ISLAMIC UNIVERSITY OF TECHNOLOGY

DESIGN AND DEVELOPMENT OF MICROSTRIP PATCH ANTENNA ARRAY

Submitted By

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A Dissertation
Submitted in Partial Fulfillment of the Requirement for the
Bachelor of Science in Electrical and Electronic Engineering
Academic Year: 2012-2013

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A Dissertation on,

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ABSTRACT

In this work, a microstrip patch antenna array is designed A rectangular patch is used as the basic element for the array. The unit and array radiation pattern are obtained by simulation and by Dolph-Chebyshev synthetic technique. The performances of the Dolph-Chebyshev array are compared with those of the uniform configuration. The weighting factors of the array are determined under the designed constraint such as side lobe level (SSL). It has been observed that the performance of the Dolph-Chebyshev array is better than that of the uniform array. Finally, critical needs for further research and development for this antenna are identified.

CONTENTS

ACKNOWLEDGEMENT

We wish to express our deepest gratitude to our research adviser Dr. Md. Ruhul Amin, Professor, Department of EEE, IUT for his continuous guidance, supervision and valuable suggestions during the entire project work.

We also wish to acknowledge and express our gratitude to Dr. Fokhrul Islam, Assistant Professor, Department of EEE, IUT for his kind help.

We also wish to express our appreciation to friends and others who directly or indirectly helped with worth suggestion and information in this work.

Finally we thank the Electrical and Electronic Department of IUT.

CHAPTER-1

INTRODUCTION AND MOTIVATION

1.1 INTRODUCTION

RF and microwave technologies are rapidly finding their way into commercial and consumer products. This has resulted in the proliferation of antennas. To be competitive in the commercial market place, design cycle times must be short, low cost and physically small. Microstrip antennas provide the technology necessary to meet the demands of future products.

Microstrip antennas have been largely used in wireless application, because of their inherent characteristics of low cost, low profile, ease of fabrication, light weight, conformability and integration with RF devices.

In this project, we mainly focused on the design of microstrip patch antenna array and measuring their performance by varying the number of array element for the frequency band of 2.4 GHz. For our design, we have used the R04003C substrate which has a dielectric constant of 3.4 and we have considered typical line impedance of 50Ω and inset-line fed model.

Nowadays, various types of software are available for the design and simulation of patch antennas. For convenience in design process, we have used Zeland IE3D and PCAAD software. We have also used MATLAB for some simulation.

1.2 MOTIVATION

Microstrip patch antennas are widely used in wireless communication due to its many useful and unique characteristics that we have already mentioned above. Apart from these useful features, we can improve the directivity of the patch antenna by introducing the term ‘array’ which implies using more number of single elements in a specific pattern. In many RF applications, it is required to get the radiation pattern in a particular direction hence it requires to improve the directivity. In such cases, we can use microstrip patch antenna array.

1.3 METHODOLOGY

Initially an inset-line fed rectangular patch antenna is designed using Zeland IE3D. The size parameters of the patch are calculated using standard equations [1].We observed S11 parameter and VSWR to match with the resonant frequency. Then we have designed for a 4 element array and again observed the result to match with the resonant frequency. After that we have synthesized our array using Dolph - Chebyshev method and plotted the radiation pattern using MATLAB for different numbers (N) of array element The radiation patterns for different value of N are compared.

1.4 APPLICATIONS

Our designed patch antenna array can be used mainly where high directive gain is required. Some of the applications of this antenna are as follows:

- It can be used in satellite imaging systems such as SEASAT and SIR-A
- It can be used in radar communication
- It can be used in aerospace
- It can be used in military application

CHAPTER-2

OVERVIEW OF MICROSTRIP ANTENNA

2.1 MICROSTRIP PATCH ANTENNA

Microstrip Antennas are planar resonant cavities that leak from their edges and radiate. There are several types of microstrip antennas (also known as printed antennas) the most common of which is the Microstrip patch antenna or patch antenna.

A patch antenna is a narrowband, wide-beam antenna fabricated by etching the antenna element pattern in metal trace bonded to an insulating dielectric substrate, such as a printed circuit board, with a continuous metal layer bonded to the opposite side of the substrate which forms a ground plane. Common microstrip antenna shapes are square, rectangular, circular and elliptical, but any continuous shape is possible. Some patch antennas do not use a dielectric substrate.

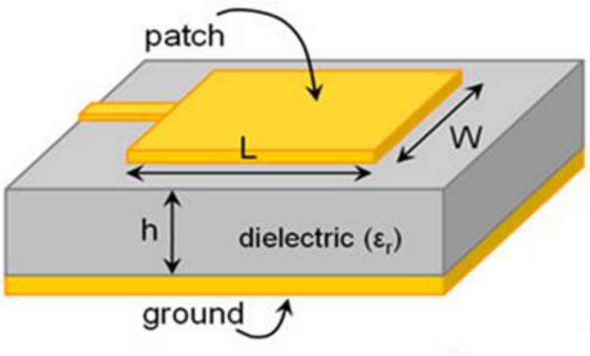


Fig 2.1: Microstrip Patch Antenna

In fig. 1, a common microstrip antenna is shown. A conducting strip with a width W and a thickness t is on the top of a dielectric substrate that has a relative dielectric constant and a thickness h and the bottom of the substrate is a conducting plane. Length of the conductor is L and relative permittivity is ε_r.

2.2 Basic Characteristics

A microstrip antenna consists of a very thin metallic strip placed a small fraction of a wave length above ground plane. For a rectangular patch, the length L of the element is usually $\lambda/3 < L < \lambda/2$. Dielectric constant is usually in range of $2.2 < \varepsilon_r < 12$. The most desirable for antenna performance are thick substrates whose dielectric constant is in the lower end of the range because they provide better efficiency and larger bandwidth. On the other hand, thin substrate with higher dielectric constant are desirable for microwave circuitry because they require tightly bound fields to minimize undesired radiation and coupling and lead to small element size [1].

2.3 Feeding Method

There are mainly four most popular method of feeding in microstrip patch antennas. Namely:

- Line feed
- Coaxial or Probe feed
- Aperture coupling feed
- Coplanar waveguide feed

2.3.1 Line Feed

The microstrip feed line is a conducting strip, usually of much smaller width compared to the patch. This feed arrangement has the advantage that it can be etched on the same substrate, so the total structure remains planar. The drawback is the radiation from the feed line which leads to an increase in the cross polar level. So the size of the feed line leads to the increase of undesired radiation [4].

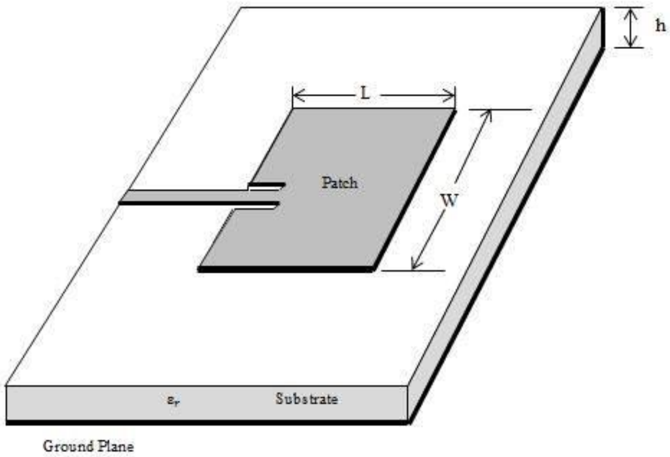


Fig 2.2: Microstrip line feed

2.3.2 Coaxial or Probe Feed

The center conductor of the coaxial connector is soldered to the patch. The main advantage of this feed is that it can be placed at any desired location inside the patch to match with its input impedance. The disadvantages are that the hole has to be drilled in the substrate and the connector protrudes outside the bottom ground plane. So that it is not completely planar. In case of increased probe length makes the input impedance more inductive, leading to the impedance matching problem [4].

