A Quad-Band Frequency Reconfigurable Antenna with Shorted Stubs for Microwave Applications

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A Quad-Band Frequency Reconfigurable Antenna with Shorted Stubs for Microwave Applications

Thesis submitted to
Malaviya National Institute of Technology, Jaipur
for the award of the degree

of

Master of Technology

by

Fateh Lal Lohar

under the guidance of

Dr. Ravi Kumar Maddila

Malaviya National Institute of Technology, Jaipur

(2017)

Dedicated to

My Family

CERTIFICATE

This is to certify that the thesis entitled **A Quad-Band Frequency Reconfigurable Antenna with Shorted Stubs for Microwave Applications**, submitted by **Fateh Lal Lohar** to Malaviya National Institute of Technology, Jaipur, is a record of bonafide research work carried out under my supervision and is worthy of consideration for the award of the degree of Master of Technology of the Institute.

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DECLARATION

I certify that

1. the work contained in this thesis is original and has been done by me under the guidance of my supervisor.
2. the work has not been submitted to any other Institute for any degree or diploma.
3. I have followed the guidelines provided by the Institute in preparing the thesis.
4. whenever I have used materials (data, theoretical analysis, figures, and text) from other sources, I have given due credit to them by citing them in the text of the thesis and giving their details in the references.

Date: **Fateh Lal Lohar**

Place: 2015PEC5100

M.Tech.(ECE).

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Fateh Lal Lohar

List of Important Abbreviations

AF	array factor
AR	axial ratio
BFSK	binary phase shift keying
BWFN	beam width between the first nulls
CCW	counter clockwise
CPW	co planar waveguide
CST	computer simulation technology
CW	clockwise
E-field	electric field
EHF	extremely high frequency
ELF	extremely low frequency
FBW	fractional bandwidth
FCC	Federal Communications Commission
FPGA	field-programmable gate array
FR-4	Fire Retardant UV-94
FSS	frequency selective surface
GPS	global positioning system
GSM	global system for mobile communication
HF	high frequency
H-field	magnetic field
HPBW	half power bemwidth
LF	low frequency
MF	medium frequency
MIMO	multiple input, multiple output
MPA	microstrip patch antenna
MTA	microstrip traveling wave antenna
PLF	polarization loss factor
RADAR	radio detection and ranging

RF-MEMS	radio frequency microelectromechanical system
RFID	radio frequency identification
SHF	super high frequency
SMA	SubMiniature version A
TE	transverse electric
TEM	transverse electromagnetic
TM	transverse magnetic
UHF	ultra high frequency
UWB	ultawideband
VHF	very high frequency
VLF	very low frequency
VSWR	voltage standing wave ratio
WiMax	worldwide interoperability for microwave access
WLAN	wireless local area network

List of Important Symbols

Ae	effective area of an antenna
B	beamwidth of an antenna
β	phase constant
c	velocity of the electromagnetic wave in free space
D	directivity of the antenna or dimension of the antenna
ε_{ap}	aperture efficiency
ε_r	relative permittivity or relative dielectric constant
ε_{reff}	effective dielectric constant
η	efficiency of an antenna
f	frequency of the wave
f_r	resonant frequency
G	gain of an antenna
Γ	reflection coefficient
k	wavenumber
λ	wavelength of the wave
ω	angular frequency
$\mathscr{P}$	instantaneous total power
P_{rad}	average radiated power
Q	qualty factor of an antenna
R	distance from the antenna
θ	steering angle
U	radiation intensity
U_0	radiation intensity of an isotropic source
v	velocity of the electromagnetic wave in medium other than free space
$\mathscr{W}$	instantaneous poynting vector
Y_0	characteristic admittance

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Abstract

Reconfigurable microstrip patch antennas has been evolved in the past decade due to its numerous merits. The need of a particular communicating equipment to be more multifunctional so that it can survive in today's competiting environment, has led to the development of reconfigurable antennas. Also they are used to overcome the degradation of the quality of the received signal due to the harsh environmental conditions. Cognitive radios makes use of frequency reconfigurable antennas so as to switch to other unused radio frequency when there is no proper reception achieved at some operating frequency. So these antennas are very much useful to improve communication links also.

In this text a novel design of compact low cost quad band reconfigurable antenna with shorted stubs resulting in frequency switching capabilities, is presented. The operating frequencies of the antenna are f1=9.92 GHz, f2=14.86 GHz, f3=18.21 GHz and f4=21.20 GHz. The four resonant frequencies of the antenna lies in standard IEEE microwave bands of X band (8-12 GHz), Ku band (12-18 GHz) and K band (18-26 GHz). This antenna is a modified version of its wideband counterpart. The multiband property is obtained by the inclusion of the partial ground and rectangular cross slots in the patch. The antenna is made reconfigurable by parasitic elements with shorted pins. This antenna is switched between the resonant frequencies by the different combinations of microwave switches. The input impedance of the antenna is matched perfectly to that of the transmission line of 50 ohm for each band. This matching property is achieved by the introduction of three corner cuts in the patch. The simulated result is carried out in CST microwave studio. This type of switchable antenna can be used in different types of RADARs and Satellite applications.

In this text initially all the basics related to the antenna have been discussed, so that the reader should feel familier to all the concepts related to antenna. Next the theory related to Microstrip Patch antennas followed by Reconfigurable antennas are discussed. Then the stepwise design procedure covering all the design related issues of the project has been discussed in detail with related simulated results. At the end, the text has some concluding remarks with some discussion on scope of future work.
Key Words - Quad Band, Reconfigurable, microstrip patch antenna, X, Ku and K band, parasitic elements, partial ground, corner cuts.

Contents

CHAPTER 1

Fundamentals of Antenna

1.1 Definition of an Antenna

"A *radio antenna* may be defined as the structure associated with the region of transition between a guided wave and a free space wave or vice versa." [41].

In connection with this definition it is also useful to consider what is meant by the *transmission line* and *resonator*.

"A *transmission line* is a device which is used for transmitting or guideing radio frequency energy from one point to another." While the transmisssion of the signal takes place it is necessary that it should suffer from minimum attenuation and heat losses. This means that while coveying the energy, transmission line acts as a guiding medium where the enrgy is bounded closely to it.

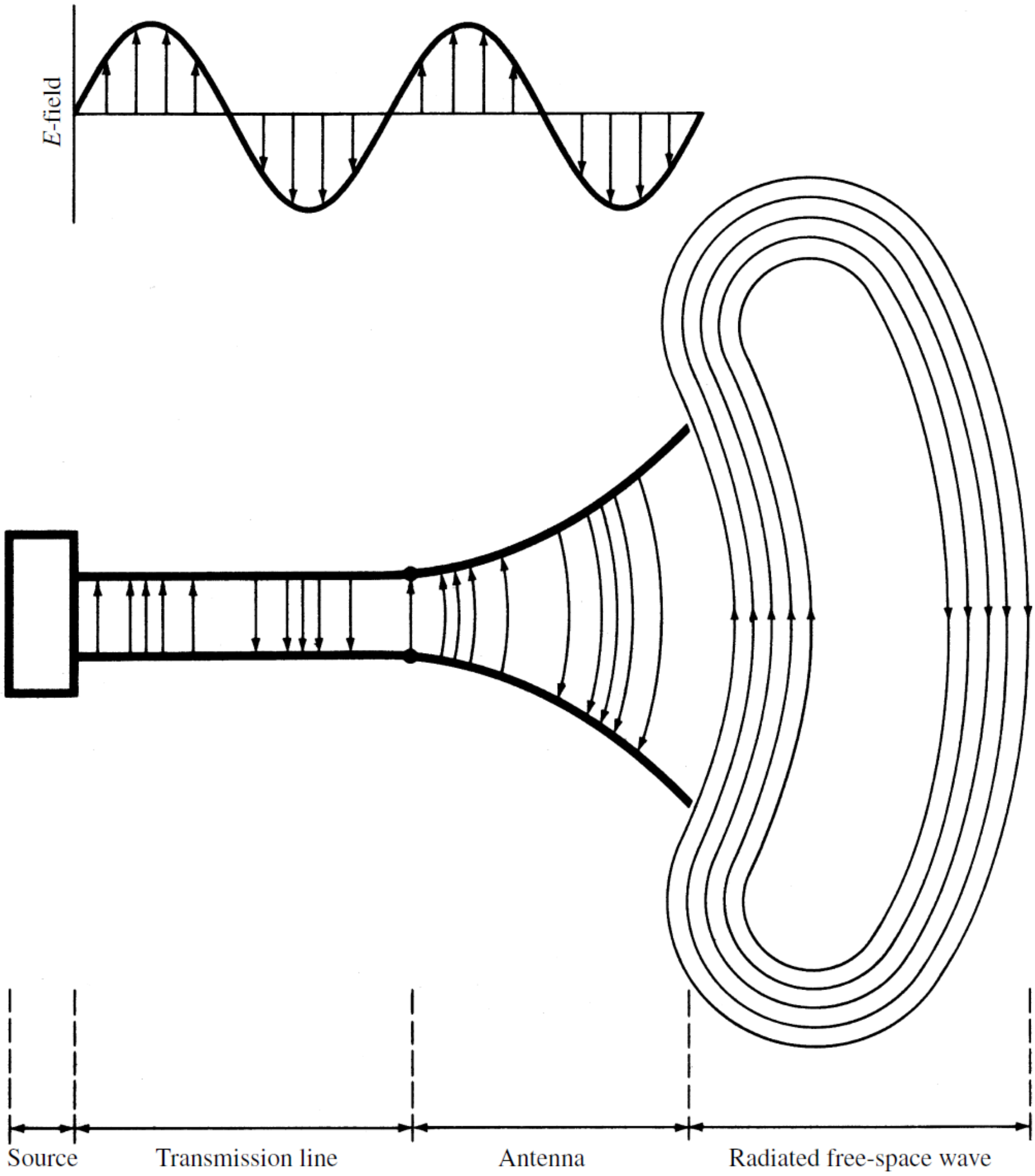


Figure 1.1: Transition region between guided wave and free space wave.

An infinite, lossless transmission line when connected with a generator consist of a uniform travelling wave along the length of the line. If the line is short circuited, the outgoing travelling wave is reflected, standing wave gets produced on the line due to the outgoing and the reflected waves interference. A standing wave consist of a local concentrations of energy. A pure standing wave gets created if the reflected wave is equal to the outgoing wave. The energy concentrations in such a wave oscillates from entirely electric to entirely magnetic and back twice per cycle. Such energy behaviour is a characteristics of a resonant circuit, or we can term it as *resonator*. Although the term resonator, may be applied to any device with standing waves, the term is usually reserved for device with stored energy concentrations that are large compared with the net flow of energy per cycle. Where there is only an outer conductor, as in a short circuited section of waveguide, the device is called a *cavity resonator*.

"Thus the antenna *radiates energy or receives energy*, transmission lines *guide energy*, while resonators *stores energy*".

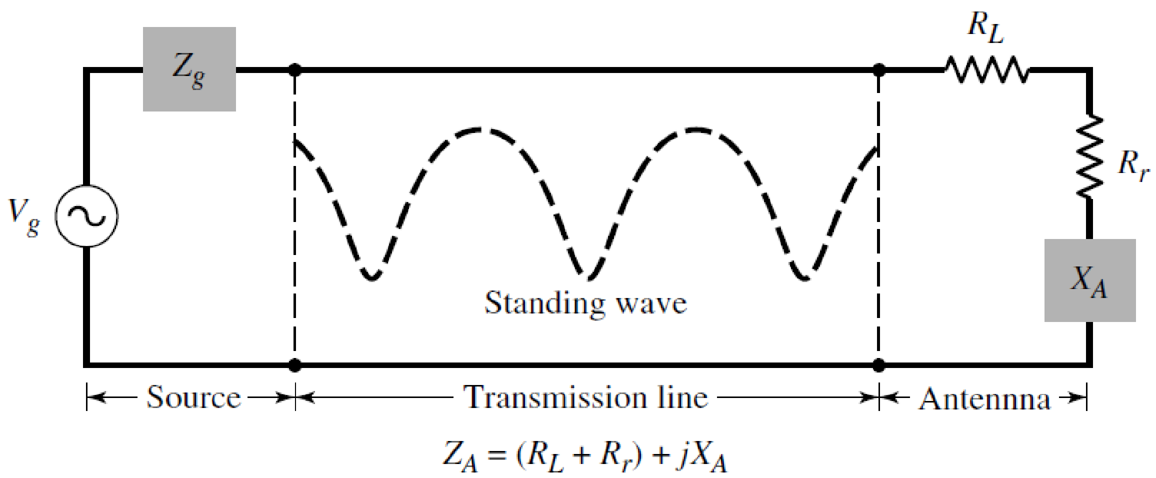


Figure 1.2: Transmission-line equivalent of antenna in transmitting mode.

