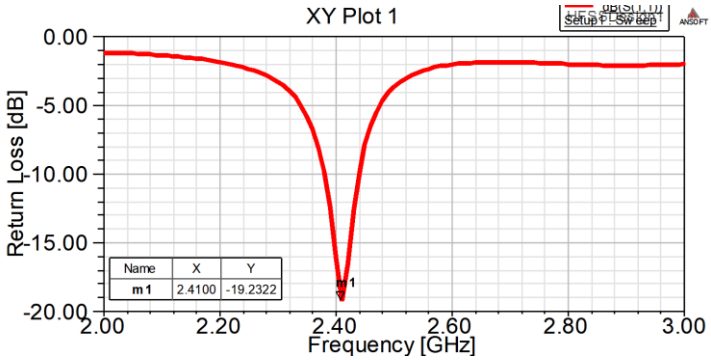
Fig. 5. Antenna Array without Directors (a) Array and Divider Dimensions (b) Fabricated Array

Table 2
Array Antenna without Directors Dimensions (mm)

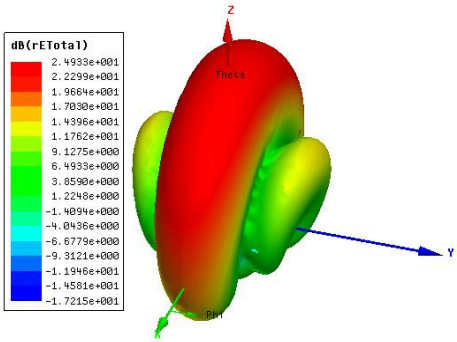
WSA	LSA	LF	S	S1	S2	S3	S4	S5	S6
234.1	97.23	16.9	25.5	35.6	70.4	122	59.5	1.5	0.7

Figure 6 depicts the performance of antenna array without directors for the suggested array simulation results such as radiation patterns, RL, VSWR, Js, and Zin are introduced.

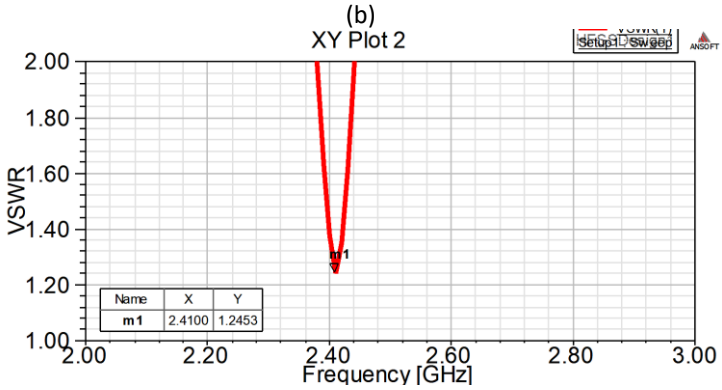
The antenna array without directors' simulation results at 2.4 GHz introduces RL=-19.23, VSWR=1.2 and Rin=47.8. Also, the current distributions over the array surface and radiation pattern are shown for the array performance as shown in Figure 6. Also, the antenna array without directors introduces a radiation intensity, directivity, and gain of 0.41 W/Str., 5.78 dB and 5.32 respectively.



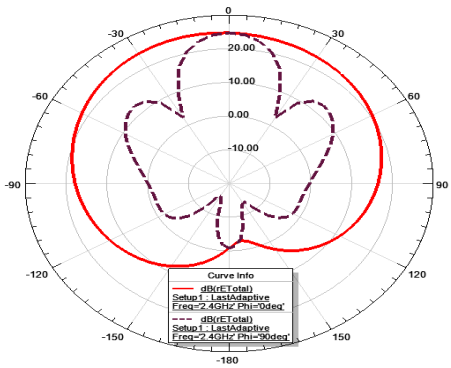
(a)



(b)



(c)



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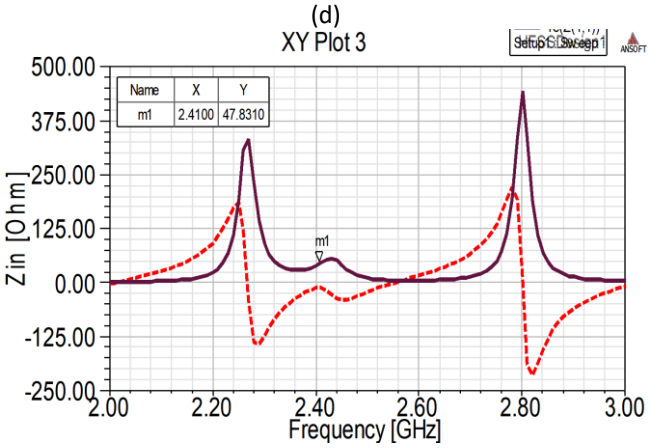