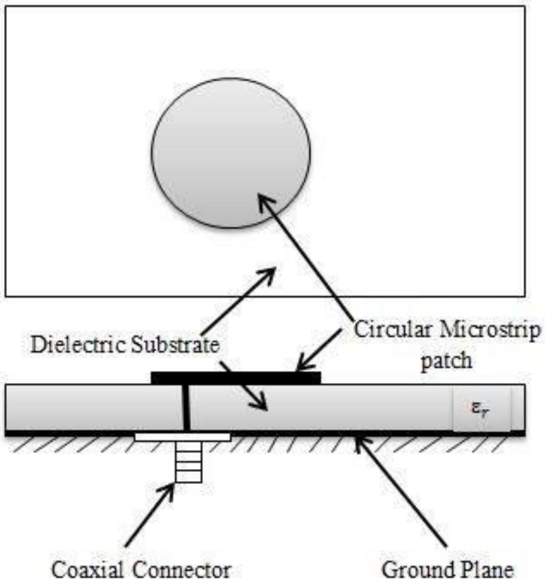


Fig 2.3: Probe feed

2.3.3 Aperture Coupling

In aperture coupled microstrip antenna configuration, the field is coupled from the microstrip line feed to the radiating patch through an electrically small aperture or slot cut in the ground plane. The coupling aperture is usually centered under the patch, leading to lower cross polarization due to symmetry of the configuration. The slot aperture can be either resonant or non-resonant. The resonant slot provides resonance in the addition to the patch resonance thereby increasing the bandwidth at the expense of an increase in back radiation. As a result a non-resonant aperture is normally used. The substrate parameters of two layers can be chosen separately for optimum antenna performance. This feeding method gives increased bandwidth [4].

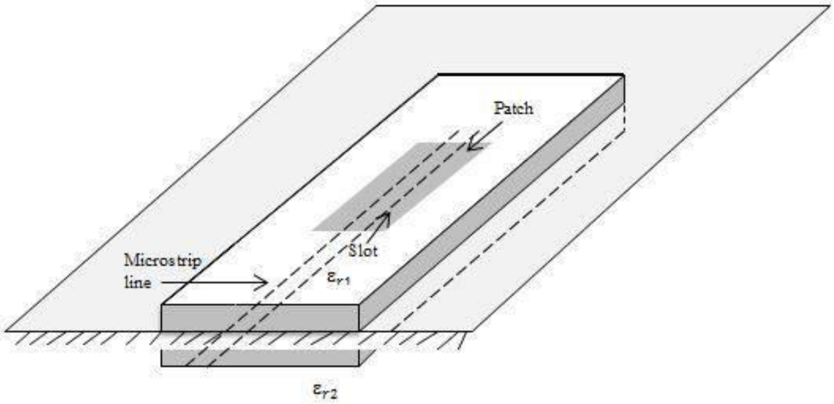


Fig 2.4: Aperture Coupled feed

2.3.4 Coplanar Waveguide Feed

The coplanar waveguide has been used to excite the microstrip antenna. The coplanar waveguide is etched on the ground plane of the microstrip antenna. The line is excited by coaxial feed line and terminated by a slot, whose length is chosen to be between 0.25 and 0.29 of slot wavelength (λ). The main disadvantage of this method is the high radiation from the rather longer slot leading to the poor front to back ratio [4].

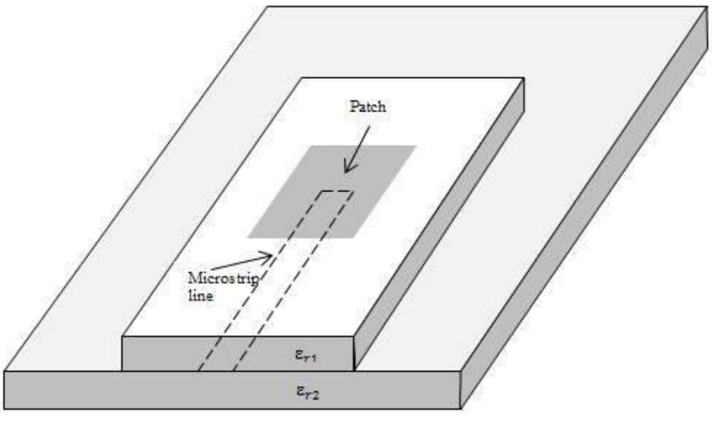


Fig 2.5: Coplanar Waveguide Feed

2.4 Method of Analysis for Rectangular Patch

Rectangular patch is analyzed using two methods which are most accurate for thin substrates. These methods are

- Transmission Line Model
- Cavity Model

2.4.1 Transmission Line Model

The transmission line model is very simple and helpful in understanding the basic performance of microstrip antenna. The microstrip radiator element is viewed as transmission line resonator with no transverse field variation and radiation occurs mainly form the fringing field at the open circuited ends. The patch is represented by two slots those are spaced by the length of the resonator. The drawback of the transmission line model is that it cannot analyze the variation of field in the orthogonal direction to the direction of the propagation .

Fringing Effect

As the dimension of the patch is finite along the length and width, the fringing undergoes at the edge of the patch. The amount of fringing is a function of the dimension of the patch and height of the substrate. For principal E-plane, fringing is a function of the ratio of the length of the patch L to the height h of the substrate and the dielectric constant ε_r of the substrate. Since for microstrip antennas L/h >> 1, fringing is reduced [1].

Fig 2.6: Fringing effect

Some of the waves travel in the substrate and some in the air. So an effective dielectric constant ε_{re} is induced to account for fringing and the wave propagation in the line.

$$\varepsilon_{re} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left[1 + 12\frac{h}{W}\right]^{-\frac{1}{2}} \quad \text{.....................................(1)}$$

A very popular and practical approximation relation for normalized extension of the length is obtained from below equation [1]-

$$\Delta L = 0.412h \frac{(\varepsilon_{re}+0.3)(\frac{W}{h}+0.264)}{(\varepsilon_{re}-0.258)(\frac{W}{h}+0.8)} \quad \text{.................................... (2)}$$

Substrate thickness should be chosen as large as possible to maximize bandwidth, but not so large to minimize the risk of surface wave excitation.

The substrate should also have low dielectric constant in order to achieve high efficiency. Since the effective length of the patch has been extended by L on each side, the effective length of the patch is expressed as-

$$L_{eff} = L + 2\Delta L \quad \text{... (3)}$$

2.4.2 Cavity Model

In the cavity model, the region between the patch and the ground plane is treated as a cavity that is surrounded by magnetic walls around the periphery and by electric walls from the top and bottom sides. Since thin substrates are used, the field inside the cavity is uniform along the thickness of the substrate. the field underneath the patch for regular shapes such as rectangular, circular, triangular and sectorial shapes can be expressed as a summation of the various modes of the two dimensional resonator [2].

The fringing fields around the periphery are taken care of by extending the patch boundary outward so that the effective dimensions are larger than the physical dimension of the patch. The effect of the radiation from the antenna and the conductor loss are accounted for by adding these losses to the loss tangent of the dielectric substrate. The far field and radiated power are computed from the equivalent magnetic current around the periphery.