A guided wave travelling along a transmission line which opens out, as in Figure 1.1, will radiate as a free space wave. The guided wave is in the form of plane wave while the free space wave is a spherically expanded kind of wave. Along the uniform part of the line, the energy is guided as a plane wave with little attenuation, provided the spacing between the conducting wires is a small fraction of a wavelength.

At the right, as the separation of the transmission line approaches a wavelength or more, the wave tends to be radiated so that the opened out line acts as a antenna which launches a free space wave. The current on the transmission line flow out on the transmission line and end there, but the associated fields keep on going.

To be more explicit,“the region of transmission between the guided wave and the free space wave may be defined as an *antenna*.”

As a receiving device the definition is completely reciprocal. Thus an antenna is the region of transition between a free space wave and a guided wave. Thus, “*an antenna is a transition device, or transducer, between guided wave and a free space wave, or vice versa*.”

While transmission lines are usually designed so as to minimize radiation, antennas are designed to radiate energy as efficiently as possible. Consider a transmission line connected to a dipole antenna which is shown in Figure1.3. The dipole is reffered as an antenna because it launches a free space wave. However, it may also be considered as a section of an open ended transmission line. In addition, it exhibits many similar characteristics as of a resonator, since energy reflected from the ends of the dipole gives rise to a standing wave and energy storage near the antenna. Thus a single device in this case the dipole, exhibits simultaneously properties characteristics of an *antenna, transmission line* and *a resonator*.

The antenna can be alternatively defined as “*a transformer (or matching section) between a two input terminals and space (in transmitting case) or is a transformer between space and the input terminals of receiver (in the receiving case)*.”

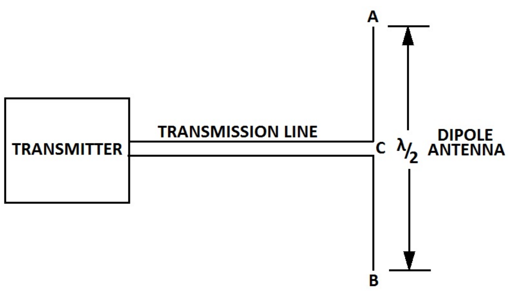


Figure 1.3: Transmission line between a transmitter and a dipole antenna.

1.2 General Classification of Antenna Types

The typical antenna classification can be observed from the Figure 1.4. The Standard Antennas comprises of fixed frequency and radiation properties. Examples of this type of antennas are standard dipole or monopole antennas, whose radiation characteristic is defined by specific and fixed type of current distribution.

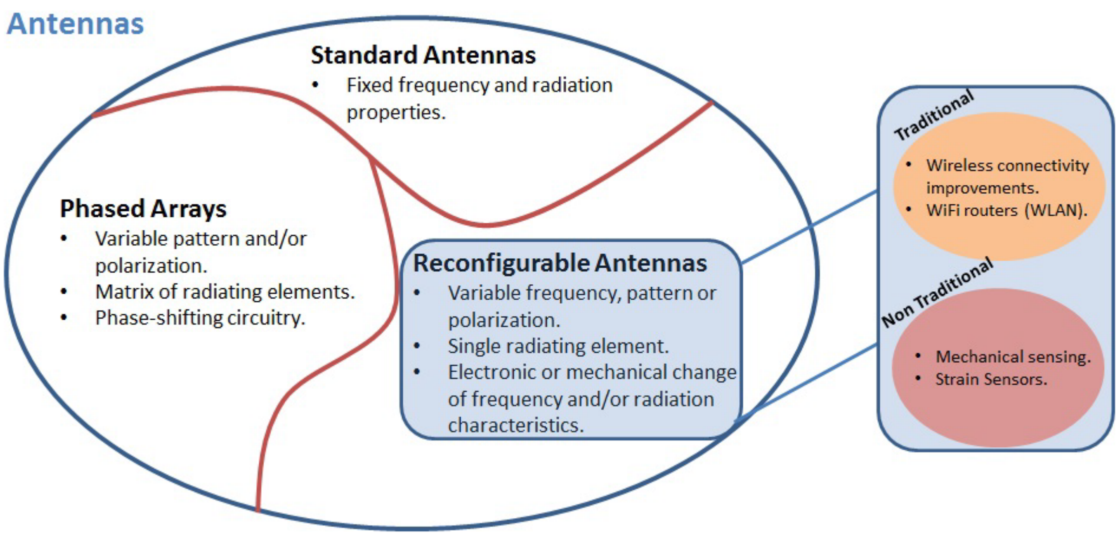


Figure 1.4: Antenna Classification.

Adaptive antennas can be divided into two basic types: *phased arrays* and *reconfigurable antennas*. Phased arrays requires a cascade of multiple elements and five types of controls can be used to change the radiation pattern:

1. Geometrical configuration of the overall array (linear, circular, rectangular, spherical,etc.)
2. Distance between the elements
3. Amplitude excitation of each element
4. Phase excitation of each element
5. Relative pattern of each element

The total field of an antenna array can be seen as the field of a single element, multiplied by a factor which is called the *array factor*. The array factor is a function of the geometry of the array and the excitation phase. The normalized array factor is given by:

$$AF = cos\left[\frac{1}{2}(kdcos\theta + \beta\right] \tag{1.1}$$

where k is the wavenumber, d is the distance between each antenna element, θ is the steering angle, and β is the phase shift between the antenna elements. The total field of an array of identical elements is equal to the product of the field of a single element and the array factor of that array:

$$\boxed{E(total) = [E(single\ element)] \times [arrayfactor]} \tag{1.2}$$

This is known as *pattern multiplication of arrays of identical elements*. Phased arrays are characterized by large form factors. They require phase shifting circuitry to steer the directional beam so as to provide the necessary phase. On the other hand, reconfigurable antennas comprises of a single radiating element, capable of generating different patterns or polarizations. The reconfigurable antenna solution is generally preferable with respect to a phased array antenna because:

i) it employs a single active element, thus occupying a smaller space and

ii) it allows for high radiation efficiency as it avoids the use of phase shifters and power dividers.

Generally the reconfigurable antennas are divided into two main classes depending upon their reconfigurable outputs.

1)***Frequency reconfigurable antennas***: These are the antennas which are able to adapt their resonant frequency based on the desired operational frequency, so as to reduce the use of multiple antennas for different applications.

2)***Pattern-reconfigurable antennas***: These are the antennas which can change their radiation pattern or state of polarization in order to enhance the capacity of the wireless communication channel.

By changing the current distribution on the metallic surface elements with the help of switches or reactive components such as PIN diodes or varactor diodes or by stretching a flexible design, the reconfigurability is achieved. Different types of reconfigurable antennas have been proposed which are capable of changing pattern and polarization state. These antennas may employ switches or variable capacitors to change the distribution of current on the metalic surface of the active element; or may employ an active antenna element surrounded by passive elements (i.e., parasitic elements) loaded with variable capacitors or connected to switches. Furthermore, these classes of reconfigurable antennas have been used for different purposes. The traditional electrically reconfigurable antennas find variety of applications for throughput maximization within WiFi routers and other WLAN devices, whereas stretchable antennas are used as frequency-reconfigurable antennas in the field of mechanical sensing, such as crack detection and other strain sensing.

1.3 Organization of the Thesis

The thesis is organised in nine chapters

Chapter 2: This chapter basically discus the important parameters of antennas. The reader must be aware of these parameters first before understanding the main operation the proposed antenna. It consist of some important derivations and formulaes associated with the basic antenna. It usually deals with some standard notations referred in many books by international authors. After reading this chapter the reader will get familiar with the important aspects of the antenna.

Chapter 3: It basically emphasizes on the introduction of microstrip patch antennas. In this section some mathematical techniques such as transmission line model and cavity model is discussed which forms the base for the analysis of the rectangular patch antenna. At the end the chapter ends with the advantages, disadvantages and applications of the patch antennas. It also deals with the introduction of the reconfigurable antennas, its types and classifications. It also consists of some practical examples carried out by the researchers. It deals with the merits and demerits of the reconfigurable antennas at the end with the application discussions.

Chapter 4: The most basic step of the design of my project was to enhance the bandwidth of the antenna. For this to understand, some bandwidth enhancement techniques have been discussed in this section. Out of these techniques the partial grounding technique is adopted for the enhancement of the bandwidth of the antenna.

Chapter 5: For here onwards the discussion on the project is started. It emphasizes on the design of the wideband antenna. Initially it was designed as a 6 GHz antenna. Then its bandwidth is enhanced by using partial ground concept.

Chapter 6: This session discusses the technique employed for the conversion of wideband antenna to the multiband antenna operating in four bands. Step wise analysis is discussed as how the notches are obtained in between the operating bands, thus having complete isolation between the adjacent bands for the antenna to operate at a particular band without any interference from the adjacent bands.

Chapter 7: It discusses the operation of the antenna in the reconfigurable mode. The operation for all the four bands has been discussed with the help of the equivalent circuits and the related derivations. It also discusses in short about the alternative design of the quad band reconfigurable antenna, which shows similar characteristics as of the previous one.

Chapter 8: It deals with the concluding remarks and the further improvement in the existing design of the antenna.

CHAPTER 2

Basic antenna parameters

Discussion on certain parameters are necessary to describe the performance of an antenna. Some of the parameters are interrelated and sometimes confusing. The other parameters also exist, but are not discussed here as they are beyond the scope of this text.

2.1 Radiation Pattern

The radiated energy from the radiator is not at all same in all the directions. It is different in some directions. The radiator radiates more in some direction and and lesser in other directions. The energy emiited by the radiator is measured in the form of Field strength of the antenna.

The radition patern of the test antenna can then be stated as the polar graph showing the field strength in all the direction at a same distance from the antenna. The points or magnitude of the field strength is calculated in all the direction and is ploted in polar plot. Thus the graph plotted will be a three dimentional figure. But this is shown in two dimensional in many textbooks hoping the reader can visualise in 3D.