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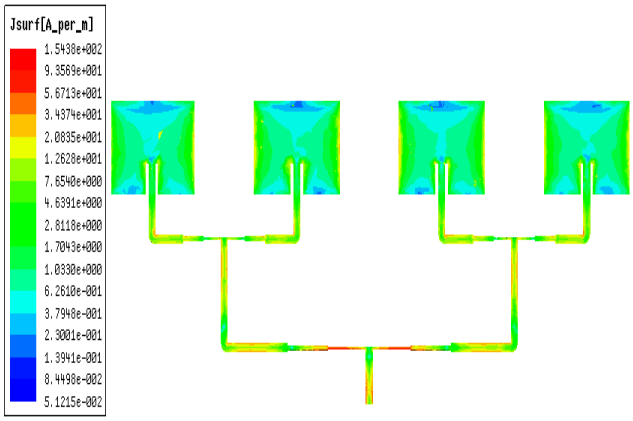


(f)

Fig. 6. Array without Directors results (a) RL [dB] (b) VSWR (c) 3D Radiation (d) 2D Radiation (e) Zin [Ω] (f) Js[A/m]

4.3 Antenna Array without Directors

This section introduces 1x4 antenna array with three directors with distinct lengths with respect to the patch length. The procedure passing through seventeen different cases. These cases are to find out the optimum number and length of director before accomplishing the final shape. The final choice is the antenna with three identical directors with length greater than the patch length and equal to 29.15mm and it is considered a proposed antenna model in this paper. Figure 7 illustrates the stages that array antenna passed through it until reaching the final proposed array loaded with three identical directors in length equal 29.15mm.

There are three different cases for antenna array with various lengths and number of directors was designed as follows:

i. Case (a) for length, $L_D < L_P = 25$mm, $L_D = L_P = 28.5$mm and $L_D > L_P = 29.15$ mm
ii. These various cases of director length arranged in ascending, descending method and repeated for different number of directors one, two and three, respectively. Figure 7 illustrates the different number of directors, where (a) is an example for one director repeated with different length, hence this model represented in three cases.
iii. Case (b) is an instance for two directors sorted ascending in length where the red arrow clarifies the shorter length, consequently this model has nine different combinations of lengths cases.
iv. Finally, case (c) clarifies three directors arranged descending in length and the black dashed arrow declares the longer length, so this model has five different combinations of lengths cases.

Figure 8 shows the simulation results for the suggested array with three directors including RL [dB], VSWR, Zin [Ω], the 3D radiation pattern, the 2D radiation pattern and Js[A/m].

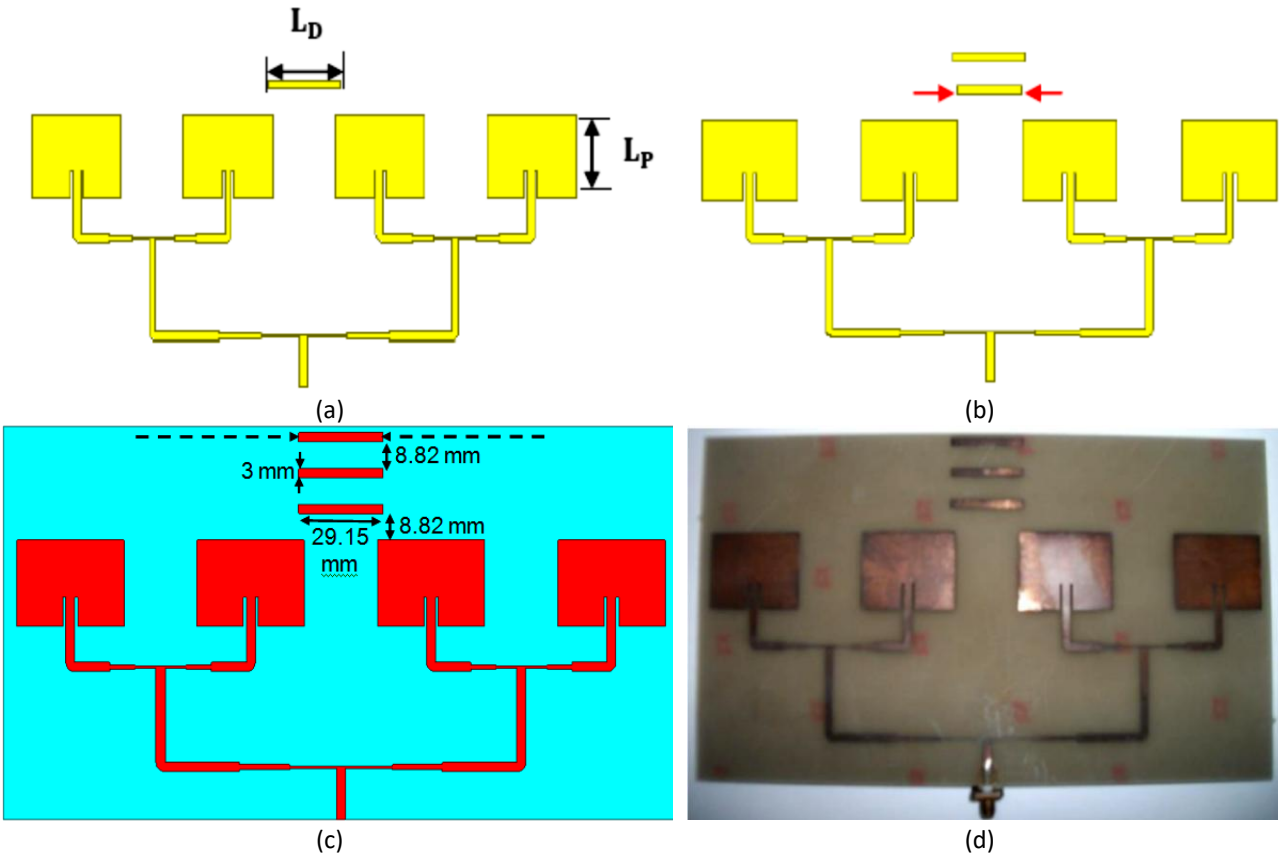
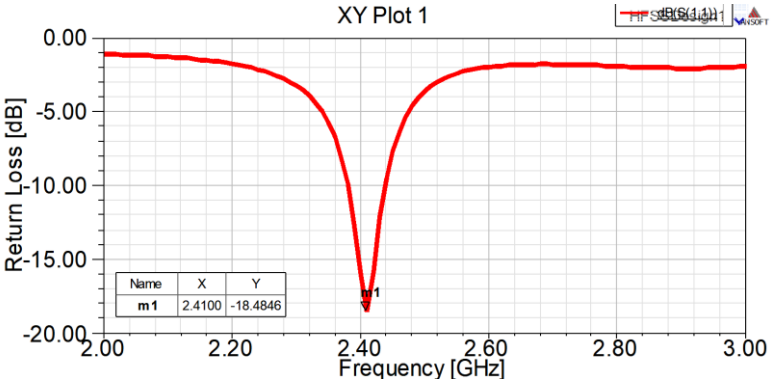
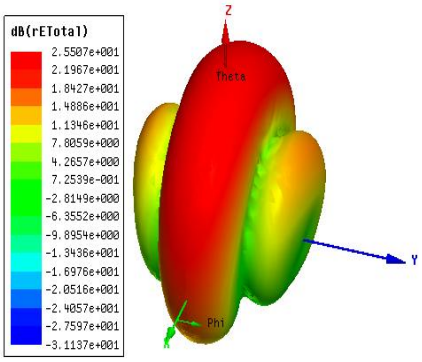