An alternate way of incorporating the radiation effect in the cavity model is by introducing an impedance boundary condition at the walls of the cavity. The fringing and the radiated power are not included inside the cavity but are localized at the edge of the cavity.

2.5 Antenna Parameters

2.5.1 Antenna Impedance

Antenna Impedance is presented as the ratio of voltage to current at the antenna's terminals. Low- and High-Frequency models are presented for transmission lines. The fundamentals of antenna theory require that the antenna be "impedance matched" to the transmission line or the antenna will not radiate. The concept of VSWR is introduced as a measure of how well matched an antenna is [7].

2.5.2 Radiation Pattern

The radiation pattern for an antenna is defined here. We have 3D graphs of real antenna radiation patterns, with a discussion on isotropic, omnidirectional and directional radiation patterns. Radiation patterns are of the utmost importance in the discussion of antenna basics [13].

2.5.3 Gain

Antenna gain is defined as how much power is transmitted in the direction of peak radiation to that of an isotropic source. It also gives the measurement of actual losses that occur [7].

2.5.4 Efficiency

The efficiency of an antenna relates the power delivered to the antenna and the power radiated or dissipated within the antenna. A high efficiency antenna has most of the power present at the antennas input radiated away.

A low efficiency antenna has most of the power absorbed as losses within the antenna or reflected away due to impedance mismatch. The losses associated within an antenna are typically the conduction losses and dielectric losses.

$$\eta = \frac{P_{radiated}}{P_{input}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (4)$$

2.5.5 Directivity

Directivity is a fundamental antenna parameter. It is a measure of how directional an antenna’s radiation pattern is. An antenna that radiates equally in all directions would have effectively zero directionality, and the directivity of this type of antenna would be 1 or 0 dB [13] .

2.5.6 Bandwidth

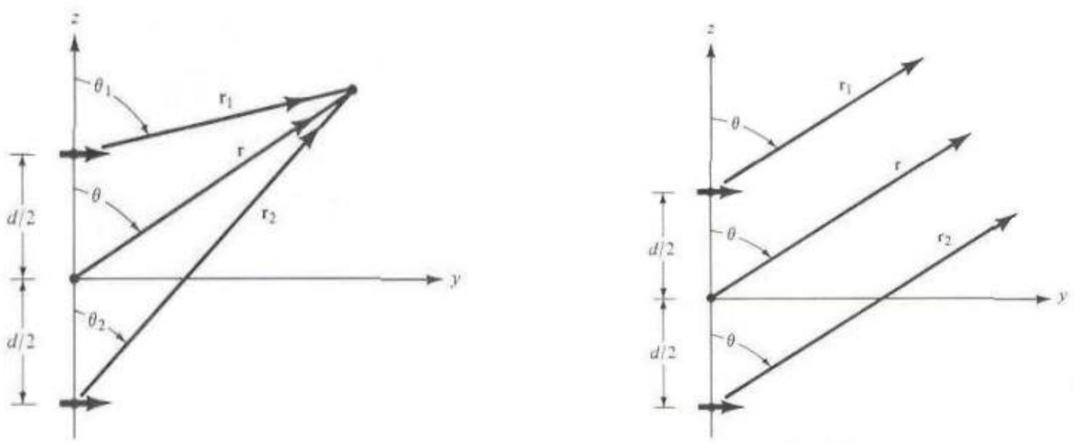
The bandwidth of an antenna is defined as “the range of usable frequencies within which the performance of the antenna, with respect to some characteristic, conforms to a specified standard. The bandwidth can be the range of frequencies on either side of the center frequency where the antenna characteristics like input impedance, radiation pattern, beam width, polarization, side lobe level or gain.

CHAPTER-3

PATCH ANTENNA ARRAY

3.1 ANTENNA ARRAY BASICS

An antenna array is a group of radiators whose currents are of different amplitudes and phases. The signals from the antennas are combined or processed in order to achieve improved performance over that of a single antenna. Antenna arrays are the solution to the problem defined as the limitations of operating a single antenna. The antenna array can be used to increase the overall gain. It also cancels out interference from a particular set of directions and steer the array so that it is most sensitive in a particular direction.



(a) (b)

Fig 3.1: Geometry of a two element array position along the z axis, (a) Two infinitesimal dipoles (b) Far-field observation [1]

The array factor is a function of the geometry of the array and the excitation phase. By varying the separation d and/or the phase β between the elements, the characteristics of the array factor and of total field of the array can be controlled.

3.1.1 ARRAY TYPES

There are a few different general types of antenna arrays as follows-

- Linear arrays (Uniform and Broadside Nonuniform)
- Planar array (Broadside Uniform)
- Circular array (Broadside Uniform)

3.1.2 ARRAY FACTOR

Array factor is a function of the positions of the antennas in the array and the weights used. Antenna array's performance equation can be optimized to achieve desirable properties by using Dolph – Chebyshev method. Array factor can be shown by eq.(6) [1]. & eq.(7) [14] that has been used in our pupose.

$$E_{\phi}^{t} = +\, j\frac{k_0 W V_0 e^{-jk_0 r}}{\pi r}\left[\sin\Theta \;\; \frac{sin\left(\frac{k_0 h}{2}\sin\Theta\right) sin\left(\frac{k_0 W}{2}\cos\Theta\right)}{\frac{k_0 h}{2} sin\Theta \;\; \frac{k_0 W}{2} cos\Theta}\right] \ldots\ldots (5)$$

$$AF = 2\cos\left[\frac{1}{2}\,(\beta d\, cos\Theta + \alpha)\right]\, e^{j\alpha/2} \ldots\ldots (6)$$

$$AF=2\sum_{m=1}^{N} i_m \cos\left[\left(m-\frac{1}{2}\right) kdw\right], \text{ For } M=2N \ldots\ldots (7)$$

3.2 ARRAY SYNTHESIS

Array synthesis is necessary to design an array that will yield desired radiation characteristics.

The categories of requirements:

- The array radiation pattern exhibits a desired distribution in the visible region-beam shaping.
- The array radiation pattern has low side lobes & a narrow main beam.

Synthesis methods are:

- The Fourier series method
- The Dolph - Chebyshev method

3.3 ARRAY PATTERN MULTIPLICATION

Pattern multiplication is multiplication of unit pattern & array factor. Where unit pattern is the pattern of the individual array element & array factor is a function dependent only on the geometry of the array and the excitation (amplitude, phase) of the elements [10].

Array Pattern=MSP single element pattern × Array factor

Array Pattern =

$$\sin\theta \frac{\sin\left(\frac{k_o h}{2}\sin\theta\right)\sin\left(\frac{k_o W}{2}\cos\theta\right)}{\left(\frac{k_o h}{2}\sin\theta\right)\left(\frac{k_o W}{2}\cos\theta\right)} \times 2\sum_{m=1}^{N} i_m \cos[(m - 1/2)k_o dw]$$

CHAPTER-4

DESIGN AND SIMULATION

4.1 DESIGN & COMPARISON BTWEEN SINGLE ELEMENT & 4 ELEMENT ARRAY MSA

The antenna is fabricated on a 60 mm R04003 substrate from Rogers Corp with the dielectric constant of 3.4 & loss tangent of 0.001.We have used IE3D to simulate 2.4GHz microstrip line feed patch antenna [6].