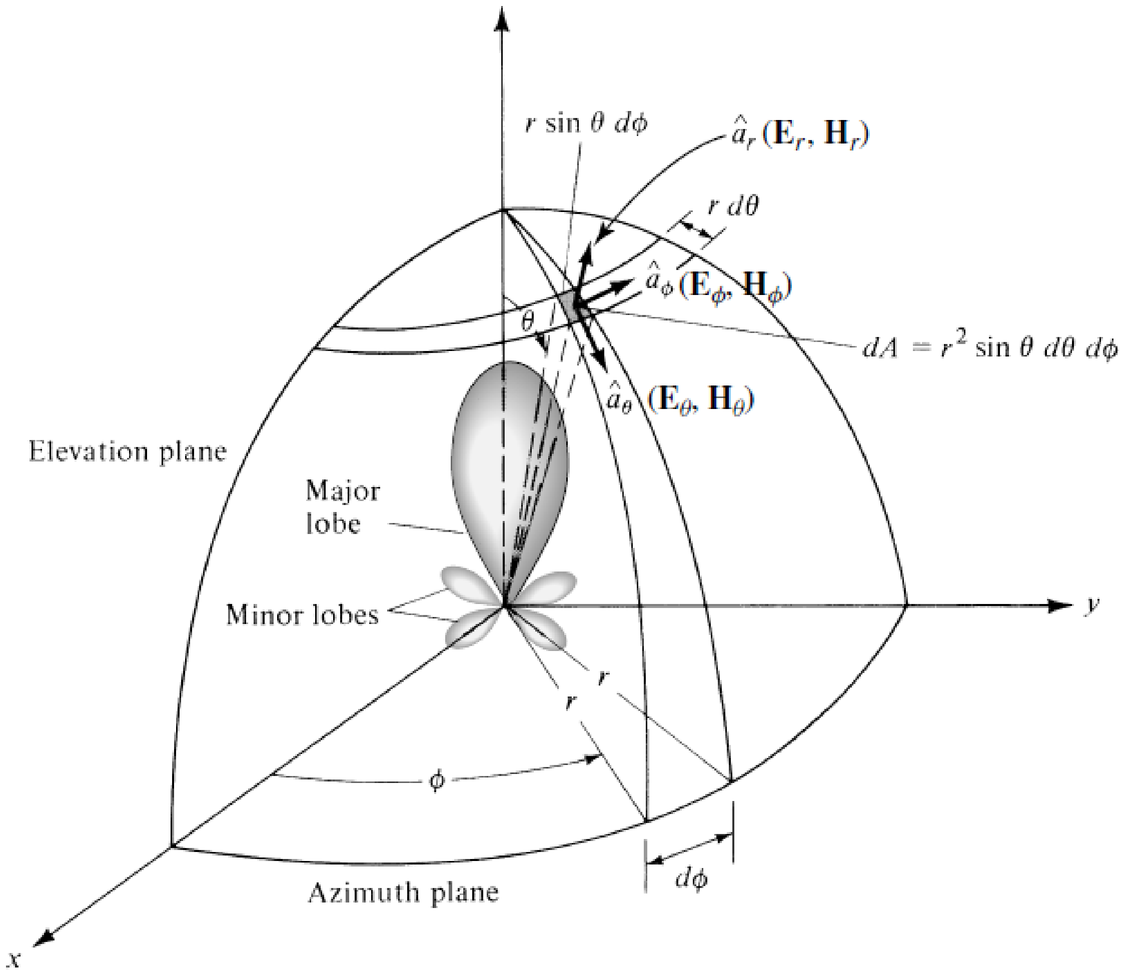


Figure 2.1: Coordinate system for antenna analysis.

Or in other wirds the three dimensional figure obtained is sliced from the centre of the figure especially a centre of sphere to indicate the radiation pattern. So if the three dimensional figure is sliced in horizonatal planes or in vertical plane, these patterns are called as *Horizontal pattern or Vertical pattern.*

The radiation patterns differs from antenna to antenna. Thus finally the radiation pattrern is again defined as "the graphical representation of the radiation characteristics of the antenna in three dimensional co-ordinates shown in Figure 2.1". In nearly all the cases the pattern is calculated in the far field region of the antenna.

A locus or polar plot of the received power is at a constant spherical distance is known as *power pattern*. Whereas the plot of the electric and magnetic field is called the *field pattern*. The point at which the field achieves the half of the maximum power is called the *Half power points* and the associated beamwidth is known as *Half power beam width(HPBW)*.

2.2 Radiation Pattern Lobes

The radiation pattern of a particular antenna is divided into several small patterns. These different patterns are referred as a *Lobes* of an antenna. These are usually separated by the weak radiation intensity of the antenna. Any antenna may consist of more than one lobes in any case. There are different nomenclature given to such types of lobes.

Major lobe: It is the lobe directed in the direction of maximum radiation. It is aligned in the direction in which maximum power is to be transferred or received.

Minor Lobe: These are the lobes excluding the major lobes having relatively smaller field intensities. It may be single or may be more than one.

Side lobe: It is associated with the direction. It should not be confused with the minor lobes. These are the lobes which are directed anywhere except the main beam direction.

Back Lobe: It is a single lobe which positioned exactly in opposite direction as that of the manor lobe. It should be as small as possible for directive antennas. These all can be observed from Figure2.2.

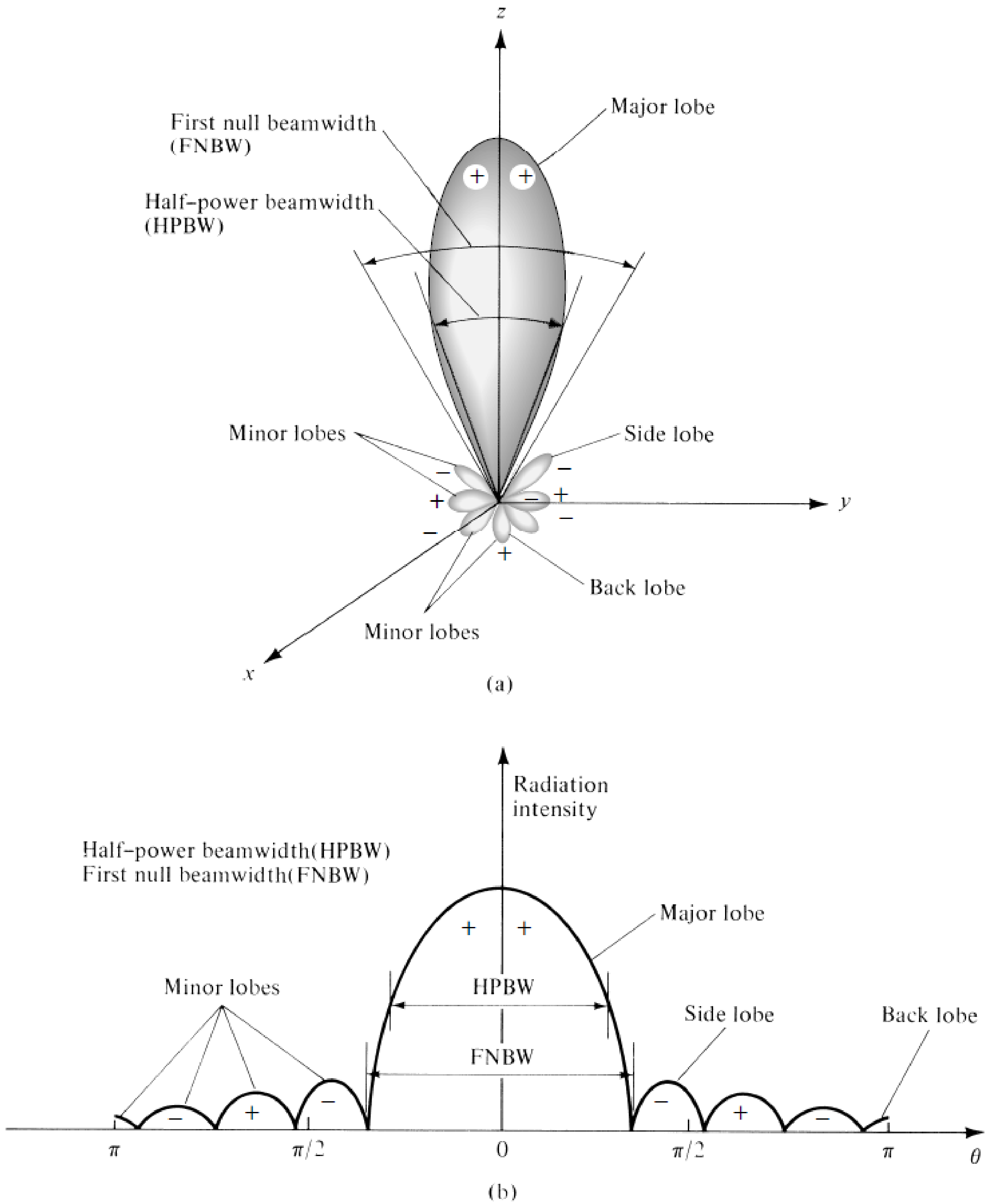


Figure 2.2: Radiation lobes and beamwidths of an antenna pattern

2.3 Isotropic, Directional, and Omnidirectional Patterns

1. ***Isotropic pattern***: These are the pattern which are practically no where available. It is usually a hypothetical case and is only exist in theory. These are the pattern radiated by the antenna in all the directions. The radiation pattern of these types of antennas will be in a shape of a sphere. These patterns are generally used as a standard patterns. It is used to calculate the associated gain, directivity of a particular antenna.

2. ***Omnidirectional pattern***: It may exist in real case with some exceptions. These are the patters radiated by the antennas in all the direction in a particular plane. Here it is a mention of a plane which makes it different from the Isotropic ones. The radiation pattern comprise of circular disc type of shape but not a sphere.

3. ***Directional pattern***: These are practically available. Antennas which shows directive property or the antennas which radiates maximum in particular direction has these types of pattern. The pattern looks like a long balloon oriented in the direction of radiation. The antennas of these types are parabolic reflectors, horn antennas, etc. The horn antennas and the associated emitted beam is shown in Figure 2.3.

2.4 Principal Patterns

In general the antenna radiation properties is usually expressed in termas of E-plane and H-palne patterns. In case of antenna having the linear polarisation properties, the E-field pattern is the electric field plane pattern of maximum radiation and the H-field pattern is the magnetic field plane pattern of maximum radiation. In most cases the orientation of the antenna is so adjusted to obtain at least one plane pattern which will be able to coincide with the “geometric principal planes”. Figure2.4

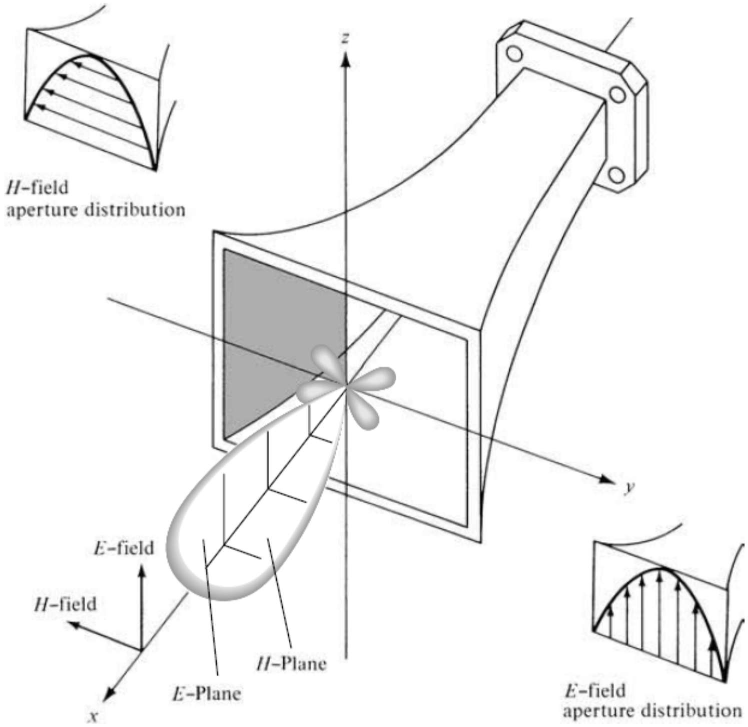


Figure 2.3: Principal E-and H-plane patterns for a pyramidal horn antenna.

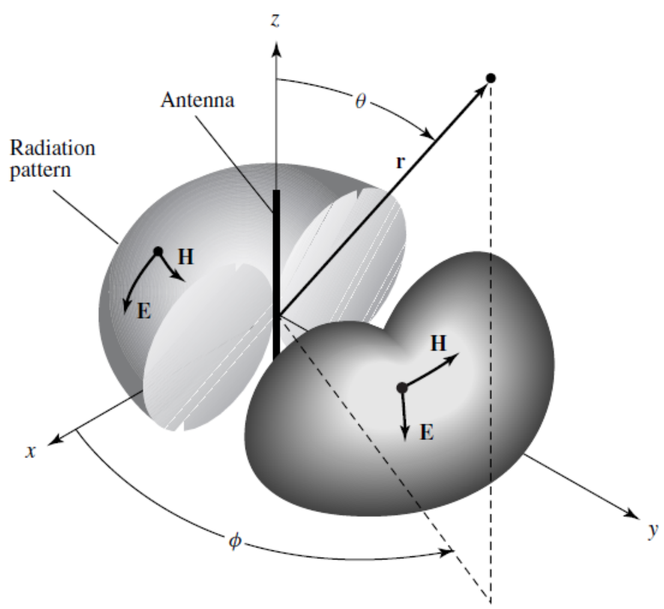


Figure 2.4: Omnidirectional antenna pattern.