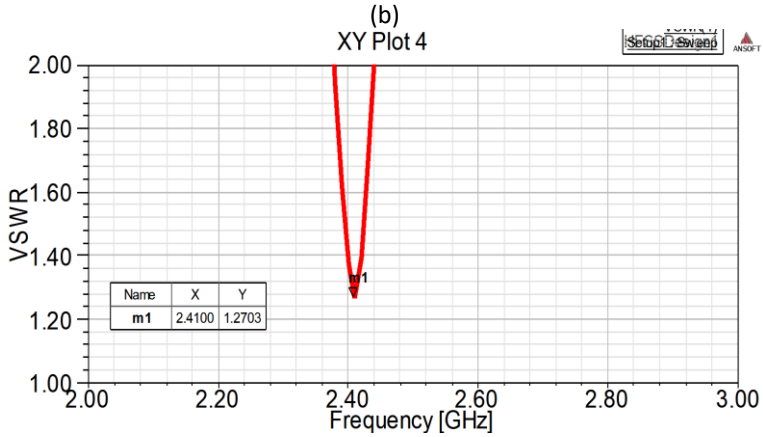
Fig. 7. Array Antenna with various length and number of Directors (a) One Director element (b) Two Director elements (c) Three Directors (d) Fabricated Array with three Directors


XY Plot 1
Return Loss [dB]
Frequency [GHz]
0.00
-5.00
-10.00
-15.00
-20.00
2.00
2.20
2.40
2.60
2.80
3.00
Name X Y
m1 2.4100 -18.4846
m1

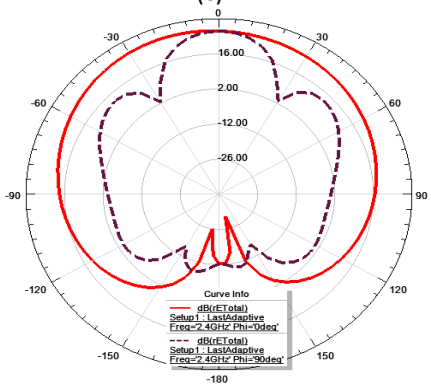
(a)


dB(rETotal)
2.5507e+001
2.1967e+001
1.8427e+001
1.4886e+001
1.1346e+001
7.8059e+000
4.2657e+000
7.2539e-001
-2.8149e+000
-6.3552e+000
-9.8954e+000
-1.3436e+001
-1.6976e+001
-2.0516e+001
-2.4057e+001
-2.7597e+001
-3.1137e+001
Z
Theta
Y
Phi

