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Design and Performance Analysis of 4-Element Multiband Circular Microstrip Antenna Array for Wireless Communications

BabatundeS. Olatujoye[1], Jeffrey C. Saturday[2]
[1]*(Department of Nanoengineering, North Carolina Agricultural and Technical State University, USA)*
[2]*(Electrical/Electronic Engineering Department, Joseph SarwuanTarkaa University,Makurdi, Nigeria)*

Abstract:
The increase in the number of low-cost, light weight, highly reliable and low-profile antennas for wireless devices poses a new challenge for the design of antennas for wireless communication. Microstrip antennas meet these requirements because of their inherent characteristics but they are however limited by a number of factors such as bandwidth, directivity and gain. Also, given the number of devices operating in the Industrial Scientific and Medical (ISM) band, issue of overcrowding the frequency band arises since it has only three (3) overlapping channels, thus the need to have a multiband antenna covering the ISM band as well as 5.2, 6.5 and 7 GHz cannot be overemphasized because 5 GHz band has eight (8) overlapping channels which can handle transfer of more sensitive data without interference and with minimal packet loss and delay. This paper presents the design and performance analysis of multi-band circular microstrip antenna array for wireless communications using transmission line model for the design and full-wave model for performance analysis. The circular multiband microstrip antenna was analyzed with the aid of Computer Simulation Technology (CST) Studio software which uses Finite Integration Technique (FIT). A combined bandwidth of 710 MHz was achieved making the proposed antenna suitable for handheld and other portable devices operating in the ISM band as well as 5, 6, and 7 GHz band for WLAN and Worldwide Interoperability for Microwave Access (WiMAX) devices.
Key Word*:Multi-band, Microstrip, Finite Integration Technique (FIT), Bandwidth, WLAN*

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I. Introduction

One of human kind's greatest natural resource is the electromagnetic spectrum and the antenna has been instrumental in harnessing this resource [1]. According to Balanis [2], an antenna is the interface between radio waves propagating through space and electric currents moving in metal conductors, used with a transmitter or receiver. Most communication devices in the modern era are characterized by their adaptability, portability and multipurpose nature thereby limiting the range of antenna types qualified to be adopted [3]. Therefore, considering these peculiar characteristics, microstrip antenna is a viable candidate among a select group of antennas that fit the required antenna specifications due to their lightweight, ease of fabrication and planar nature [4].

Modern wireless communications systems, such as Global System for Mobile Communications (GSM), Digital Communication Systems (DCS), Personal Communication Systems (PCS), Wireless Local Area Networks (WLAN), Wireless Local Loops (WLL) and future broadband systems have instigated a flurry of interest in microstrip antennas [5] [6]. That is, from application point of view, microstrip antennas can be designed to perform some functions that other antenna structures cannot perform such as, circularly polarized radiation and multiband operations. Since a good number of wireless communications systems co-exist in the same geographic area, a single mobile device is required to integrate some of these services which requires multimode or at least dual-mode operation [7]. This multimode requirement necessitates the need to have multifrequency antenna capable of operating with specified parameters.

Among the three popular methods used for designing microstrip antennas capable of multi-band operation, use of multiple patch elements arranged to form an array is proposed in this study with each element uniquely designed to resonate at a different frequency from the next. Transmission line equations for circular microstrip antenna geometry will be used in obtaining the radius, substrate dimensions as well as that of the ground plane. Finite Integration Technique (FIT) which is a variant of Finite Difference Time Domain (FDTD) will be used for the antenna parameter analysis.