2.5 Field Regions

The three dimensional space around the antenna can be bifurcated in three different categories.

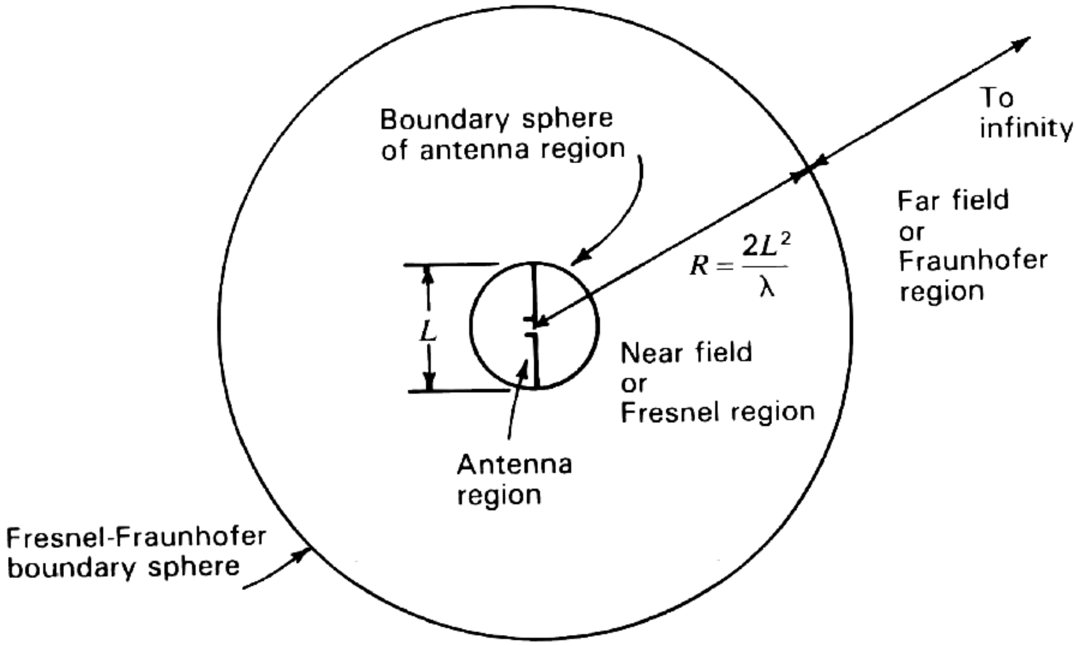


Figure 2.5: Field regions of an antenna.

1. ***Reactive near-field***: It is defined as the area or space around the antenna in which the amount of reactive field is comparably larger than the other fields. It exist at a distance very close to the physical antenna.It is at a distance of approximately R<$0.62\sqrt{D^3/\lambda}$ from the antenna.

2. ***Radiating near field or the well known Fresnel region***: It is the field away from the antenna in which the radiation field percentage is more. Here the distribution of the field is totally depended on the distance from the antenna where this field is measured. It exist in between $R \geq 0.62\sqrt{D^3/\lambda}$ and $R < 2D^2/\lambda$.

3. ***Far field region or well known Fraunhofer region***: As the name suggest, it is the field far away from the antenna. In these field the distribution of the field is totally independent of the distance from the antenna where this field is measured. The region beyond $2D^2/\lambda$ is actually a Far field region.

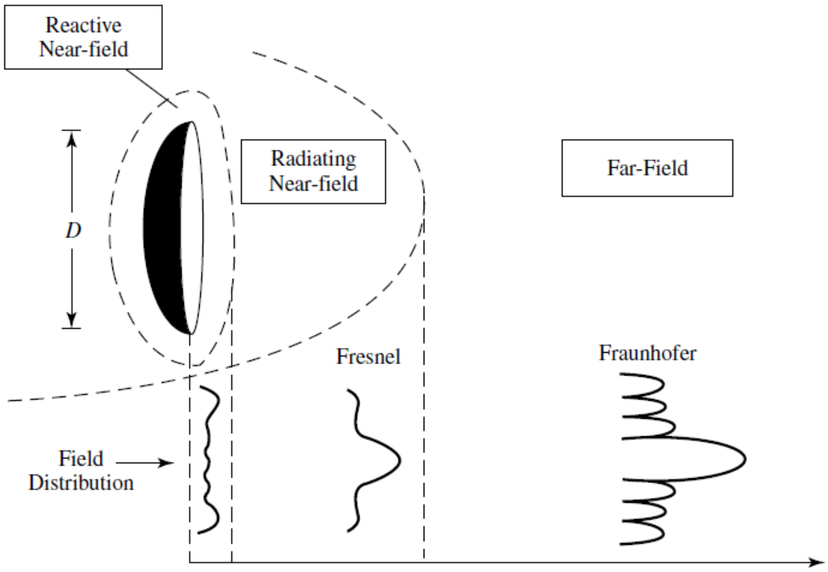


Figure 2.6: Typical changes of antenna amplitude pattern shape

The Figure2.5 clearly indicates the three different types of field regions.
The variation of the amplitude pattern of the antenna at three different field regions is shown in the Figure2.6. We can observe, as the field starts to radiate from the antenna, it is nearly uniform and the major, minor lobes are undistinguishable. But as the filed progresses from near to far, slowly the lobes starts forming and the major lobe can be easily determined.

2.6 Radiation Power Density

The analysis of the electromagnetic wave emitted by the radiating element, can be easily carried out by first knowing the associated power within it. With the help of Poynting Vector we can calculate the associated power of the electromagnetic wave. It is given by,

$$\mathscr{W} = \mathscr{E} \times \mathscr{H} \tag{2.1}$$

$\mathscr{W}$ = instantaneous Poynting vector (W/m^2)

$\mathscr{E}$ = instantaneous electric-field intensity (V/m)

$\mathscr{H}$= instantaneous magnetic-field intensity (A/m)

If the power crossing a particular closed surface is to be calculated, then we make use of contour integration in which the normal component of the vector is integrated over closed surface. It is given by,

$$\mathscr{P} = \oiint \mathscr{W}.\mathrm{ds} = \oiint \mathscr{W}.\hat{n}\mathrm{da} \tag{2.2}$$

$\mathscr{P}$= instantaneous total power (W)

$\hat{n}$= unit vector normal to the surface

da= infinitesimal area of the closed surface (m^2)

Average power density is need to be calculated for the pupose of time varying field analysis. Since it is an average, it is calculated by integrating the pointing vector and dividing by the period. Thus the complex $\mathscr{E}$ and $\mathscr{H}$ field are related to E and H by

$$\mathscr{E}(x,y,z;t) = Re[E(x,y,z)e^{j\omega t}] \tag{2.3}$$

$$\mathscr{H}(x,y,z;t) = Re[H(x,y,z)e^{j\omega t}] \tag{2.4}$$

Using the definitions of Equation2.3 and 2.4 the identity $Re[Ee^{j\omega t}] = \frac{1}{2}[Ee^{j\omega t} + E^{*}e^{j\omega t}]$, Equation2.1 can be written as

$$\mathscr{W} = \mathscr{E} \times \mathscr{H} = \frac{1}{2}Re[E \times H^{*}] + \frac{1}{2}Re[E \times He^{j2\omega t}] \tag{2.5}$$

We can observe that the first term is independent of time, whereas the second term depends on twice the frequency. Thus the average pointing vector is given by

$$W_{av}(x,y,z) = [\mathscr{W}(x,y,z;t)]_{av} = \frac{1}{2}Re[E \times H^*](W/m^2) \tag{2.6}$$

The E and H filed is representing the peak values that's why the term $\frac{1}{2}$ is coming in the eq. is should be noted that this $\frac{1}{2}$ can be omitted in case of RMS value calculatons. We should emphasize on $(E \times H^*)/2$ component. The real part of it represents the average power density and the imaginary part is representing the stored power density of electromagnetic fields. However in the far field region the power density of the EM wave is referred as radiation intensity [39]. Thus by Equation 2.6 the average power radiated is given by

$$\boxed{P_{rad} = P_{av} = \oiint W_{rad}.\text{ds} = \oiint W_{av}.\hat{n}\text{da} = \frac{1}{2}\oiint Re(E \times H^*).\text{da}} \tag{2.7}$$

2.7 Radiation Intensity

The famous definition of the radiaton intensity is given by the many authors as “Power radiated by the antenna per unit solid angle.” It is the parameter which is independent of the distance from the antenna. It is denoted by U . Here the solid angle is given by

$$\boxed{U = r^2 W_{rad}} \tag{2.8}$$

where

U=radiation intensity (W/unit solid angle)

W_{rad}= radiation density (W/m^2)

The total power is obtained by integrating the radiation intensity, as given by Eq.2.8, over the entire solid angle of 4π. Thus

$$P_{rad} = \oiint_{\Omega} U.\text{d}\Omega = \int_0^{2\pi}\int_0^{\pi} U sin(\theta)\text{d}\theta\text{d}\phi \tag{2.9}$$

where dΩ = element of solid angle = $sin(\theta)d(\theta)d(\phi)$.

For anisotropic source U will be independent of the angles θ and ϕ, as was the case for

W_{rad}. Thus (2-13) can be written as

$$P_{rad} = \oiint_{\Omega} U_0 \mathrm{d}\Omega = U_0 \oiint_{\Omega} \mathrm{d}\Omega = 4\pi U_0 \tag{2.10}$$

or the radiation intensity of an isotropic source as

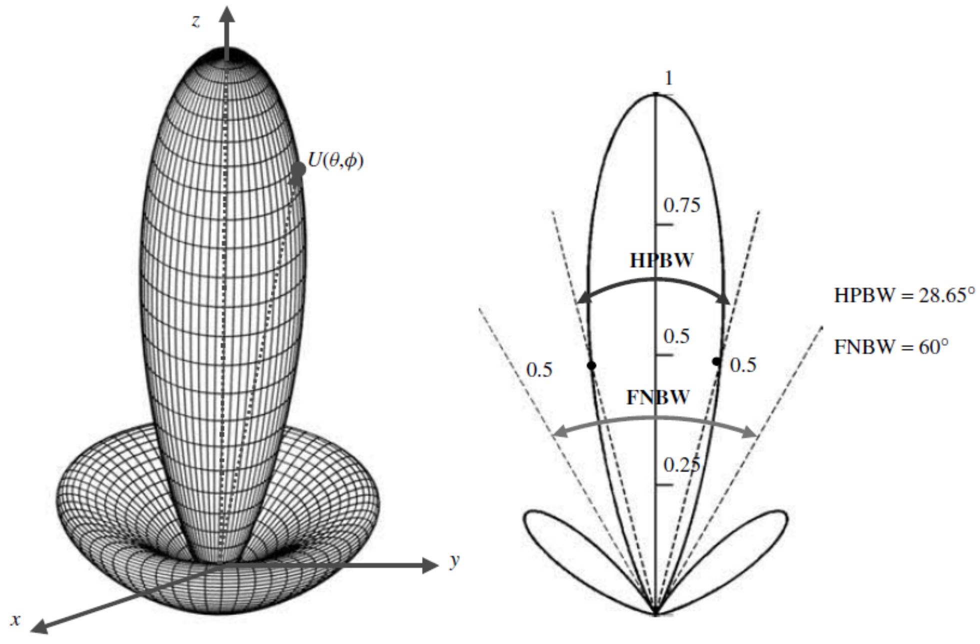
$$\boxed{U_0 = \frac{P_{rad}}{4\pi}} \tag{2.11}$$

2.8 Beamwidth

It is basically used to determine the directive properties of the antenna. The beam width of the antenna is defined as "*the angular distance between the points where the radiated power is half as compared to its maximum value*" or in another way "*it is the angular separation of the points on either side of the maximum value where the power is half of its maximum value.*" It is also called *beamwidth between half power points* or directly *Half power beam widthv(HPBW)*. In some applications the beamwidth is defined by considering the nulls in the radiation pattern. It is generally reffered as Beamwidth between the first null or BWFN which is the angular separation between the first nulls from the main lobe.
The beamwidth of a particular antenna depends on the following factors:

1) Radiation pattern shape
2) Wavelength
3) Dimension of a particular test antenna.