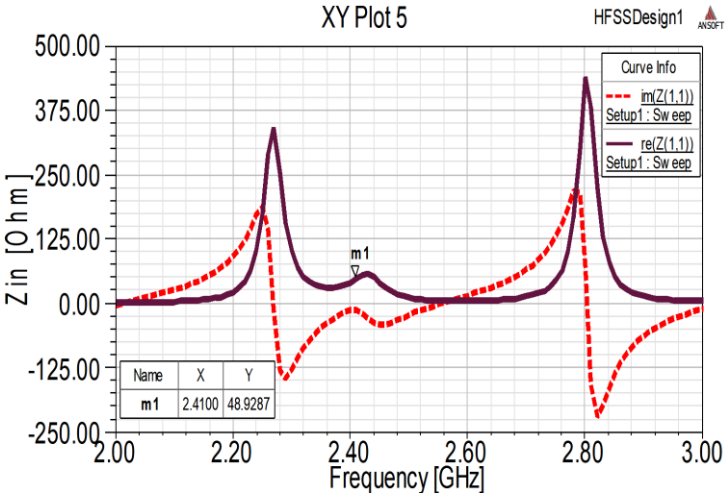
(b)


XY Plot 4
VSWR
Frequency [GHz]
2.00
1.80
1.60
1.40
1.20
1.00
2.00
2.20
2.40
2.60
2.80
3.00
Name X Y
m1 2.4100 1.2703
m1

(c)


0
30
60
90
120
150
-180
-150
-120
-90
-60
-30
16.00
2.00
-12.00
-26.00
Curve Info
dB(rETotal)
Setup1 : LastAdaptive
Freq='2.4GHz' Phi='0deg'
dB(rETotal)
Setup1 : LastAdaptive
Freq='2.4GHz' Phi='90deg'

(d)



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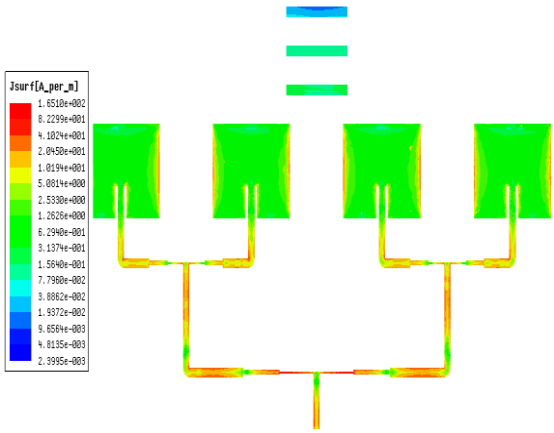


(f)

Fig. 8. Array with three Directors (a) RL [dB] (b) 3D Radiation (c) VSWR (d) 2D Radiation (e) Zin [Ω; (f) Js[A/m]

Based on the simulation findings displayed in Figure 8, the suggested structure antenna array with three identical directors adds a matching antenna parameter of -18.48 dB return loss with 1.27 VSWR at the 48.9-ohm real component of the input impedance with a bandwidth of 0.1 GHz. The radiation pattern and current distributions over the antenna surface indicates a good performance of the patch antenna array with directors as shown in results. Also, the antenna array with directors introduces a radiation intensity, directivity and gain of 0.471 W/Str., 6.581 dB and6.73 respectively.

5. Simulation and Implementation Results

This antenna took a wide range of factors into account. This section explains how varying the number and length of directors LD in relation to the length of a single patch LP affects these parameters. The maximum antenna characteristics such as the values of maximum power intensity (U_{max}), peak directivity (D_0), and peak gain (G_0), which can be computed, respectively, use the Eq. (9), Eq. (10) and Eq. (11) [24].

$$U = r^2 W_{rad} \tag{9}$$

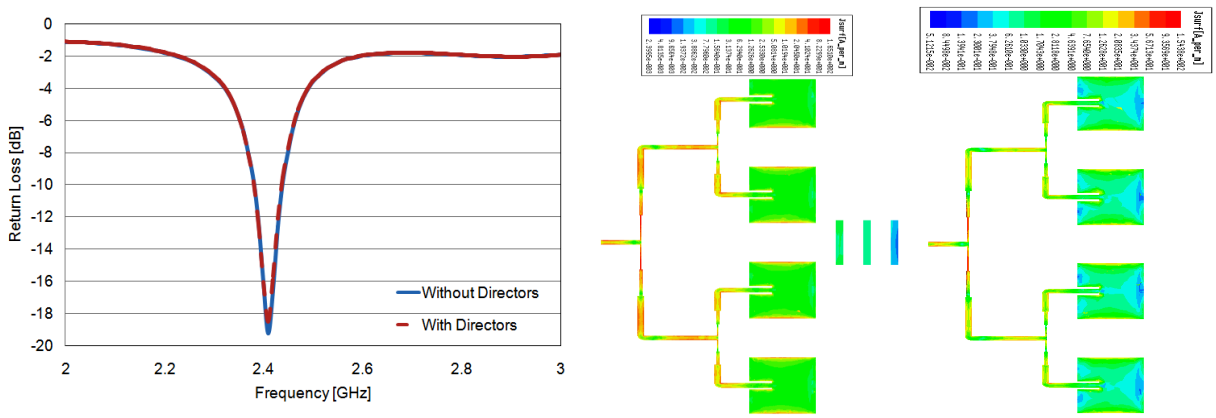
$$D = \frac{U}{U_0} = \frac{4\pi U}{P_{rad}} \tag{10}$$