II. Review of Related Literature

The introduction of microstrip antenna in the 1950s by Deschamps and its subsequent fabrication by Munson and Howel in the 1970s there has been a number of publications put forward by different authors exploring the possibility of using microstrip antenna for multiband applications using diverse techniques. Pawar and Joshi [8] presented the design and analysis of design of dual band circular microstrip patch antenna with defected ground structure for Industrial Scientific and Medical (ISM) and Wireless Local Area Network (WLAN) band applications. Their proposed antenna resonated at frequencies of 2.48 GHz and 5.32 GHz. Elliptical slot circular patch antenna array with dual band behavior for future 5G mobile communication networks was proposed by [9]. The antenna was configured to a linear 1 x 4 outlay on a Rogers 5880 substrate designed at resonating frequencies of 28 GHz and 45 GHz as a unit cell with an extra resonance at 34 GHz when configured as a slotted array. Maximum gain of 7.6 dB was achieved at 28 GHz for unit cell and 7.21 dB at 45 GHz was similarly achieved. The authors in [10] presented a dual-band circular microstrip antenna for wireless local area network applications with effective return loss of -29.43 dB and -55.90 dB at 1.609 GHz and 2.239 GHz, respectively.

III. Research Methodology

3.1 Single Element Antenna Design Procedure

In setting out to design microstrip antennas, three fundamental parameters are usually specified at inception according to [11], these are: resonant frequency $(f_r = 2.4, 5.2, 6.5\ and\ 7\ GHz)$, dielectric constant of the substrate material $(\varepsilon_r = 2.2)$ and height of substrate $(h = 1.6\ mm)$. The procedures for the determination of each parameter used in the complete design of the circular microstrip antenna (CMSA) are outlined in the following steps using equations (1) to (6):

Step One: Specify the resonant frequency (f_r), select substrate relative permittivity (ε_r) and a substrate thickness (h). The loss due to surface waves can be neglected when h satisfies the following condition given as[12]:

$$h \leq 0.3 \times \frac{\lambda_{air}}{2\pi\sqrt{\varepsilon_r}} \quad (1)$$

$$\lambda_{air} = \frac{c}{f_r} \quad (2)$$

where h is the height of substrate, ε_r is the dielectric constant, λ_{air} wavelength in free space (air), c is the speed of light = 3×10^{10} cm/s, f_r is the selected resonant frequency = 2.4×10^9 Hz, tan δ is the loss tangent, = 0.025, Z_o is the transmission impedance $= 50\ \Omega$

Evaluating (1) and (2) given that $\varepsilon_r = 2.2$ respectively, yield;

λ_{air} = 12.5 cm

$h \leq\approx 0.402$ cm

The selected centre frequency is 2.4 GHz, RT Duroid (Rogers RT5880) substrate is chosen for this design with substrate relative permittivity ε_r of 2.2 and height, h of 0.1588 cm. The choice of substrate material was informed by the availability and cost effectiveness of Rogers RT5880 substrate material. Since the proposed antenna is a narrow band antenna, the chosen substrate height is a good approximation.

Step Two: Calculate the radius and effective radius of the patch using equations (3) to (5) [11], [12]:

$$F = \frac{8.791\times 10^9}{f_r\sqrt{\varepsilon_r}} \quad (3)$$

$$= 2.4695$$

$$a = \frac{F}{\left\{1+\frac{2h}{\pi\varepsilon_r F}\left[\ln\left(\frac{\pi F}{2h}\right)+1.7726\right]\right\}^{1/2}} \quad (4)$$

$$= 2.3627\ cm$$

$$a_e = a\left\{1 + \frac{2h}{\pi\varepsilon_r a}\left[\ln\left(\frac{\pi a}{2h}\right) + 1.7726\right]\right\}^{1/2}$$

(5)

The effective radius becomes;

$$a_e = 2.4733\ cm$$

Step three: Calculate the radial distance, ρ of the patch using (6) as follows [11], [12]:

$$\rho = \frac{2(2a)}{\lambda_{air}} \quad (6)$$

$$= 0.75606\ cm$$

Step four: Calculate the width of the transmission line, W_f adopting (7) thus [11], [12]:

$$W_f = \left(\frac{2h}{\pi}\right) \times \begin{bmatrix} \frac{60\pi^2}{Z_o\sqrt{\varepsilon_r}} - 1 - \ln\left[2 \times \left[\frac{60\pi^2}{Z_o\sqrt{\varepsilon_r}}\right] - 1\right] + \left(\frac{\varepsilon_r - 1}{2\varepsilon_r}\right) \ldots \\ \ldots \times \left(\ln\left[\left[\frac{60\pi^2}{Z_o\sqrt{\varepsilon_r}}\right] - 1\right] + 0.39 - \frac{0.61}{\varepsilon_r}\right) \end{bmatrix} \quad (7)$$