Usefulness of antenna beamwidth in practical applications: If the antenna having the narrower beamwidth is used at the receiving side, it will give perfect results of, from where the signal is coming from the transmitter. As the beam is very narrow it can find the direction where the transmitter is located. If the angle is slightly deviated the considerable changes is obtained at the output of the receiver.



(a) Three dimensional (b) Two-dimensional

Figure 2.7: Three-and two-dimensional power patterns.

Thus we can state the relation between the directivity and the beamwidth as

$$D = \frac{4\pi}{\Omega} = \frac{4\pi}{B} \tag{2.12}$$

$$D \propto \frac{1}{Beamwidth} \tag{2.13}$$

Thus *the sharper the pattern the higher the gain or directivity*. This property is very much usefull in RADAR applications for detecting an echo from a particular target. Conical scanning makes use of such narrow beams.

2.9 Directivity

The directivity of an antenna is nothing but the ratio of radiation intensity of the antenna under test and the radiation intensity of a standard isotropic antenna used as a reference.

$$\boxed{D = \frac{U}{U_0} = \frac{4\pi U}{P_{rad}}} \tag{2.14}$$

If the direction is not known or not stated, then it is convenient to take it as a direction of maximum radiation. In other words the maximum directivity is given by

$$\boxed{D_{max} = D_0 = \frac{U_{max}}{U_0} = \frac{4\pi U_{max}}{P_{rad}}} \tag{2.15}$$

where

D= directivity (dimensionless)

D_0= maximum directivity (dimensionless)

U= radiation intensity (W/unit solid angle)

U_{max}= maximum radiation intensity (W/unit solid angle)

U_0= radiation intensity of isotropic source (W/unit solid angle)

P_{rad}= total radiated power (W)

Directivity of the subject or test antenna can be referred as a how effectively that antenna is able to concentrate power into a limited solid angle.

2.10 Antenna Efficiency

The efficiency of the antenna can be well defined as "*the ratio of total power radiated by the antenna to the power supplied to a particular antenna.*"

$$\boxed{\text{Antenna Efficiency } (\eta) = \frac{RadiatedPower}{InputPower}} \tag{2.16}$$

Let I be the current flowing in the antenna, then

$$\eta = \frac{I^2 R_r}{I^2(R_r + R_l)} \tag{2.17}$$

$$\%\eta = \frac{R_r}{R_r + R_l} \times 100 \tag{2.18}$$

where,

R_r is the radiation resistance,

R_l is the resistance associated with the losses.

It is usually an indirect estimation of how well the antenna is working. It is associated with the losses at the input side and also the losses in the physical antenna structure. The total antenna efficiency η_0 is used to take into account losses at the input terminals and within the structure of the antenna. Such losses may be due to

1. reflections because of the mismatch between the transmission line and the antenna
2. I^2R losses (conduction and dielectric).

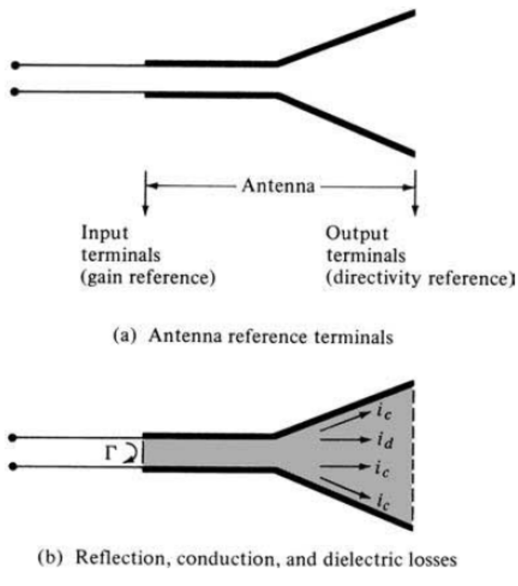


Figure 2.8: Reference terminals and losses of an antenna.

In general, the overall efficiency can be written as

$$\boxed{\eta_0 = \eta_r \eta_c \eta_d} \tag{2.19}$$

where

η_0 = total efficiency (dimensionless)

η_r = reflection(mismatch) efficiency = $(1-|\Gamma|^2)$ (dimensionless)

η_c = conduction efficiency (dimensionless)

η_d = dielectric efficiency (dimensionless)

Γ= voltage reflection coefficient at the input terminals of the antenna

$\Gamma = \frac{Z_{in}-Z_0}{Z_{in}+Z_0}$ where Z_{in} = antenna input impedance Z_0=characteristic impedance of the transmission line

VSWR = voltage standing wave ratio $= \frac{1+|\Gamma|}{1-|\Gamma|}$

Usually η_c and η_d are very difficult to compute, but they can be determined experimentally. Even by measurements they cannot be separated, and it is usually more convenient to write Eq.2.19 as

$$\boxed{\eta_0 = \eta_r \eta_{cd} = \eta_{cd}(1-|\Gamma|^2)} \tag{2.20}$$

where $\eta_{cd} = \eta_c \eta_d$ = antenna radiation efficiency, which is used to relate the gain and directivity.

2.11 Gain

Gain of an antenna is sometimes referred as a *figure of merit* of a antenna. The property of the antenna to concentrate the entire power radiated in a given or desired direction or in the receiving case the ability to absorb power efficiently from a desired direction is known as the *gain* of the antenna. Mathematically it is "*the ratio of maximum radiation intensity of the antenna under test to the maximum radiation intensity from reference antenna applying the same input power*". The radiation intensity of the isotropic antenna which here in this case acts as a reference antenna is nothing but the power accepted divided by 4π. Although the definition is similar to that of the directivity, it takes into consideration the efficiency of the antenna along with it directional properties.

The relative gain is another concept which generally used in many areas and is given as the ratio of power gain in a specified direction to the power gain of the reference antenna in the direction which is referred. If the antenna is 100% perfect i.e it does not have any losses such as I^2R, ohmic mismatch in dielectric, then the directivity and the gain can be used interchangeably.

$$\boxed{Gain = 4\pi \frac{radiation\ intensity}{total\ input\ power} = 4\pi \frac{U(\theta,\phi)}{P_{in}}} \tag{2.21}$$

In most cases we deal with *relative gain*, which is defined as "the ratio of the power gain in a given direction to the power gain of a reference antenna in its referenced direction." Thus

$$\boxed{G = \frac{4\pi U(\theta,\phi)}{P_{in}\, lossless\ isotropic\ source}} \tag{2.22}$$

When the direction is not stated, the power gain is usually taken in the direction of maximum radiation. We can write that the total radiated power (P_{rad}) is related to the total input power (P_{in}) by

$$P_{rad} = \eta_{cd} P_{in} \tag{2.23}$$

Using Eq.2.23 reduces Eq.2.22) to

$$G(\theta,\phi) = \eta_{cd}\left[4\pi \frac{U(\theta,\phi)}{P_{rad}}\right] \tag{2.24}$$

which is related to the directivity of Eq. 2.14 by

$$\boxed{G(\theta,\phi) = \eta_{cd} D(\theta,\phi)} \tag{2.25}$$

In a similar manner, the maximum value of the gain is related to the maximum directivity of Eq.2.15 by

$$\boxed{G_0 = G(\theta,\phi)|_{max} = \eta_{cd} D(\theta,\phi)|_{max} = \eta_{cd} D_0} \tag{2.26}$$

2.12 Bandwidth

The bandwidth Δf of an antenna is the range of frequencies at which

1) The gain of the antenna is higher than some desired value,

2) The satisfactory front to back ration is achieved,

3) The standing wave ratio on the transmission line or the feed line can be obtained below the standard value,

4) The return loss or typically the S11 parameter is below -10 dB line in case of patch antennas.

Alternatively, the bandwidth is the range of frequency on both side of the centre frequency at which the antenna fullfills all the desired performance characteristics.

As the wavelength decreases exponentially with frequency, two adjacent frequencies on the lower side of the frequency axis (e.g. 1 to 2 GHz) will have a much larger wavelength difference than two adjacent frequencies on the higher frequency axis (e.g. 5 to 6 GHz). Designing an antenna with larger bandwidth (S11 and AR) is more challenging at lower frequencies than higher frequencies. Therefore, fractional bandwidth is a just way of representing an antenna impedance or AR bandwidth (BW for AR dB). Bandwidths > 10% are considered as wideband and they are called ultra-wideband if they have a FBW > 20%.

The bandwidth of antenna is also related to the *quality factor(Q)* of the antenna as:-

$$\Delta f = f_2 - f_1 = \frac{f_r}{Q} = Bandwidth \tag{2.27}$$

$$\Delta f = \frac{f_r}{Q} \tag{2.28}$$

$$\Delta f \propto \frac{1}{Q} \tag{2.29}$$

where,

f_r is the resonant frequency,

Q=quality factor of an antenna which is given by,

$$\boxed{Q = 2\pi \frac{Total\ energy\ stored\ by\ the\ antenna}{Energy\ dissipated\ or\ radiated\ per\ cycle}} \tag{2.30}$$

This means "*the lower the value of Q the higher will be the Bandwidth of an antenna*."

The normalized or the *fractional bandwidth (FBW)* of an antenna can be expressed as:

$$\boxed{FBW = \frac{BW}{f_c} = \frac{f_1 - f_2}{\frac{f_1+f_2}{2}}} \tag{2.31}$$

2.13 Polarization

The *polarization* of the antenna is stated in many text as "the orientation of the electric field vector of an electromagnetic wave in the given direction" or it may also be defined as "the shape or the locus made by the tip of the vector electric field while propagating in space from one point to another point".