4.1.1 SINGLE ELEMENT DESIGN EQUATIONS

Design Equations are –

$$L = \frac{c}{2f_r\sqrt{\varepsilon_{re}}}$$

$$L_{eff} = L \pm \Delta L$$

$$W = \frac{c}{2\sqrt{\left(\frac{\varepsilon_{re}+1}{2}\right)}f_0}$$

$$\varepsilon_{re} = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2}\left[1+12\frac{h}{W}\right]^{-\frac{1}{2}}$$

Here,

L = Length

W = Width

L_{eff} = Effective Length

ε_r = Dielectric Constant

ε_{re} = Effective Dielectric Constant

H = Height of the substrate

f_r = Resonant frequency

4.1.2 SINGLE ELEMENT DESIGN SPECIFICATIONS

Operating frequency = 2.4GHz

Polarization = Linear

Input connector = Inset Line Feed

Substrate & dielectric permittivity (ε_r) = RO4003C, 3.4

Shape of the patch antenna = Rectangle

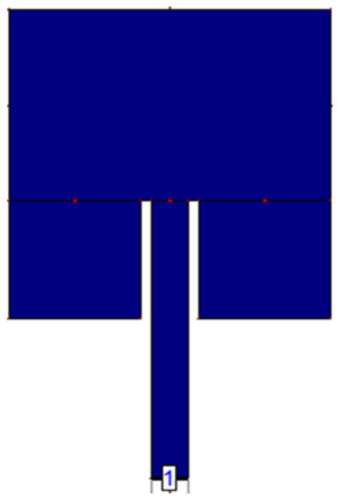


Fig 4.1: Single element microstrip antenna

4.1.3 ARRAY DESIGN SPECIFICATION

Operating frequency = 2.4GHz

Polarization = Linear

Input connector = Inset Line Feed

Substrate & dielectric permittivity (ϵ_r) = RO4003C, 3.4

Shape of the patch antenna = Rectangle

Number of element = 4

Element spacing = 125mm

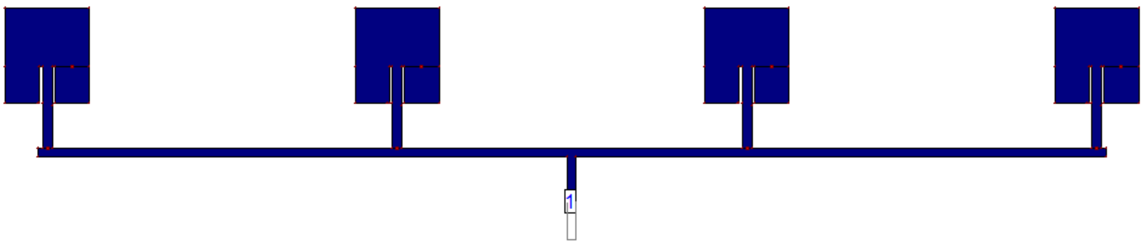
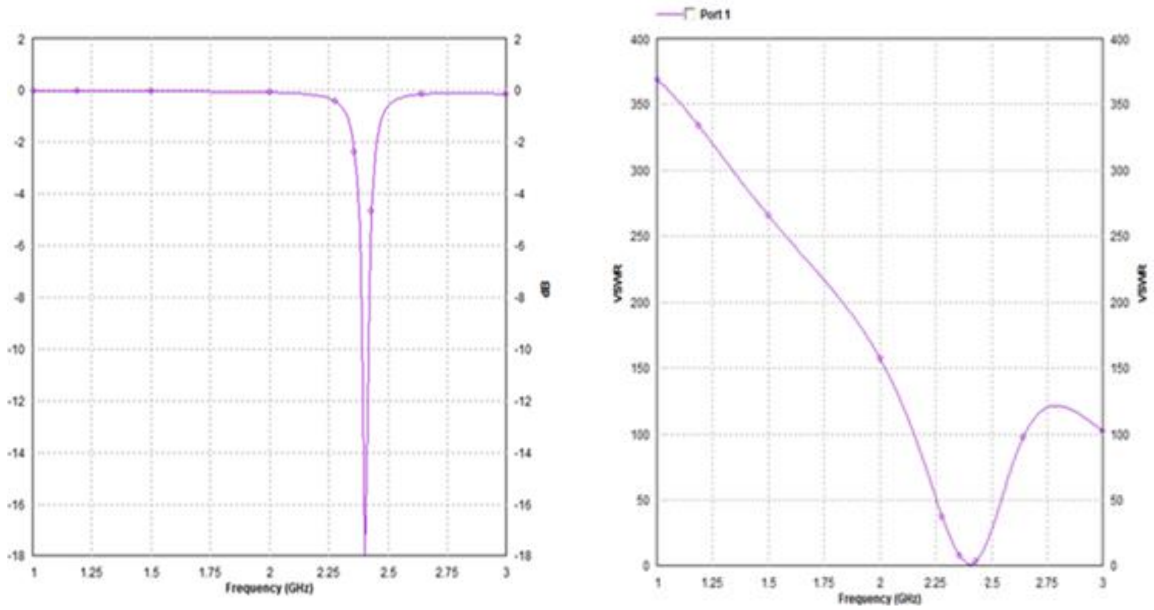


Fig 4.2: 4 element microstrip array antennas

4.1.4 COMPARISON BETWEEN SINGLE ELEMENT AND 4 ELEMENT LINEAR ARRAYS

4.1.4.1 SINGLE ELEMENT CHARACTERISTICS

We have simulated single element antenna and 4 element linear array antennas using IE3D software and compared the result through S11andVSWR parameters, Current Density and Polar Pattern plot. The results are shown below-



(a) (b)

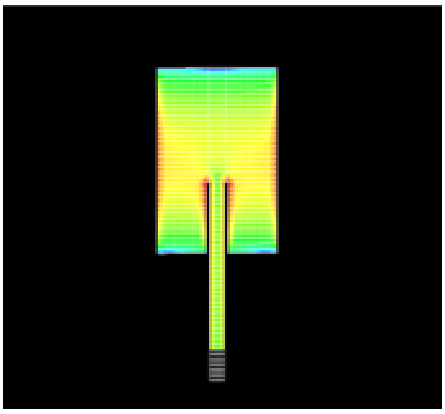
Fig 4.3: Single element simulation (a) S11 parameter, (b) VSWR

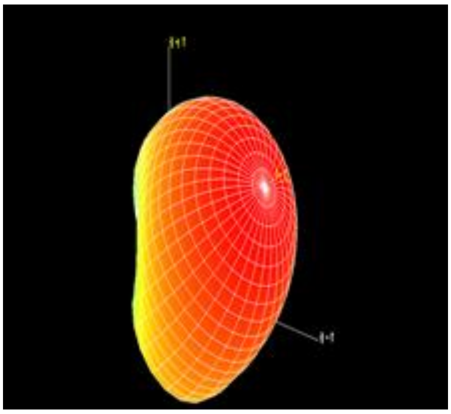
We specified earlier that the operating frequency is 2.4 GHz. In fig 4.3(a), we can see that S11 parameter has well matched with our design frequency. Also in fig 4.3(b), VSWR is matched with that frequency. So we can say that our design is compatible with the specified frequency band.

S-parameters describe the input-output relationship between ports (or terminals) in an electrical system. A port can be loosely defined as any place where we can deliver voltage and current. So, if we have a communication system with two radios (radio 1 and radio 2), then the radio terminals (which deliver power to the two antennas) would be the two ports. S11 then would be the reflected power radio 1 is trying to deliver to antenna 1.

VSWR stands for Voltage Standing Wave Ratio. It is a function of the reflection coefficient, which describes the power reflected from the antenna.