$= 0.48915\ cm$

Step Five: Calculate the notch width, g using (8) [12]:

$$g = \frac{\mathrm{c\ f_r} \times 10^{-9} \times 4.65 \times 10^{-9}}{\sqrt{2\varepsilon_r}} \quad (8)$$

$= 0.19594$ cm

Step Six: Calculate the length of transmission line, L_f using (9) [13]:

$$L_f = \frac{6h}{2} \quad (9)$$

$= 0.48$ cm

Step Seven: Calculate the ground plane dimensions using (9) thus:

L = 6h + a (10)

$$L = 3.3155 \text{ cm}$$

3.2 Design of 4-element multiband Circular Microstrip Patch Antenna Array

The feedline to the antenna consists of microstrip lines of three distinct capacities connecting to each other at bends (mitre bend) and T-junctions. These will be designed as follows:

Microstrip Lines: This is made up of three branches of 50 Ω , 100 Ω and 70.7 Ω (obtained from the transformation of 50 Ω and 100 Ω feed lines). A microstrip-feed line of $Z_0 = 50\ \Omega$ branching off into two feed lines of $2Z_0$ ($Z_1 = 2 \times 50 = 100\ \Omega$) which further ramose into a $Z_2 = 70.7\ \Omega$ feed line as expressed (11) is used for in a parallel array feed network for the proposed antenna.

$$Z_3 = \sqrt{Z_0 Z_1} \quad (11)$$

$$Z_3 = 70.7\ \Omega$$

Since the originating feed line is rated at 50 Ω, all the elements of the array are to be matched to the standard 50 Ω impedance and hence the width the various feed lines are to be computed accordingly. The 50 Ω feed line width was calculated earlier as $W_f = 3.06$ mm.

Width of 70.7 Ω and 100 Ω line are computed using (12) and (13) where Z = 70.7 or 100 Ω, $\varepsilon_r = 4.4$, h=1.6 mm.

Width of 70.7 Ω therefore is computed as:

$$\mathrm{A} = \frac{\mathrm{Z}}{60}\sqrt{\frac{\varepsilon_r + 1}{2}} + \frac{\varepsilon_r - 1}{\varepsilon_r + 1}\left(0.23 + \frac{0.11}{\varepsilon_r}\right) \quad (12)$$

$= 2.70$

$$\frac{W_Q}{h} = \begin{cases} \frac{8e^{A}}{e^{2A} - 2} & \text{for } \frac{W_Q}{h} < 2 \\ \frac{2}{\pi}\left[B - 1 - \mathrm{In}\left((2B - 1) + \left(\frac{\varepsilon_r - 1}{2\varepsilon_r}\right)\left\{\ln(B - 1) + 0.39 - \frac{0.61}{\varepsilon_r}\right\}\right)\right] & \text{for } \frac{W_Q}{h} > 2 \end{cases} \quad (13)$$

$W_3 = 1.01\ mm$

Width of 100 Ω therefore is computed thus:

$A = 2.90$

$W_2 = 0.44\ mm$

Therefore, width of 70.7 Ω, $W_3 = 1.01\ mm$ and that of 100 Ω, $W_2 = 0.44$ mm. The lengths of the quarter-wave lines were calculated in previous section.

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 doesn't have any isolation between the output ports [14]. 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 (a)

Mitred Bend: In prominent cases of the cooperate 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, [15]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 1 (b).