The polarization radiation sphere can be subdivided in two categories *Co-polarisation* and *Cross-polarisation*. Suppose the antenna is designed to operate in the vertical polarisation. So for this antenna the vertical polarisation is called the *Co-polarisation*. However due to some spurious radiation, some orthogonal polarisation componets also gets radiated which in the present case is the horizontal polarisation which usually undesired. This type of polarisation is called as *Cross polarisation*. This cross polarisation component interferes with th co-polarisation component to distort the signal. So to keep the distortion minimum the value of the cross polarisation must be less as compared to the co polarisation component. Let the instantaneous field of a plane wave, traveling in the negative z direction be

$$\mathscr{E}(z;t) = \hat{a}_x \mathscr{E}_x(z;t) + \hat{a}_y \mathscr{E}_y(z;t) \tag{2.32}$$

The instantaneous components are related to their complex counterparts by

$$\mathscr{E}_x(z;t) = Re[E_x^- e^{j(\omega t+kz)}] = Re[E_{x0}e^{j(\omega t+kz+\phi_x)}] = E_{x0}cos(\omega t+kz+\phi x) \quad (2.33)$$

$$\mathscr{E}_y(z;t) = Re[E_y^- e^{j(\omega t+kz)}] = Re[E_{y0}e^{j(\omega t+kz+\phi_y)}] = E_{y0}cos(\omega t+kz+\phi y) \quad (2.34)$$

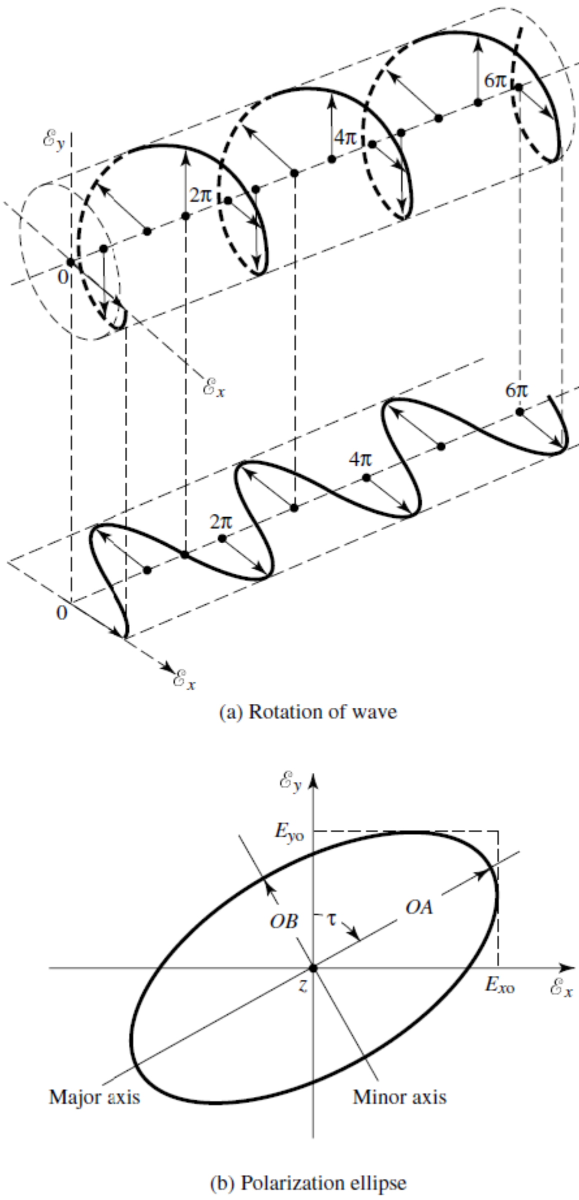


Figure 2.9: Rotation of a plane electromagnetic wave

A.***Linear Polarization***

The phase difference of the linearly polarized wave can be expressed as:

$$\Delta\phi = \phi_y - \phi_x = n\pi, \;\; n = 0, 1, 2, 3, ... \tag{2.35}$$

The electromagnetic wave is said to be a *linearly polarized* one, if the vector of the electric field does not rotate while travelling from one point to another. It should be fixed along one particular direction.

B.***Circular Polarization***

If the magnitude of the orthogonal component is similar and their associated phase difference is $\frac{\pi}{2}$ or its odd multiples. Then the resultant wave is said to be *circularly polarized* wave. That is,

$$E_{x0} = E_{y0}$$

$$\Delta\phi = \phi_y - \phi_x = \begin{cases} +(\frac{1}{2} + 2n)\pi, n = 0, 1, 2, ... & for\, CW \\ -(\frac{1}{2} + 2n)\pi, n = 0, 1, 2, ... & for\, CCW \end{cases} \tag{2.36}$$

In other words, if the tip of the electric field vector traces a perfect circle of constant radius while propagating, then the wave will be a circularly polarized one. This has two types, *Left circularly polarized wave* and *Right circularly polarized wave*.

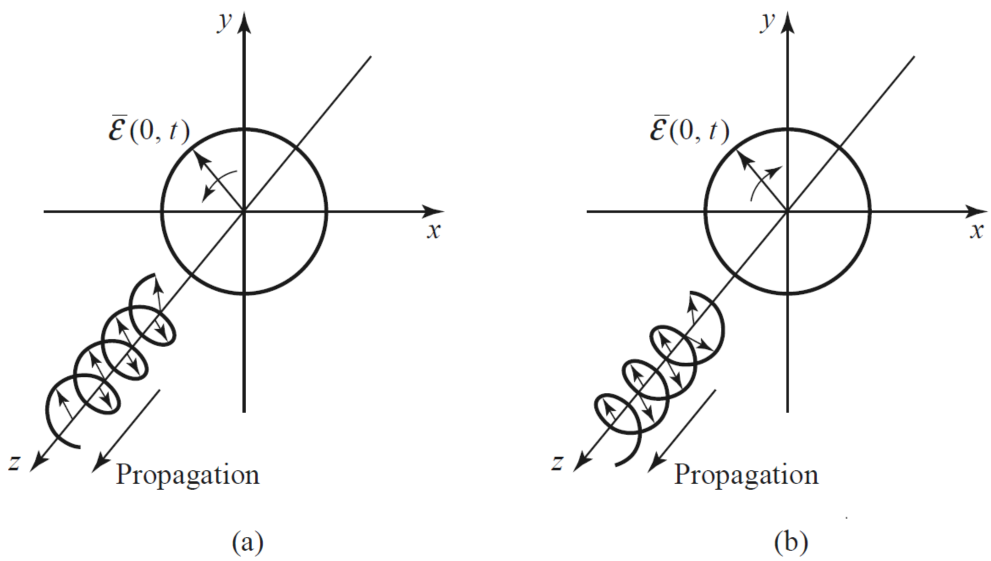


Figure 2.10: Electric field polarization for a) RHCP and b) LHCP plane waves.

To judge the type of polarization, the observer should assume that the wave is coming towards him. If the observer sees the electric field vector coming towards him in clockwise direction then the wave is *Left handed circularly polarized wave*. If the observer sees the electric field vector coming towards him in an anti-clockwise direction then the wave is *Right handed circularly polarized wave*.

C.***Elliptical Polarization***

The most basic definition of the *elliptically polarized wave* is that the wave which is neither linearly polarized nor is circularly polarized, is called the *elliptically polarized wave*. Or it can be stated mathematically as, if the magnitude of the orthogonal component is not similar but have the phase difference of $\frac{\pi}{2}$ or odd multiples of $\frac{\pi}{2}$. Or if the orthogonal component has the phase difference other than of $\frac{\pi}{2}$ or multiples of $\frac{\pi}{2}$.. That is,

$$E_{x0} \neq E_{y0}$$

$$\Delta\phi = \phi_y - \phi_x = \begin{cases} +(\frac{1}{2}+2n)\pi, n = 0,1,2,..... & for\,CW \\ -(\frac{1}{2}+2n)\pi, n = 0,1,2,..... & for\,CCW \end{cases} \tag{2.37}$$

or

$$\Delta\phi = \phi_y - \phi_x \neq \pm\frac{n}{2}\pi = \begin{cases} > 0 & for\, CW \\ < 0 & for\, CCW \end{cases} \tag{2.38}$$

If the tip of the electric field vector traces an ellipse while propagating, then the wave will be a elliptically polarized one. This has also two types, *Left elliptically polarized wave* and *Right elliptically polarized wave*. If the observer sees the electric field vector coming towards him in clockwise direction then the wave is *Left handed elliptically polarized wave*. If the observer sees the electric field vector coming towards him in an anti-clockwise direction then the wave is *Right handed circularly polarized wave*.

Axial Ratio The ratio of the major axis to the minor axis is referred to as the axial ratio (AR), and it is equal to

$$AR = \frac{major\ axis}{minor\ axis} = \frac{OA}{OB}, \qquad 1 \leq AR \leq \infty \tag{2.39}$$

So we can conclude from the formula that the

AR=1 for circular polarization;

$1 < AR < \infty$ for elliptical polarization;

$AR = \infty$ for linear polarization.

2.14 Polarization Loss Factor and Efficiency

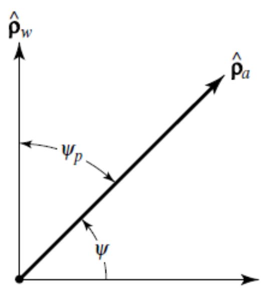


Figure 2.11: Polarization unit vectors of incident wave

The polarizatio of the EM wave radiated by the antenna plays very important role in almost all communication links. If not adjusted properly situation may arise that our entire communication system may fail. In many circumstances the receiving antenna polarization will not be identical to that of the transmitting antenna.

This phenomenon is generally referred as a *Polarization mismatch* and it should not be ignored. The power absorbed or extracted by the receiving antenna from the input electromagnetic waves will fail to reach its desired values because of this phenomenon of Polarization mismatch.

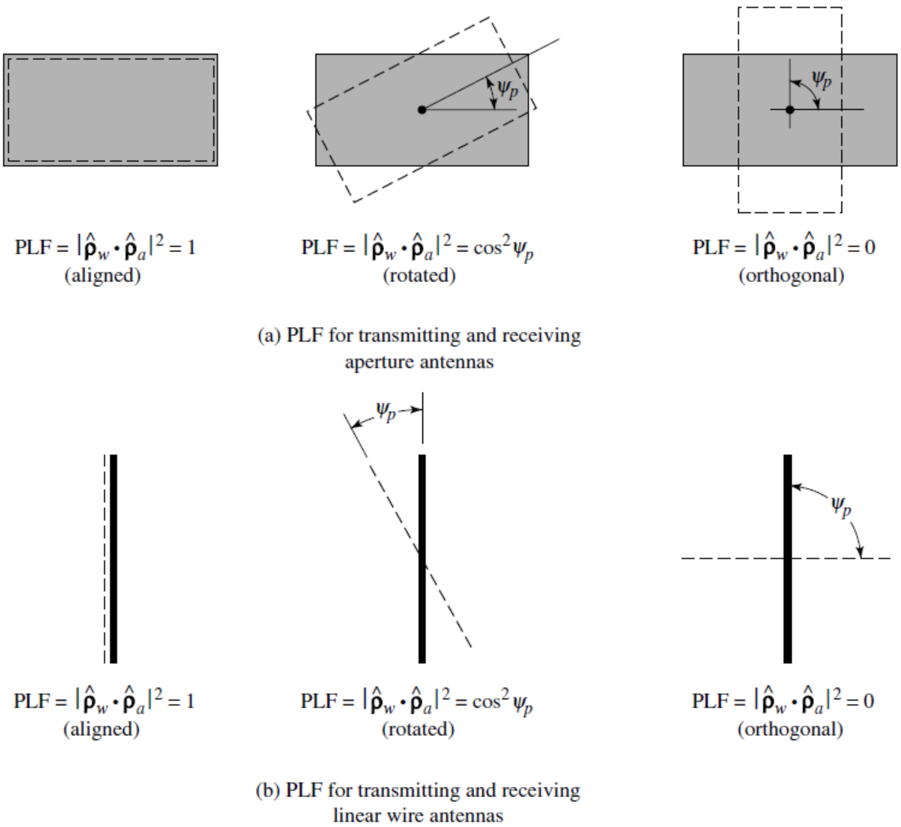


Figure 2.12: Polarization loss factors (PLF) for aperture

Let us assume the electric field if the input signal is given as

$$E_i = \hat{\rho}_w E_i \tag{2.40}$$

The $\hat{\rho}_w$ is the associated unit vector of the incoming wave The receiving antennas electric field polarization state is given by

$$Eai = \hat{\rho}_a E_a \tag{2.41}$$

Where $\hat{\rho}_a$ is the corresponding unit vector The polarization loss factor is then calculated as the square of these unit vector quantities. ψ_p denotes the angular separation between these two vectors.

$$PLF = |\hat{\rho}_w.\hat{\rho}_a|^2 = |cos(\psi_p)|^2 \tag{2.42}$$

If the received antenna is perfectly aligned to its transmitting counterpart, then the PLF factor will be unity due to which the receiving antenna will absorb maximum power.

The polarization efficiency is generally stated as as "*the ratio of the power received by an antenna from a given plane wave of arbitrary polarization to the power that would be received by the same antenna from a plane wave of the same power flux density and direction of propagation, whose state of polarization has been adjusted for a maximum received power.*" This is similar to the PLF and it is expressed as

$$p_e = \frac{|l_e.E^{inc}|^2}{|l_e^2||E^{inc}|^2} \tag{2.43}$$

where,

l_e= vector effective length of the antenna

E^{inc}= incident electric fieldwhere.