Later we simulate current density in a single element patch antenna and its polar plot in 3D.





(a) **(b)**

Fig 4.4: (a) Current density, (b) 3D polar plot for single element MSA

The fig shows that the current density is very high at the center and becomes gradually low at the edge.

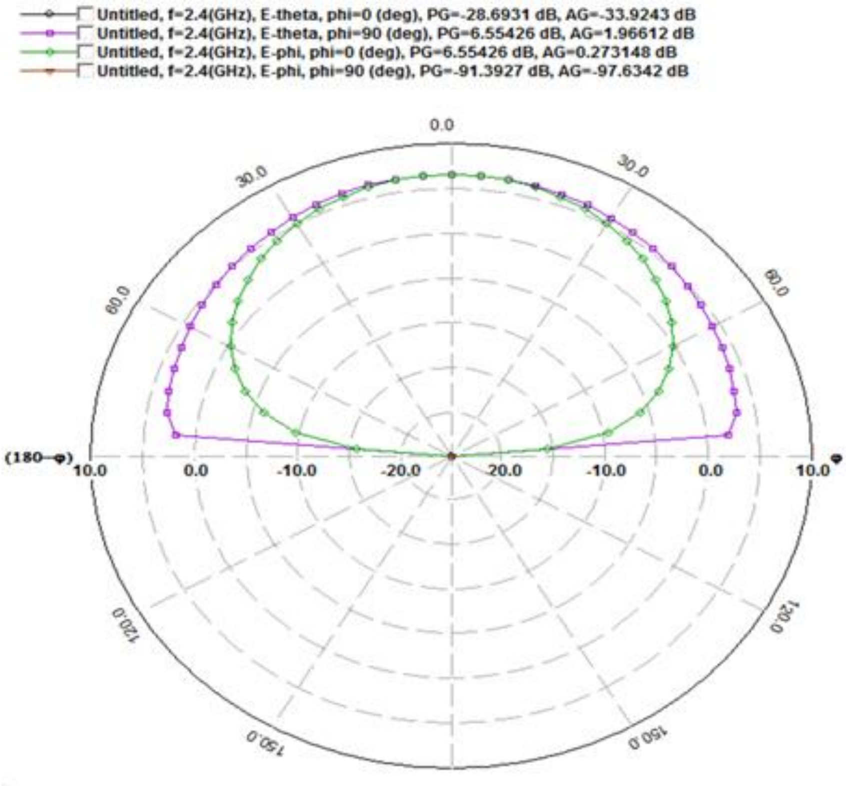
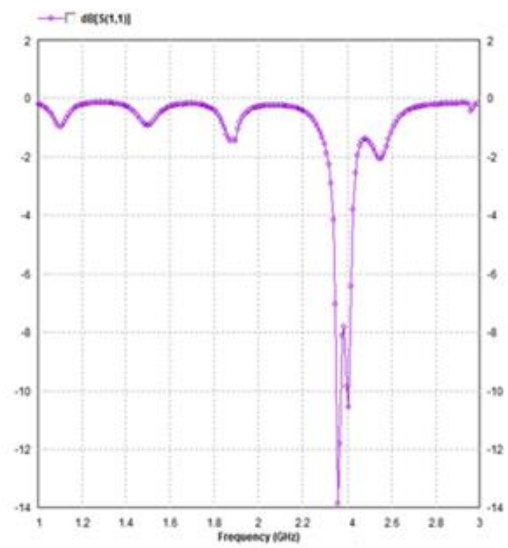
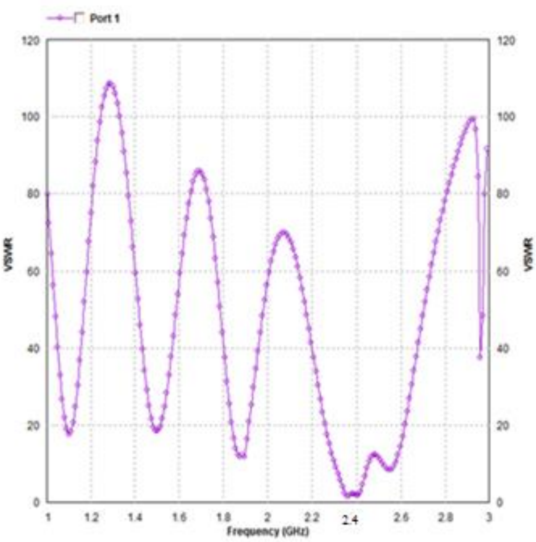


Fig 4.5: Directivity of single element MSA

4.1.4.2 4-ELEMENT PATCH ARRAY CHARACTERISTICS





(a) **(b)**

Fig 4.6: 4-element patch array simulation (a) S11 parameter, (b) VSWR

In fig 4.6(a), we can see that S11 parameter has well matched with our design frequency. Also in fig 4.6(b), VSWR is matched with that frequency. So we can say that single element design is compatible with array design.

Simulation of antenna array for current density-

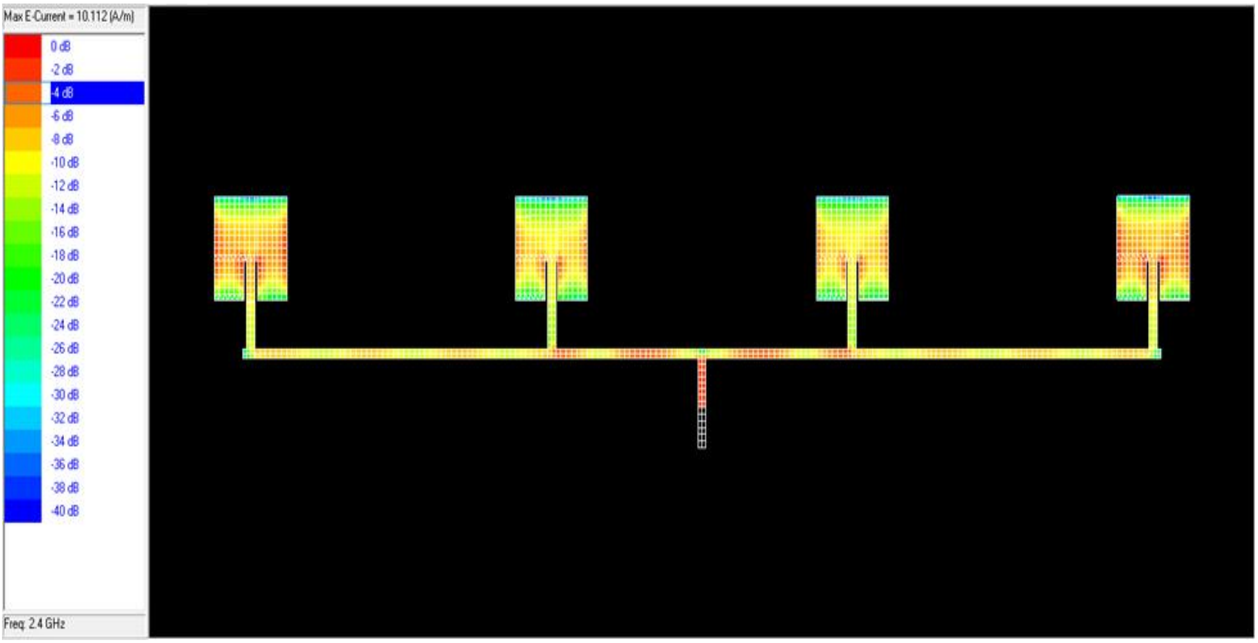


Fig 4.7: Current density for microstrip patch antenna array

Like single element, the fig shows that the current density is also very high at the center and becomes gradually low at the edge for microstrip patch antenna array.