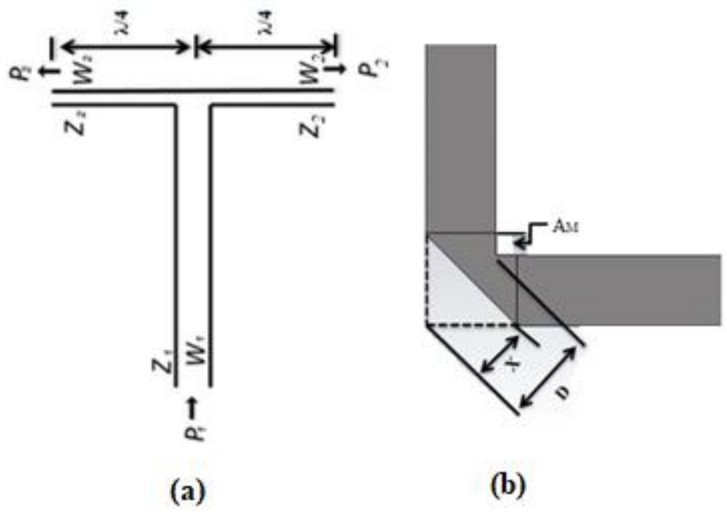

Figure 1: Microstrip feedline constituents (a) T-junction (b) Mitred bend

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; $Z_2 = 2 \times Z_1$.
Expressions for A_M, X and D are given by (14) to (15) as:

$$D = W \times \sqrt{2} \quad (14)$$

where W is the width of the transmission line and h is the height of the substrate. Only the input 70.7 Ω line will incorporates the bend in the antenna design, $W_3 = 1.01\ mm$.
Hence;

$$D = 1.43\ mm$$

$$X = D \times \left[0.52 + 0.65e^{\left(-1.35\frac{W}{h}\right)}\right] \quad (15)$$

$$= 1.14\ \text{mm}$$

$$A_m = \left(X - \frac{D}{2}\right) \times \sqrt{2} \quad (16)$$

$$= 0.60\ mm$$

Inter-element spacing: [16] specified that to lower the risk of mutual coupling, maintain single mode propagation among radiating elements and to have in-phase array elements and radiation in normal direction, the distance between array elements is taken to be about half wavelength $\left(\frac{\lambda_{air}}{2}\right)$; thus
patch spacing, d $= \frac{\lambda_{air}}{2} = \frac{125}{2} = 62.5\ mm$
Table 1 contains the computed antenna dimensions obtained from design equations while the geometry of the designed antenna in CST MWS is given in Figure 2.

Table 1: Design parameters for the proposed 4-element multiband CMSA array antenna

Parameter	Value (cm)
Array network feed dimensions: Width of 50 Ω transmission line, W_f	 0.306
Width of 70.7 Ω transmission line, W_3	0.101
Width of 100 Ω transmission line, W_2	0.044
Inset distance, y_o	1.490
Inset gap, g	1.276
Length of transmission line, L_f	0.480
Ground plain dimensions: Length of ground plain, L_g Width of ground plan, W_g	 40.00 40.00

Mitred bend dimensions:	
A_m	0.060
X	0.114
D Distance between Patches, d	0.143 6.250