2.15 Input Impedance

The input impedance antenna is the impedance or the load observed by the feed line or transmission line when it delivers power to the antenna or radiating element. It is the main parameter of the antenna and it should be given by the manufacturer. The input impedance of the antenna is generally frequency dependent i.e. it varies with frequency. For faithful working of the antenna and to radiate maximum power, complete power must be transferred from transmission line to the radiating element. For this to happen the role of input impedance comes into picture. We know from theory that maximum power transmission is possible if the characteristic impedance of the feed line is matched to the load. Here the load is the input impedance of the antenna. Several means are adapted by the researchers to match these two parameters either by employing quarter wave transformer or by using stubs. The input impedance is a combination of resistance and reactance thus making it frequency dependent.

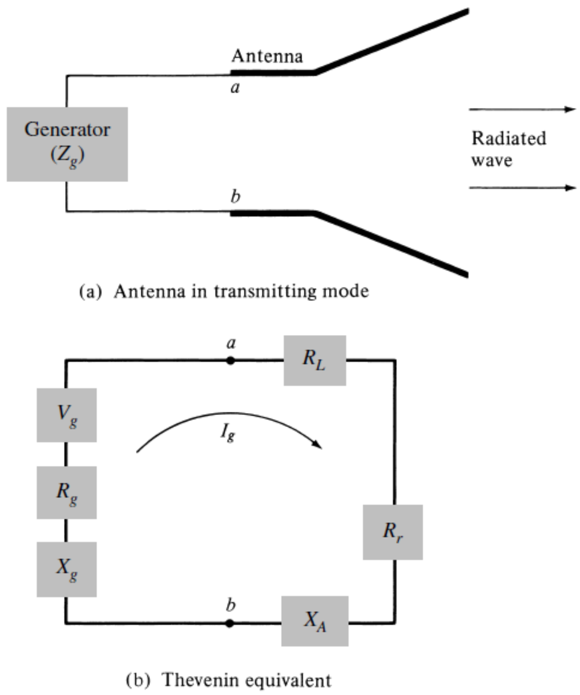


Figure 2.13: Transmitting antenna and its equivalent circuits

$$\boxed{Z_a = R_a + jX_a} \tag{2.44}$$

where

Z_A = antenna impedance at terminals a-b (ohms)

R_A = antenna resistance at terminals a-b (ohms)

X_A = antenna reactance at terminals a-b (ohms)

In general the resistive part of Eq.2.44 consists of two components; that is

$$\boxed{R_a = R_r + R_L} \tag{2.45}$$

where

R_r = radiation resistance of the antenna

R_L = loss resistance of the antenna

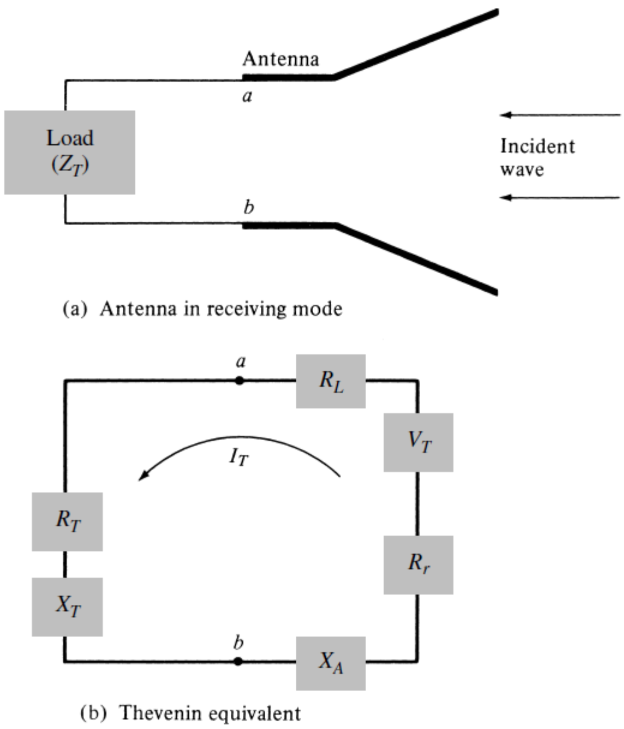


Figure 2.14: Antenna and its equivalent circuits in the receiving mode.

Assuming that the antenna is attached to a generator with internal impedance, then

$$\boxed{Z_g = R_g + jX_g} \tag{2.46}$$

R_g = resistance of generator impedance (ohms)

X_g = reactance of generator impedance (ohms)

The input impedance of an antenna is generally a function of frequency. Thus the antenna will be matched to the interconnecting transmission line and other associated equipment only within a bandwidth.

2.16 Equivalent Areas of Antenna

The *effective area* of a particular antenna is stated as "the ratio of the available power at the terminals of a receiving antenna to the power flux density of a plane wave incident on the antenna from that direction, the wave being polarization-matched to the antenna.". The direction of maximum radiation intensity is implied in case when the direction is not given. In equation form it is written as

$$A_e = \frac{P_T}{W_i} = \frac{|I_T|^2 R_T/2}{W_i} \tag{2.47}$$

A_e = effective area (effective aperture) (m^2)

P_T = power delivered to the load (W)

W_i = power density of incident wave (W/m^2)

The effective aperture is the quantity which gives the power delivered to the load when it is multiplied by the incident power density.

$$A_e = \frac{|V_T|^2}{2W_i}\left[\frac{R_T}{(R_r+R_L+R_T)^2+(X_A+X_T)^2}\right] \tag{2.48}$$

In case of maximum power transfer condition (matching of conjugate condition), $R_r+R_L = R_T$ and $X_A = X_T$, the effective area of Eq.2.48 can be reduced to the maximum effective aperture given by

$$A_e = \frac{|V_T|^2}{8W_i}\left[\frac{R_T}{(R_L+R_r)^2}\right] = \frac{|V_T|^2}{8W_i}\left[\frac{1}{(R_L+R_r)}\right] \tag{2.49}$$

The power received by the antenna or intercepted by the antenna is not fully delivered to the load. This can be seen in Figure2.13. the power transfered to the load is almost half due to the conjugate matching condition. The other half of the power is either scattered or is dissipated as heat. Therefore for understanding the concept of scattered and dissipated power need arises to define the effective area, the scattering, loss and capture equivalent areas. In equation form these can be defined similarly to Eq.2.47-2.49 for the effective area.

The *scattering area* is defined as "the equivalent area when multiplied by the incident power density is equal to the scattered or reradiated power".It is given by

$$A_s = \frac{|V_T|^2}{8W_i}\left[\frac{R_r}{(R_L+R_r)^2}\right] \tag{2.50}$$

The *loss area* is defined as the "equivalent area, which when multiplied by the incident power density leads to the power dissipated as heat through R_L." It is given by

$$A_L = \frac{|V_T|^2}{8W_i}\left[\frac{R_L}{(R_L+R_r)^2}\right] \tag{2.51}$$

Finally the *capture area* is defined as "the equivalent area, which when multiplied by the incident power density leads to the total power captured, collected, or intercepted by the antenna."

$$A_c = \frac{|V_T|^2}{8W_i}\left[\frac{R_T+R_r+RL}{(R_L+R_r)^2}\right] \tag{2.52}$$

The total capture area is thus the sum of the other three areas as given below

Capture Area = Effective Area + Scattering Area + Loss Area

Aperture Efficiency: The *aperture efficiency* ε_{ap} of an antenna, is the ratio of the maximum effective area A_{em} of the antenna to its physical area A_p,

$$\varepsilon_{ap} = \frac{A_{em}}{A_p} = \frac{\text{maximum effectivec area}}{\text{physical area}} \tag{2.53}$$

Relationship between Maximum Effective Aperture A_{em} and Maximum Directivity D_0. The maximum *effective aperture A_{em}* of any antenna is related to its *maximum directivity* D_0 by

$$\boxed{A_{em} = \frac{\lambda^2}{4\pi}D_0} \tag{2.54}$$

When Eq.2.54 is multiplied by the incident wave's power density it leads to the maximum power which can be supplied to the load. If the losses of the antenna is taken into consideration, its maximum effective aperture of Eq.2.54 can be modified for conduction-dielectric losses (radiation efficiency). Thus,

$$\boxed{A_{em} = \eta_{cd}\left(\frac{\lambda^2}{4\pi}D_0\right)} \tag{2.55}$$

CHAPTER 3

Microstrip Patch Antenna Background

3.1 Introduction

The microstrip patch antennas or simply MPA's are the planar antennas [14] which is gaining much popularity in the past decade. It finds variety of applications in many areas due to its numerous advantages [17]. It is especially the main research topics of many researchers across the world. These antennas are assumed to replace the other conventional antennas in the coming years.

It consists of a substrate material of some dielectric constant. The upper layer of this substrate consists of the radiating element known as the *patch*. And finally at the backside it consists of a ground plane. The name microstrip antenna comes due to the use of *microstrip line* which is used to give or supply microwave power to the radiating element [17].

Initially the microwave enginners usually employs *striplines* to fabricate the circuits in microwave devices. It consists of two conductors acting as a ground plane and a strip in the middle of it, for guiding the signal. As the advancement of technology has taken place in the past years, it is replaced by the similar structure known as a *microstrip line*. The main advantage of microstrip line as compared to strip line is that the former can be made by monolithic integrated circuits [10] [3].

3.2 Basic Characteristics

Microstrip antennas, as shown in Figure3.1 consist of a very thin $t \ll \lambda_0$, where λ_0 is the free-space wavelength) metallic strip (patch) placed a small fraction of a wavelength (h< λ_0, usually $0.003\ \lambda_0 \leq h \leq 0.05\ \lambda_0$) above a ground plane. The microstrip patch is designed so its pattern maximum is normal to the patch.

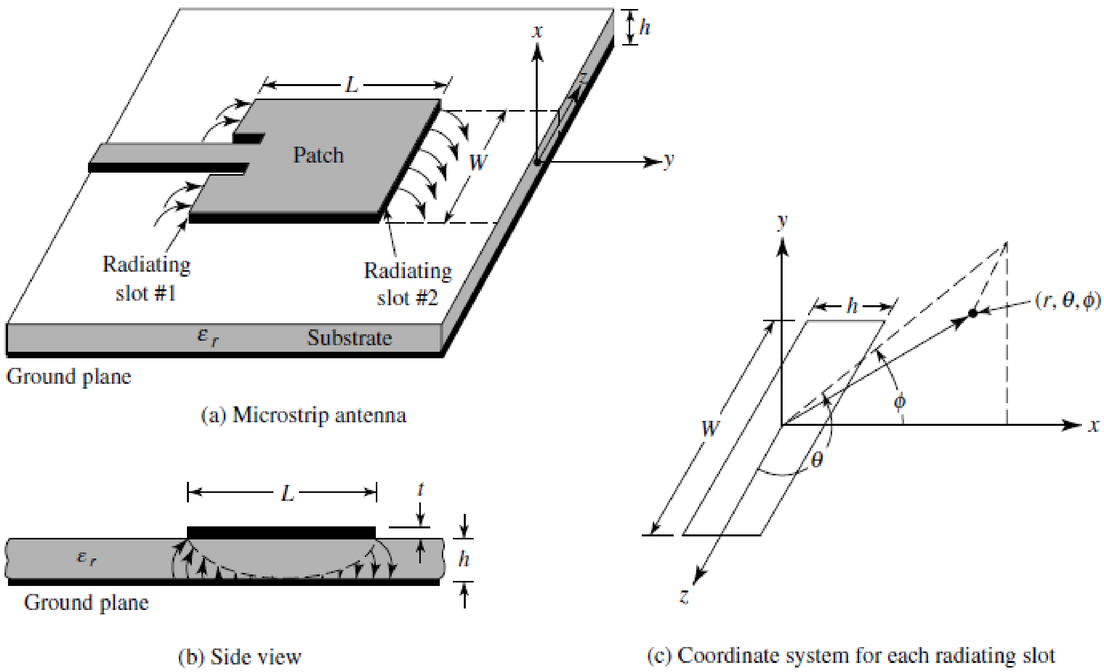


Figure 3.1: Microstrip antenna and coordinate system.