$$G = 4\pi \frac{U}{P_{in}} \tag{11}$$

Where, U is the radiation intensity (Watt/unit solid angle), U_{max} is the maximum radiation intensity, U_0 is the radiation intensity of isotropic source, Prad is the total radiated power (Watt), and Pin is the total input (watt).

5.1 Compare and Analyze Simulation Results

This section introduces a comparison between arrays without and with directors. Figure 9 illustrates return loss and current distribution on surface comparison between array without and with directors. Table 3 and Table 4 declares two comparisons effect between array without directors and array with directors in antenna parameters such as Umax, gain, and directivity, based on length and the number of directors respectively.



(a) (b)

Fig. 9. Array without and with Directors (a) RL [dB] (b) Js[A/m]

From Table 3 and Table 4 there is notable variation in the array parameters, firstly when the comparison done between array without and with directors. The value of directivity parameter gives a good example for the difference between the two cases. In other words, the effect of the directors in the case of antenna array with directors is very clear.

Secondly the comparison in the case of array with directors with different number and director lengths, but the results give indication that the best value is in the case of three identical directors with length equal to 29.15mm, consequently model (2) with directors with length equal to 29.15 mm is the considered model in the proposed array.

Table 3
Array Antenna without and with Directors Comparison Sorted in length

Array Antenna without and with Directors									
Comparison	Without Directors	With Directors							
Antenna Parameters	Without Directors	Length of Two Directors (L_D) in mm sorted in ascending and descending						Three Directors	
		25	25	28.53	8.53	29.15	29.15	25 28.53	29.15 28.53
		28.53	29.15	25	29.15	25	28.53	29.15	25
U_{max}	0.41	0.462	0.464	0.463	0.466	0.463	0.463	0.469	0.468

Directivity	5.78	6.469	6.475	6.493	6.533	6.483	6.477	6.522	6.542
Gain	5.32	5.960	5.972	5.963	6.020	5.969	5.962	6.027	6.025

Table 4
Array Antenna without and with Directors Comparison Sorted in number of Directors

Array Antenna without and with Directors										
Comparison	Without Directors	With Directors								
Antenna Parameters	Without Directors	Length of One Directors (L_D) in mm			Two Directors			Three Directors		
		25	28.53	29.15	25	28.53	29.15	25	28.53	29.15
U_{max}	0.41	0.454	0.454	0.451	0.464	0.464	0.465	0.469	0.470	0.471
Directivity	5.78	6.344	6.324	6.303	6.452	6.494	6.496	6.516	6.564	6.581
Gain	5.32	5.841	5.831	5.803	5.945	5.983	5.987	6.021	6.053	6.073

The bar charts in Figures 10 and Figure 11 depict the calculated parameters for each case. Green bars indicate an antenna without directors, while blue, red, and black bars show the antenna parameters with one, two, and three directors, respectively, with three different lengths: LD<LP, LD=LP, and LD>LP.

The bar chart shown in Figure 10 illustrate that, in comparison to the other examples, the three directors with length LD>LP=29.15mm (best case) satisfied improvements in antenna characteristics. To get a sense of the antenna's performance, Figure 10 focuses on the optimal scenario.