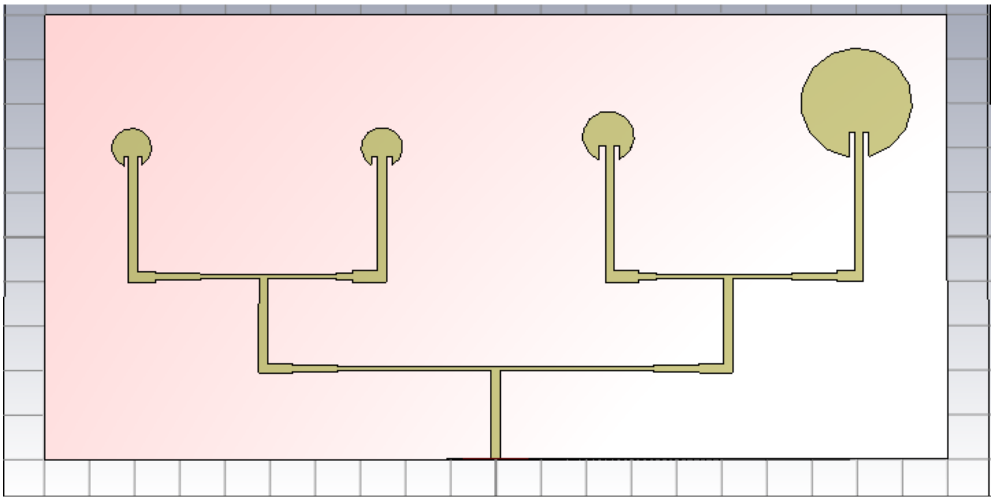

Figure 2: Proposed multiband CMSA array designed in CST MW Studio

IV. Discussion

The results (return loss, bandwidth, directivity and gain) obtained from the simulation of the designed antenna in CST MWS is presented in this section. The return loss of the proposed multiband CMSA array as can be seen in Figure 3. shows that a return loss and resonance frequency of -16.453 8 dB and 2.4089 GHz was achieved at the design frequency of 2.4 GHz and a return loss and resonance frequency of -15 dB and 5.2134 GHz were respectively obtained at 5.2 GHz. This shows a bandwidth of 70 MHz at 2.4 GHz and 190 MHz at 5.2 GHz. Similarly, return loss and resonance frequency of -14.526 dB and 6.5008 GHz was achieved at the design frequency of 6.5 GHz and a return loss and resonance frequency of -21.447 dB and 6.964 GHz were respectively obtained at 7 GHz; this shows a bandwidth of 180 MHz at 6.5 GHz and 270 MHz at 7 GHz. This sums up to a combined bandwidth of 710 MHz with percentage bandwidth of 2.92%, 3.65%, 2.77% and 3.86%, at 2.4 GHz, 5.2 GHz, 6.5 GHz and 7 GHz, respectively.

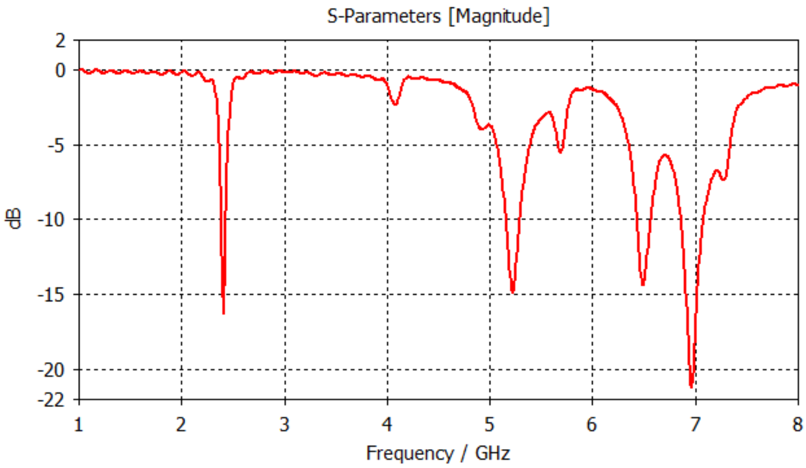

Figure 3:Return loss of CMSA multiband antenna array

The directivity ($\phi = 90^0$) of the multiband array CMSA is depicted in Figures 4 and 5. The Half Power Beam Width (HPBM) and main lobe magnitude at 2.4 GHz and 5.2 GHz are $82.5^0$and 6.37 dBi, and 45.5^0 and 2.36 dBi, respectively as seen in Figure 4. Also,HPBM and main lobe magnitude of the proposed antenna at 6.5 GHz and 7 GHzare shown in Figure 5 to be57.8^0 and 7.04 dBi, and45^0 and 4.56 dBi.Similarly, the directivity ($\phi = 0^0$) of the proposed antenna is illustrated in Figures 6 and 7.