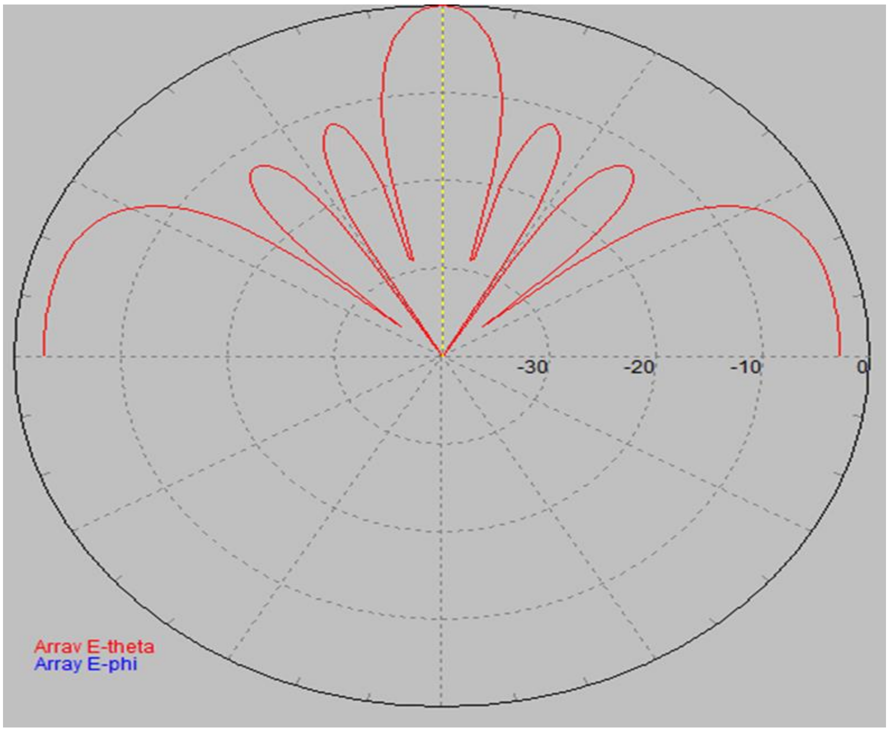


Fig 4.8: Directivity for 4-element MSA

Fig 4.8 shows the directivity for a 4-element MSA. Comparing between fig 4.5 and 4.8, it is seen that directivity for 4-element array is much better than single element antenna. So antenna directivity increases b using array.

4.2 DESIGN OF DOLPH CHEBYSHEV ARRAY

We have found the current elements of Dolph Chebyshev using following Matlab program

```
phi=0:0.01:2*pi;
shi=pi*cos(phi);
i1=chebwin(4,20);
E=abs(freqz(i1,1,shi))
EdB(1,:)=20*log10(E/max(E));
i2=taylorwin(4,2,-20);
E=abs(freqz(i2,1,shi))
EdB(2,:)=20*log10(E/max(E));
plot(phi*180/pi,EdB,'LineWidth',2)
axis([0 180 -30 10])
```

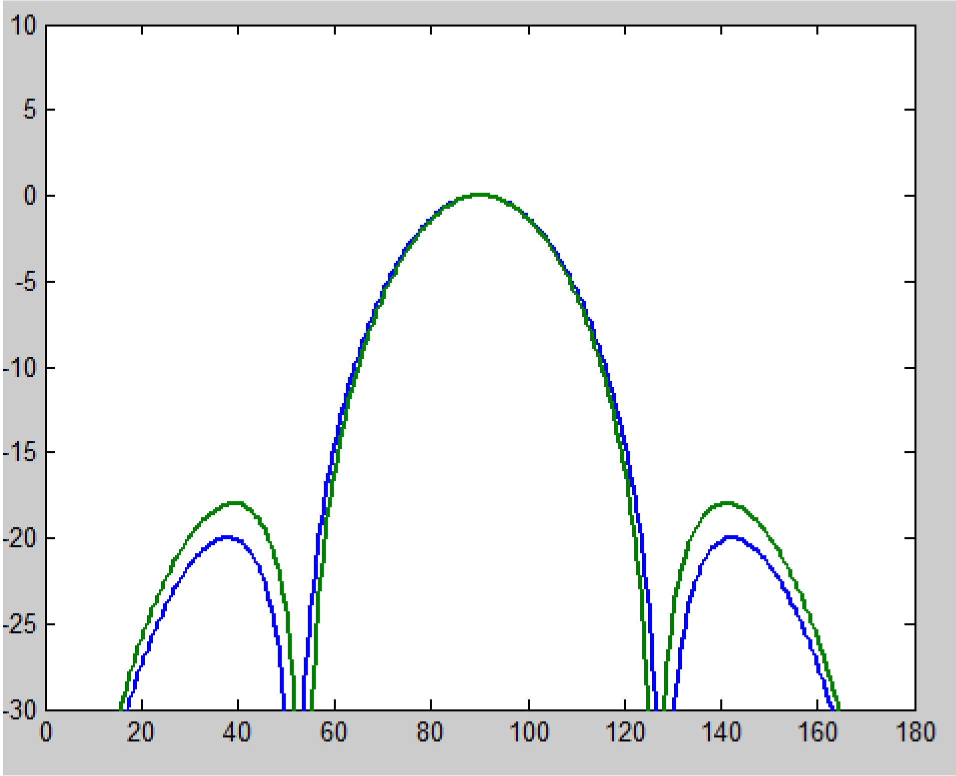


Fig 4.9: Synthesized pattern of Chebyshev & Taylor arrays

Then by using those current elements we have found the Chebyshev pattern from following Matlab programme

```
phi=0:0.01:2*pi;
shi=pi*cos(phi);
i1=[currents];
E=freqz(i1,1,shi);
polar(phi,E);
```