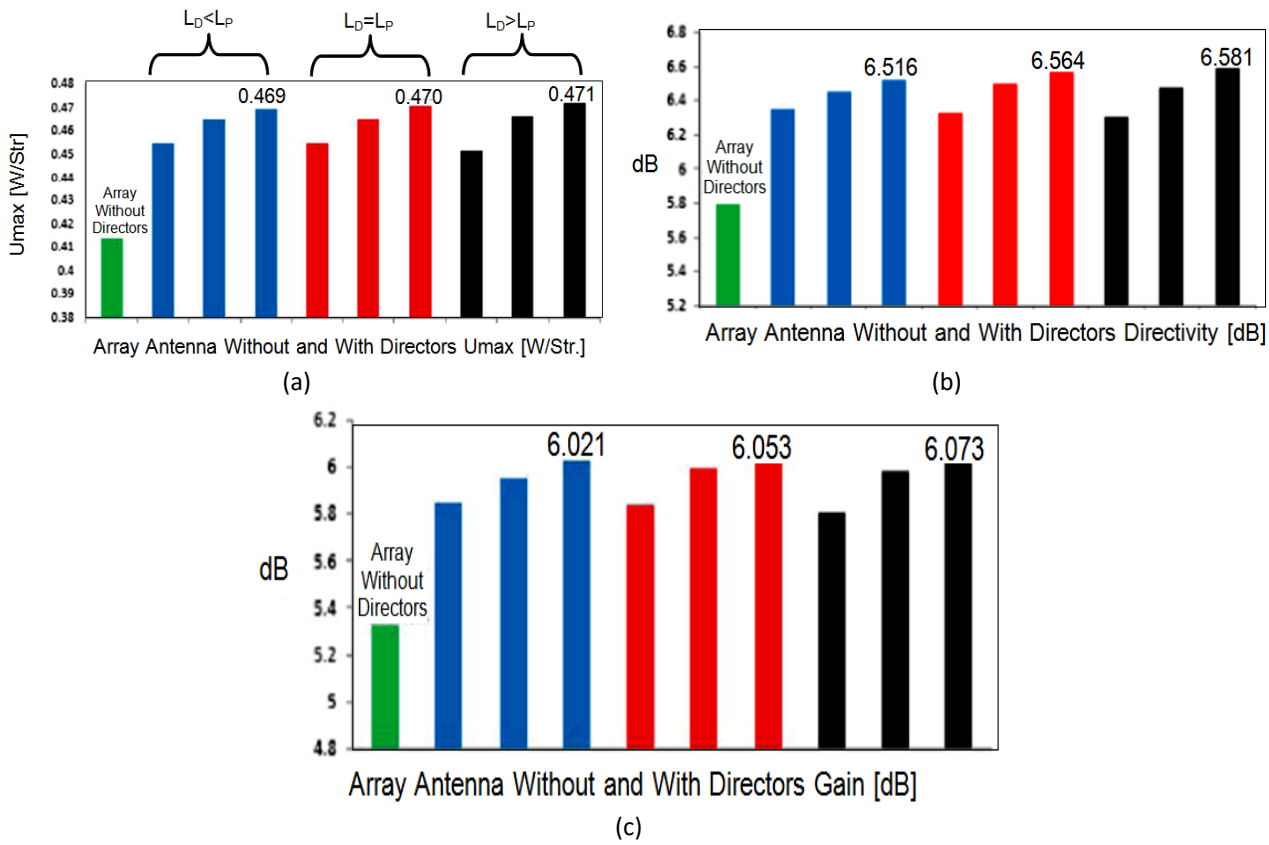


Fig. 10. Array Antenna without and with Directors Parameters (a) Umax. [W/Str.] (b) Directivity [dB] (c) Gain [dB]