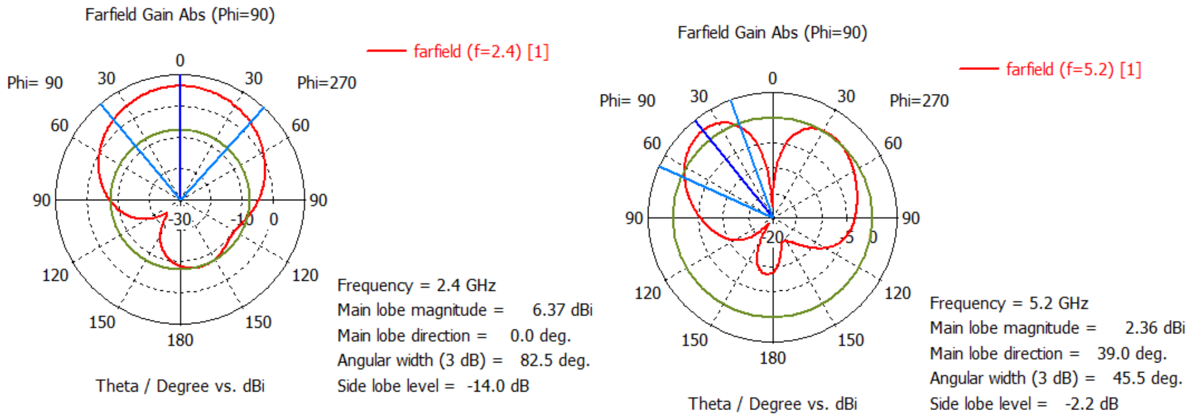

Figure 4:Directivity ($\phi = 90^0$) of CMSA multiband antenna at 2.4 and 5.2 GHz