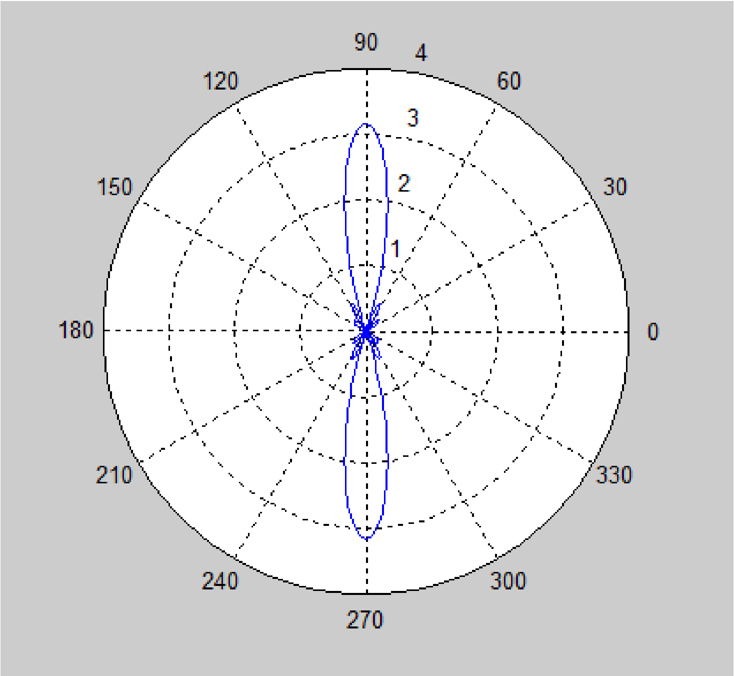


Fig 4.10: Chebyshev Array Pattern

After having that Chebyshev pattern, we multiplied the Chebyshev pattern & single element MSA pattern by using following Matlab program

```
 ko=50; h=1.524e-3; w=21e-3; d=125e-3; i1=1; i2=.5821;l=10e-3;

%x=[0, pi/6,pi/4, pi/3, pi/2,3*pi/2, pi];


 x=pi/10000:pi/1000:pi
EE= sin(x).*(((sin((ko*h/2).*sin(x))).*(sin((ko.*w/2)*cos(x))))/...
    (((ko*h/2).*sin(x)).*((ko.*w/2).*cos(x))));

AF=(2*i1*cos(((ko*d)/2).*cos(x)))+(2*i2*cos(((3*ko*d)/2).*cos(x)));
%AF1=(cos((ko*l)/2)*sin(x));



%final=EE.*AF1;
final=EE.*AF;

polar(x,AF)
polar(x,final)
polar(x,EE)
%ylim([0 2*pi])
```

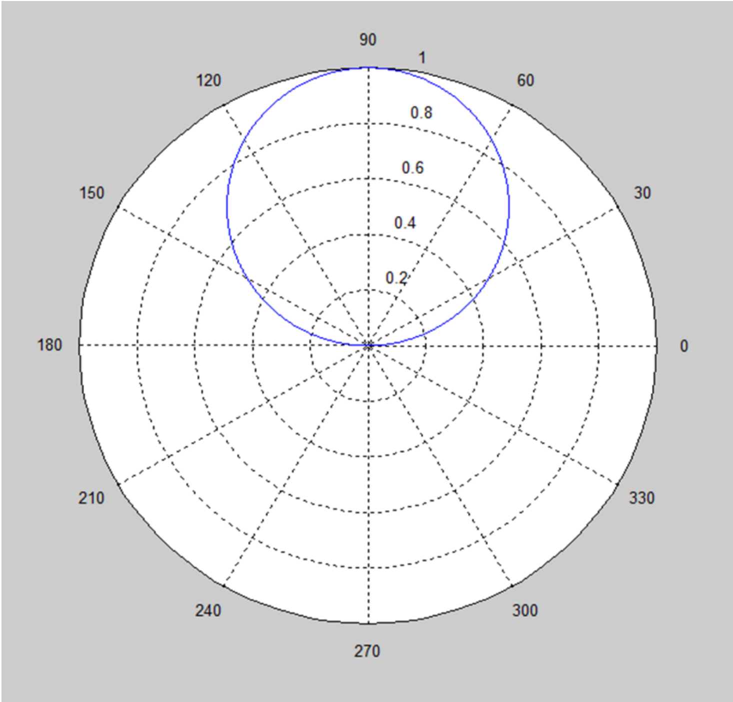


Fig 4.11: E-Plane Radiation Pattern for Single Element

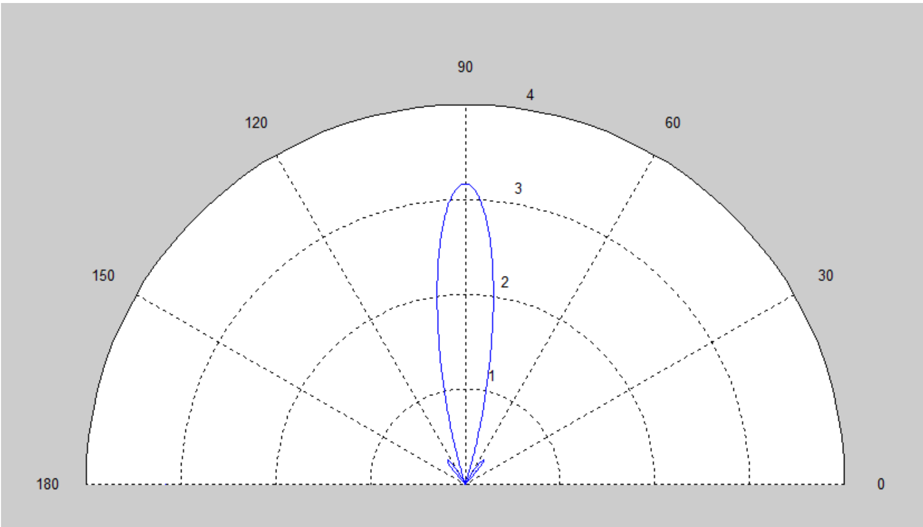


Fig 4.12: Radiation Pattern for 4 Element Array Factor

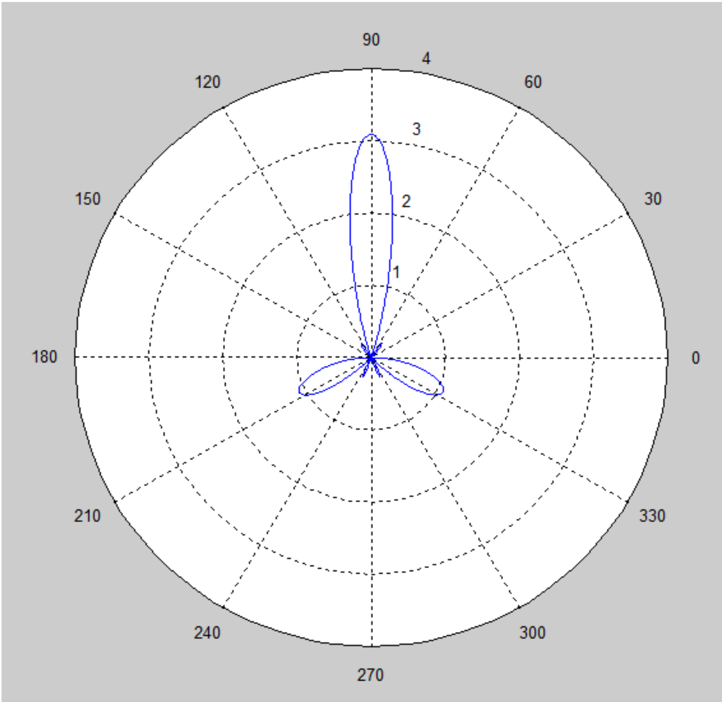


Fig 4.13: Pattern Multiplication for 4 Element Array

We have multiplied fig 4.11 & fig 4.12 and got the corresponding pattern multiplication for 4 elements array in fig 4.13