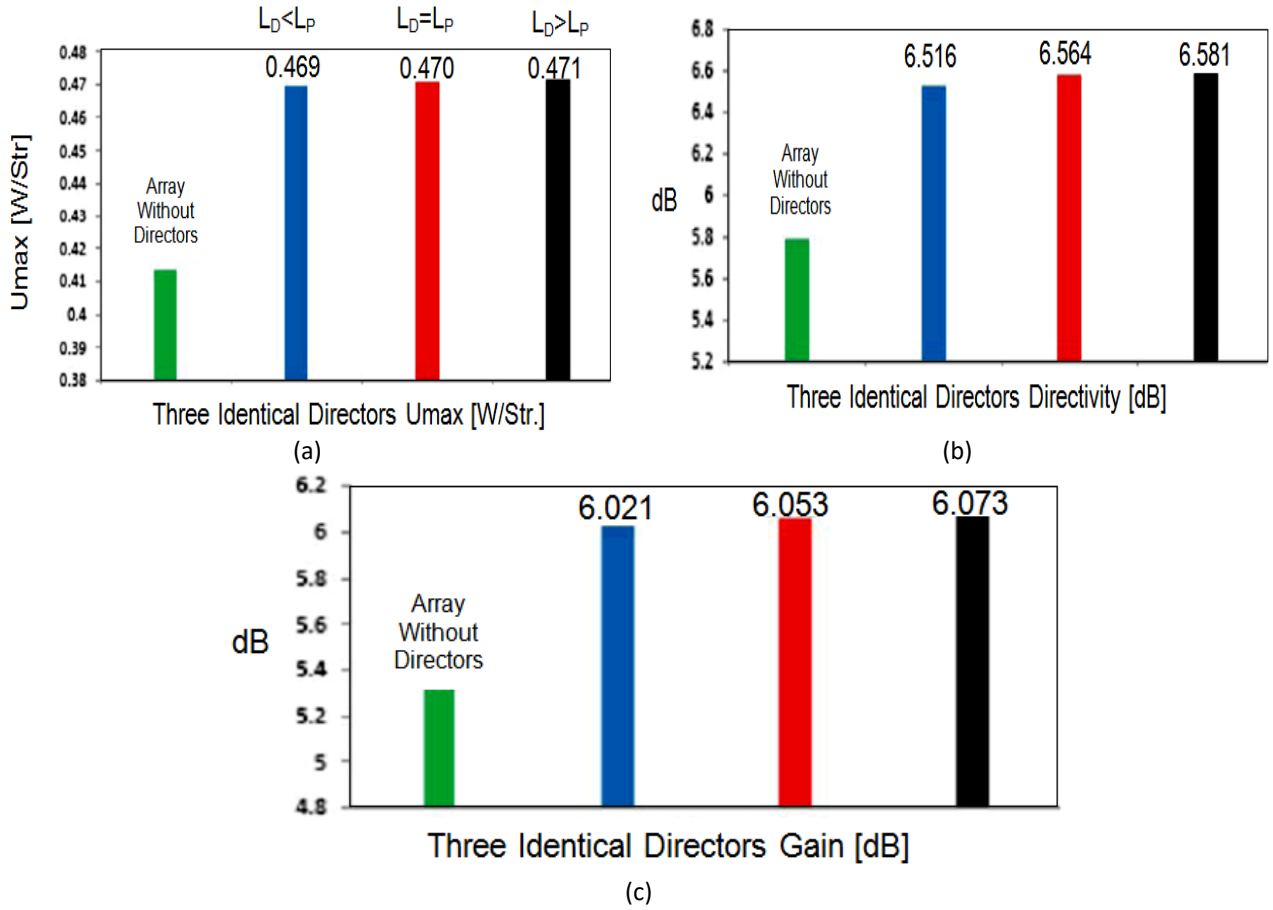


Fig. 11. Array Parameters improvement utilizing Three Directors (a) Umax. [W/Str.] (b) Directivity [dB] (c) Gain [dB]

In Figure 11 the bar charts illustrate how Umax, directivity, and gain characteristics are improved when the best-case LD>LP=29.15mm is used as opposed to the scenario when there are no directors. With Umax rising from 0.41 to 0.47 W/Str., the directivity and gain improved as well, rising from 5.78 to 6.58 and 5.32 to 6.07 dB, respectively. The comparison of antenna parameters for the proposed structures are illustrated in Table 5.

Table 5
Comparison Antenna Parameters without and with Three Identical Directors, f=2.41 GHz

Parameters	Umax[W/Str.]	D[dB]	G[dB]	Pin[W]	Pacc. [W]	Prad. [W]	e_0[%]
Element Without Director	0.12	1.6	1.5	1	0.98	0.92	0.94
Array Without Director	0.41	5.7	5.3		0.97	0.8	0.90
Array With Director	0.471	6.58	6.073		0.97	0.9	0.92

From Table 5 as a comparison result between single element without directors, array with and without three identical directors, it was found that there is an improvement in the radiated power intensity, directivity, gain, radiated power, and the radiation efficiency for the array loaded with directors compared without directors.

5.2 Compare and Analyze Measured Results

Photographs of the implemented antenna array without and with directors at the microwave Lab. are shown in Figure 12 (a) and Figure 12 (b). The comparisons between simulated and measured

results are shown in Figure 12 (c) Figure 12 (d) for both structures respectively with an agreement between them. The little different between simulated and measured results due to the effect of implementation process includes the connector welding and practical design accuracy.