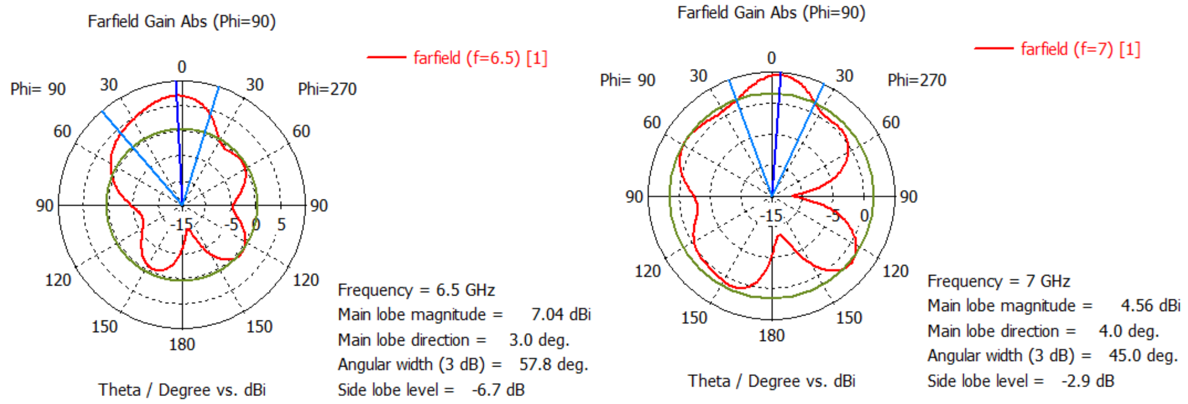

Figure 5:Directivity ($\phi = 90^0$) of CMSA multiband antenna at 6.5 and 7 GHz

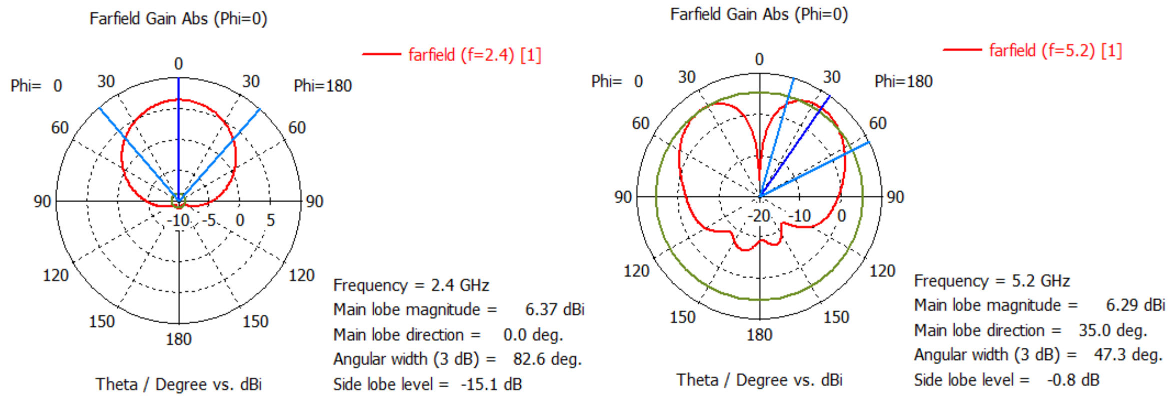

Fig 6. Directivity ($\phi = 0^0$) of CMSA multiband antenna at 2.4 and 5.2 GHz

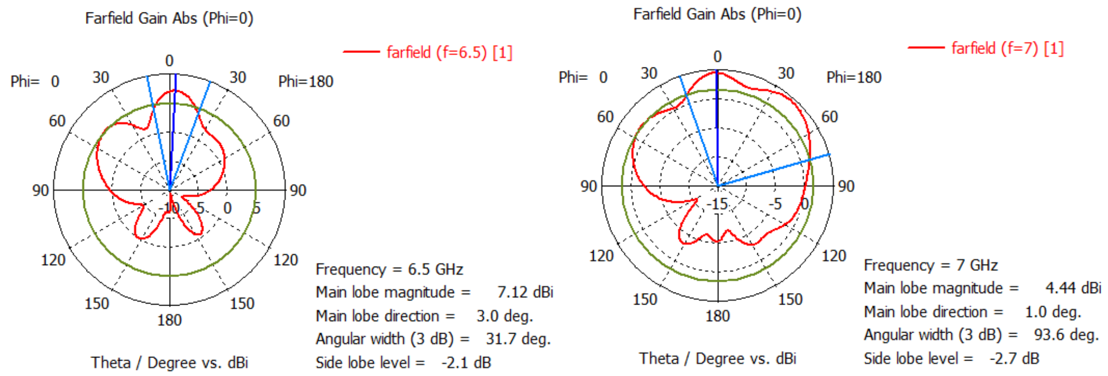

Figure 7: Directivity ($\phi = 0^0$) of proposed antenna at 6.5 and 7 GHz in CST MW studio

The Half Power Beam Width (HPBM) and main lobe magnitude at 2.4 GHz and 5.2 GHz are 82.6^0 and 6.37 dBi, and 47.3^0 and 6.29dBi, respectively as seen in Figure 6. Figure 7 showed the HPBM and main lobe magnitude of the proposed antenna at 6.5 GHz and 7 GHz to be 31.7^0 and 7.12dBi, and 93.6^0 and 4.44dBi.

In terms of antenna gain, the multiband array antenna achieved gain of 6.39 dB and 6.91 dB at 2.4 GHz and 5.2 GHz, respectively. Also, gain values of 7.35 and 7.01 dBi were achieved at 6.5 and 7 GHz.

V. Conclusion

In this paper, a 4-element multiband CMSA microstrip antenna array designed to resonate at four distinct frequencies, (2.4/5.2/6.5/7 GHz) have been designed and simulated, clarifications have been made on several parameters such as return loss, bandwidth and directivity. From the computed and simulation results, it has been observed that the major parameters that determined the behavioural characteristics of the antenna were the relative permittivity (ε_r) of the dielectric material under the patch, the width (Wf) of the microstrip line, the position of the array elements constituting the array patch, and the radius (a) of the patch. With a combined bandwidth of 710 MHz and antenna gains greater than that of typical single band microstrip antenna ($> 5\ dB$) at design frequencies considered, the proposed multiband array antenna has met the objectives outlined for the study.

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