CHAPTER-5

RESULT COMPARISON

5.1 COMPARISION BETWEEN 4 ELEMENTS MSA ARRAY & 4 ELEMENT DOLPH CHEBYSHEV ARRAY

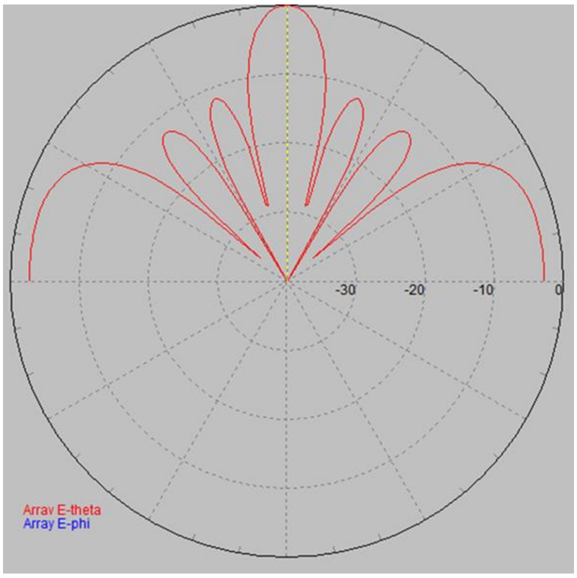


Fig 5.1: Polar pattern plot of Uniform Array

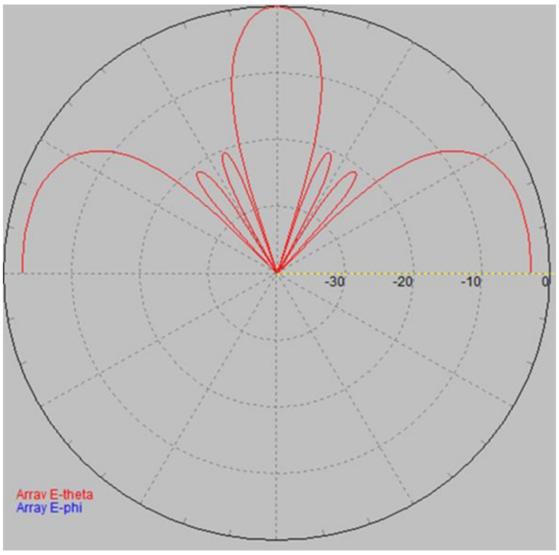


Fig 5.2: Polar pattern plot of Chebyshev Array

The fig 5.1 and 5.2 show that the side lobe level of the Chebyshev array is lesser than the side lobe level of the uniform array. So the directivity of the Chebyshev array is better than uniform array.

5.2 COMPARISION BETWEEN 4 ELEMENTS DOLPH CHEBYSHEV ARRAY & 8 ELEMENTS DOLPH CHEBYSHEV ARRAY

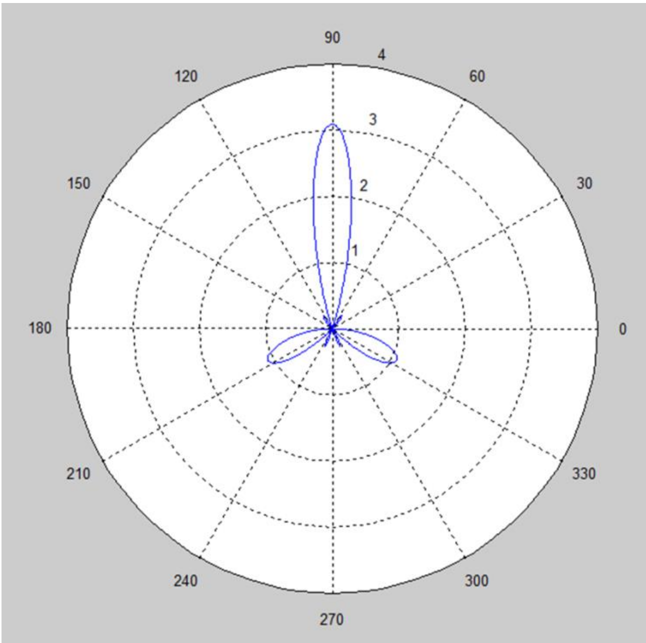


Fig 5.3: Polar pattern plot of 4 elements Chebyshev Array

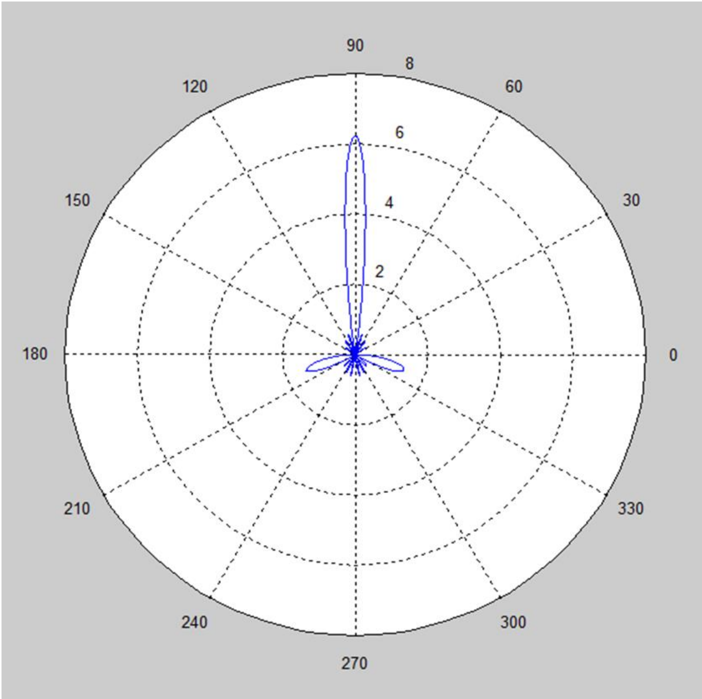


Fig 5.4: Polar pattern plot of 8 elements Chebyshev Array

Comparing between fig 5.3 and 5.4, it is convenient to say that if we increase the number of elements in array directivity increases. Hence, in fig 5.4 array radiation patterns is more directive and giving more pencil-like beam than that of fig 5.3.

CHAPTER-6

CONCLUSION

In our project, we designed the MSA array and tried to improve its directivity and performance by changing the number of elements. To synthesize the array, we used Dolph-Chebyshev method. And then compared the results of uniform and Dolph-Chebysev array.

In future, we wish to do the same by varying other parameters such as by changing the substrate, changing the element spacing, considering phase differences between the elements. MSA array antenna has narrow bandwidth but high directivity. Our vision will be improving the bandwidth by keeping the directivity fixed.

This array antenna can be applied in any cellular base station by improving it for that particular frequency band. In that case other relevant parameters such as bandwidth of the cellular network can be considered.

REFERENCES

[1] Balanis, C. (2005). Antenna Theory: Analysis and Design, 3rd Edition, Wiley and Sons, 047166782X, Hoboken, New Jersey, USA.

[2] CAD of Micrsotrip Antennas for Wireless Applications by Robert A. Sainati

[3] Broadband Microstrip Antennas by Girish Kumar & K.P. Ray

[4] Lebert, H. & Boyd, S. (1997). Antenna array pattern synthesis via convex optimization, IEEE Trans. Signal Process. , vol. 45, no. 3, pp. 526-532

[5] Ioannides, P. & Balanis, C. (2005). Uniform circular and rectangular arrays for adaptive beam forming applications, IEEE Antennas Wireless Propag. Lett. , vol.4, no., pp.351-354

[6] Simulation of a 2.4 GHz Patch Antenna using IE3D, a tutorial by Nader Behdad, EEL, 6463, Spring 2007.

[7] http://www.edaboard.com/forums.html - An online electronic discusion forum.

[8] T.R.Harris The Design Process of a Rectangular Microstrip Antenna

[9] http://www.antenna-theoy.com

[10] Elements of Electromagnetics, 3rd ed., Matthew N.O. Sadiku

[11] Norbahiah Misran, Mohammed N. Shakib, Mohammad T. Islam, and Baharudin Yatimb “DesignAnalysisof a Slotted Microstrip Antenna for Wireless Communication” World Academy of Science, Engineering and Technology 49, 2009

[12] DR. John L.Volakis, McGraw-Hill Antenna Engineering Handbook, 4th Edition

[13] http://www.en.wikipedia.org

[14] Array Synthesis, EEE 6832 by Hon Tat Hui, NUS/ECE.