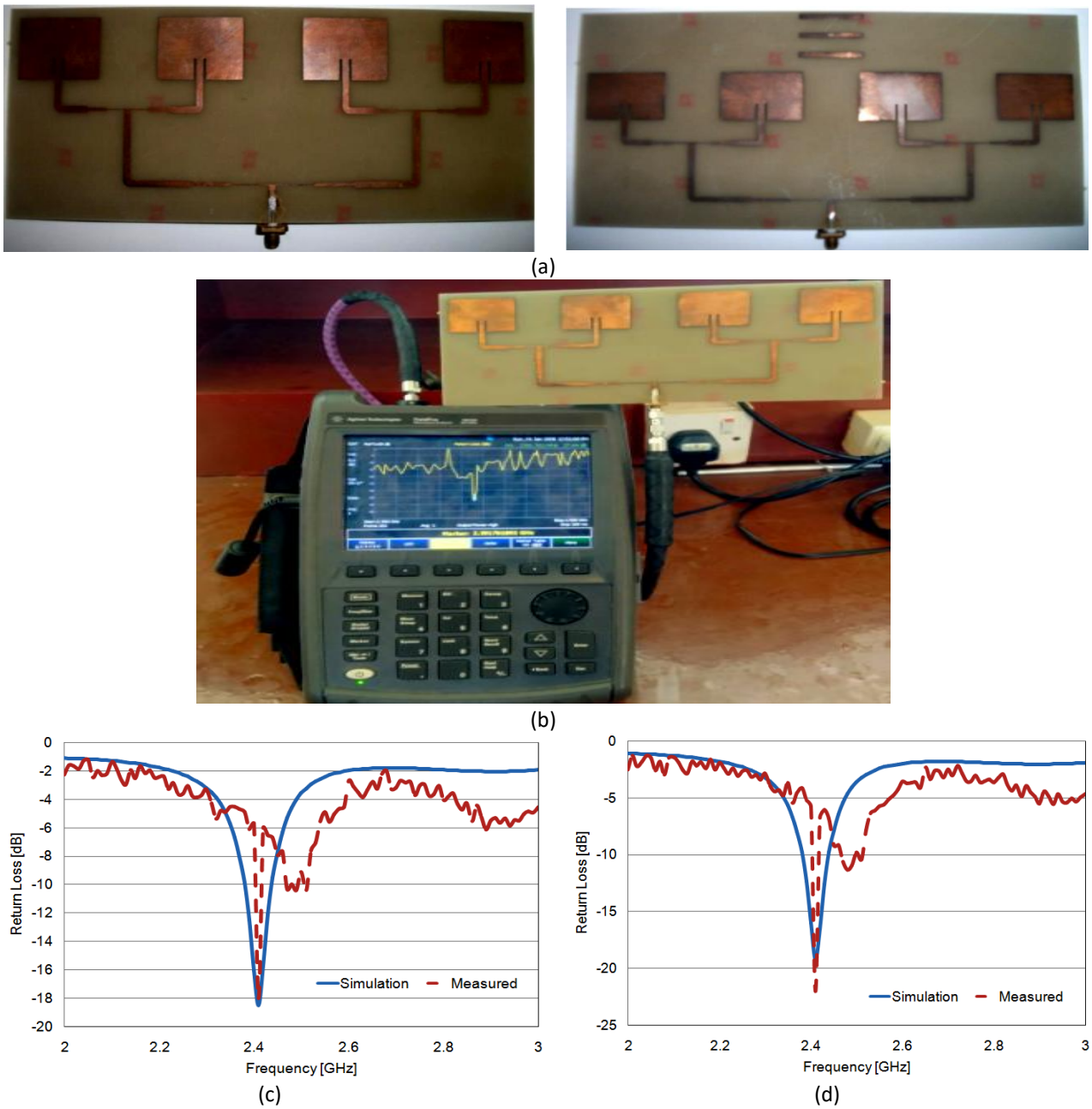


Fig. 12. Lab. measurements and comparison (a) Without Directors (b) With Director (c) Without Directors comparison between simulation and implementation (d) With Directors comparison between simulation and implementation

A comparison with recent current research models is presented in Table 6. Also, the results compared with reference [22] and reference [27] found that antenna array parameters introduced and investigated in this paper are improved.

Table 6
Performance comparisons with recent research published work

Comparisons with recent research papers									
Parameters	Reference								This Paper
	[13]	[14]	[15]	[16]	[17]	[18]	[19]	[20]	
Application	LTE	LTE	5G	5G	WLAN	GSM	LTE	LTE	LTE
Technique	Recon-figure Antenna	Quasi-Yagi Antenna	Di-electric Resonator	Slotted Array Antenna	Finite Inte-gral	Planar Antenna	Planar Antenna	Quasi-Yagi Antenna	Micro-strip / Quasi-Yagi
RL [dB]	-18	-31.5	-35	-25	-32	-32	-16	-50.5	-18.48
BW [GHz]	0.7	0.22	0.9	1.7	5.8	2.6	0.1	0.17	0.15
U_{max}[W/Str.]	-	-	-	-	-	-	-	-	0.471
D [dB]	-	-	-	-	-	-	-	-	6.581
G [dB]	2.5	6	4.27	5.02	5	2.5	2	6.7	6.037
Eff. e_0 [%]	-	73	80	-	96	66	-	83	92
Substrate	FR-4	FR-4	FR-4	Arlon	FR-4	FR-4	FR-4	FR-4	FR-4

6. Conclusions

When compared to an antenna without directors based on the Yagi-Uda antenna, the proposed design produces a very significant boost in the antenna's directionality and gain. It was determined that the suggested antenna array with directors is straightforward and has small dimensions.

The trend of results while using one, two, and three directors suggests that while adding length and more directors than the suggested amount will not significantly alter the antenna's characteristics, it will significantly expand the array antenna's dimensions.

For an antenna array loaded with directors, the antenna's Umax, D, G, Prad and e_0 improvement percentage compared with the array without directors reaches to (1.1, 1.13,1.14,1.125 and 1.02) % respectively using directors for the current mobile communication technology, known as LTE at 2.4 GHZ which is being employed in a substantial number of mobile devices, including smart phones, laptops, and tablets, due to its high spectrum efficiency, high-speed transmission, and high data rate capabilities. The antenna array parameters improvements are tabulated in Table 7.

Table 7
Improvement comparison array without and with three identical Directors (L_D>L_P=29.15 mm) at f=2.41 GHz

Improvement Comparison Array (L_D>L_P)					
Parameters	Umax[W/Str.]	D [dB]	G [dB]	Prad. [W]	e_0[%]
Without Directors	0.41	5.78	5.32	0.8	90
With Directors	0.471	6.581	6.073	0.9	92
Improved [%]	1.1	1.13	1.14	1.125	1.02

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