For a rectangular patch, the length L of the element is usually $\lambda_0/3$ < L < $\lambda_0/2$. The strip (patch) and the ground plane are separated by a dielectric sheet (referred to as the substrate), as shown in Figure3.1.

There are numerous substrates that can be used for the design of microstrip antennas, and their dielectric constants are usually in the range of $2.2 \leq Ir \leq 12$. The ones that are most desirable for good antenna performance are thick substrates whose dielectric constant is in the lower end of the range because they provide better efficiency, larger bandwidth, loosely bound fields for radiation into space, but at the expense of larger element size. Thin substrates with higher dielectric constants are desirable for microwave circuitry because they require tightly bound fields to minimize undesired radiation and coupling, and lead to smaller element sizes; however, because of their greater losses, they are less efficient and have relatively smaller bandwidths.

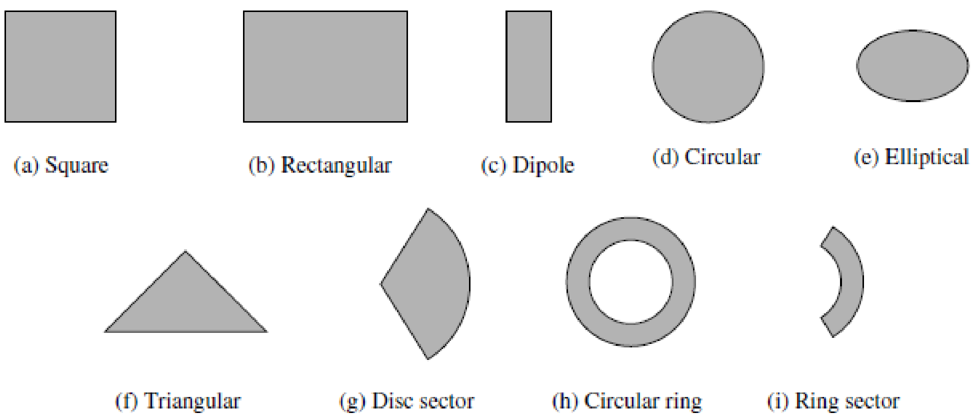


Figure 3.2: Representative shapes of microstrip patch elements.

3.3 Feeding Methods

There are large numbers of techniques used to feed microstrip patch antenna,

(a) Microstrip line feed,

(b) Coaxial probe feed,

(c) Aperture coupled feed,

(d) Proximity-coupled feed.

Each method has some advantages and disadvantages. According to requirement we can choose any one of suitable technique. The main work of feedline is to transfer electrical power from transmission line to radiating patch. There should be proper impedance matching between feed line and radiating patch. For impedance matching we need extra matching circuit. Therefore feedline should be design in such a way that matching circuit should be design with radiating patch. If we increase the thickness of dielectric substrate, it will increase bandwidth but also introduce surface wave as well as spurious feed radiation.

Two parameters, spurious feed radiation as well as surface wave depend on the feedline structure. Spurious feed radiation introduce side lobe in radiation pattern as well as increase the cross polarisation and surface wave reduce the efficiency of antenna.

Out of the above four feeding techniques, Microstrip line feed and Coaxial probe feed are contacting feeding technique because feedline directly connected to radiating patch. Whereas Proximity coupled and Aperture coupled feeding techniques are non-contacting feeding techniques because feedline mutually coupled to radiating patch. In contacting feeding techniques spurious feed radiation is more causes compare to non-contacting feeding techniques. So in both microstrip line feed as well as coaxial feed, introduction of side lobe and generate higher order mode cause increase cross-polarization are more compare to aperture coupled and proximity coupled feeding techniques.

3.3.1 Microstrip Line Feed

Microstrip line feed is a metal stripline of thickness equal to radiating patch. Its width is much less compare to radiating patch. In this method antenna consist of two metal layers of patch and ground plane on both side of dielectric substrate.

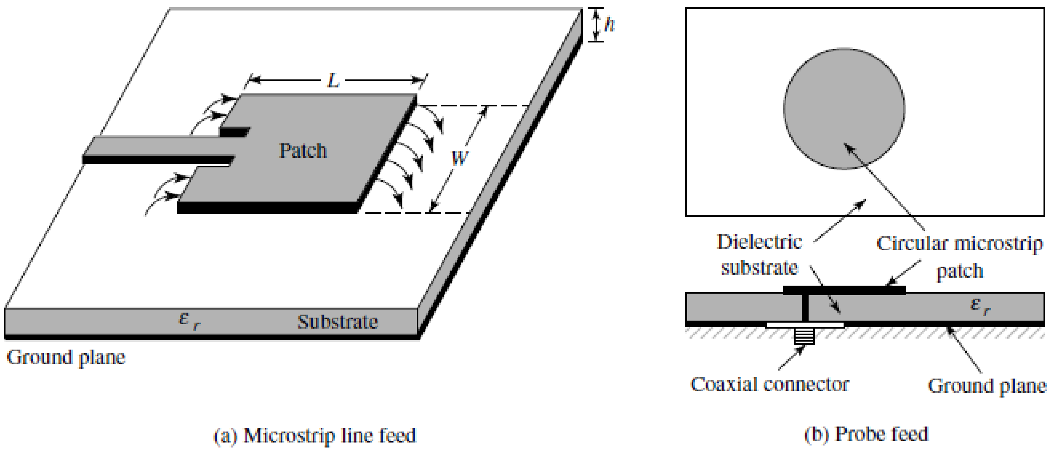


Figure 3.3: Feeding Methods

This is most basic form of feeding technique and easy to fabricate. In this method impedance matching is also very easy by position control only. This technique is contacting technique, so feedline is directly connected to patch [39]. Therefore it introduce more surface wave and higher order mode causes cross-polarization. Its bandwidth is also very less about 2-5%.

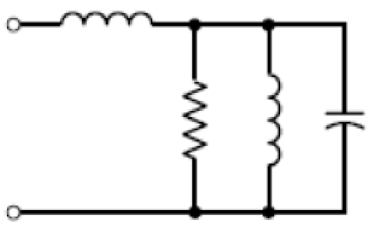


Figure 3.4: Equivalent circuit of Microstrip Line Feed.

3.3.2 Coaxial Probe Feed

It is a contacting feed technique. Coaxial probe consists of two coaxial conductors. Inner conductor is connected to metallic patch and outer conductor is connected to ground plane. It is simple in structure and matched line. It is very difficult to design if thickness of substrate is very high. Here spurious feed radiation is less compare to microstrip line feed. It also generate higher order mode and surface wave causes introduce cross-polarization and side lobe.

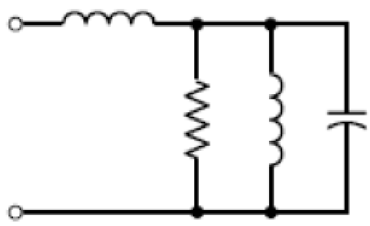


Figure 3.5: Equivalent circuit of Coaxial Probe Feed

Its bandwidth is also very less like microstrip feeding technique. To overcome problems in contacting feeding techniques, non-contacting feeding techniques are introduced.

3.3.3 Aperture-coupled feed

In aperture coupled technique two different substrates are used, separated by metallic ground plane. Radiating patch is on the top side of upper substrate and feedline is placed below of bottom substrate. This technique is most difficult as compare to others. Bandwidth and field pattern depends on dimensions and dielectric constant of bottom substrate i.e. feedline substrate. Thickness of bottom dielectric substrate is less and permittivity is high as compare to upper substrate to increase the bandwidth good field pattern. Thickness of upper dielectric should be less to reduce the fringing field. Field is mutually coupled to the patch from feed line through slot created in ground plane. Different types of shape of slot are used. Generally circular and rectangular slots are used. This is a non-contacting technique.

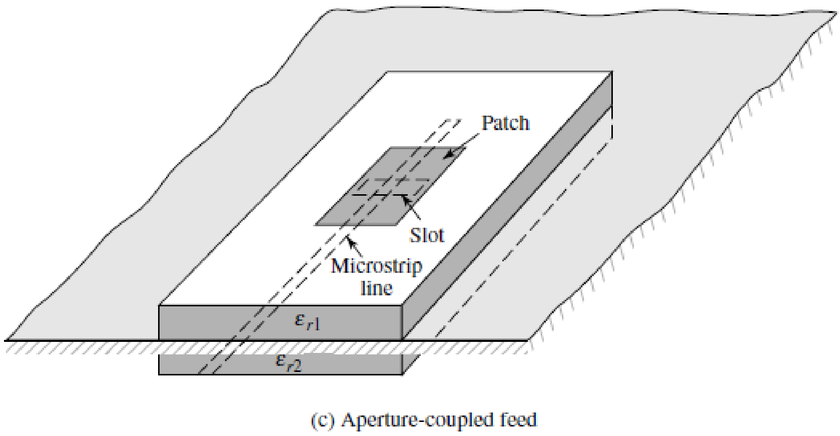


Figure 3.6: Aperture coupled feed.

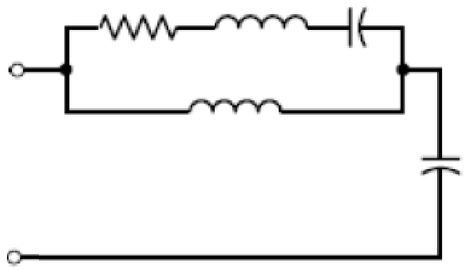
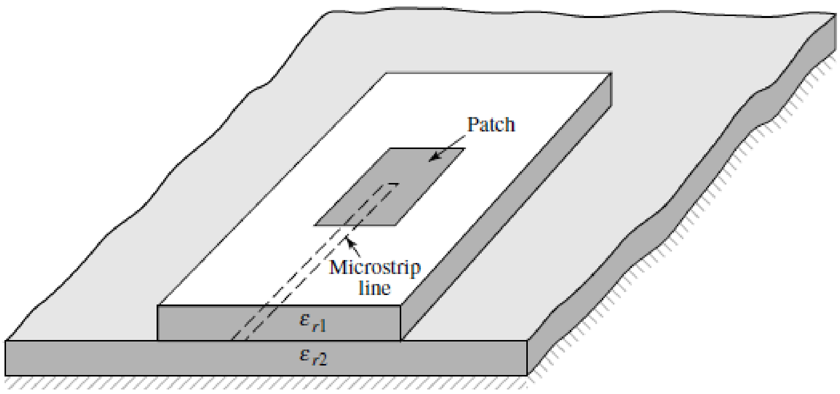


Figure 3.7: Equivalent circuit of Aperture-coupled feed.

Field coupling can be maximum by proper dimension of slot and position of slot and feedline. Its bandwidth is very less and fabrication is easy. Because of ground plane, feedline is separated from radiating patch. Therefore spurious feed radiation is very less causes low cross-polarization and high polarization purity. In this design dimension of substrate, slot, feedline and permittivity of substrate optimize the design. In the case of circular polarization we are using cross and ring slots are used. From electrical theory of 16 distribution of voltage and current, at the corner E-field is max and at the centre H-field is max. If aperture slot is just below the centre of the patch then H-field is max and E-field is zero. For better impedance matching, feedline length is stretched over slots. The extra portion of extended feedline acts as open circuit stub. Stub reduces the reactive component of aperture or slot.

3.3.4 Proximity-Coupled Feed

Proximity-coupled technique is a non-contacting technique. In this technique also two dielectric substrates are used. Two substrates are separated by microstrip feedline. Energy is mutually coupled to patch from feedline. High dielectric constant and thin substrate is used as bottom substrate as compare to upper substrate to increase the bandwidth and improve the field pattern. To reduce the fringing field upper substrate should be thin.



(d) Proximity-coupled feed

Figure 3.8: Proximity-Coupled Feed

Since, feedline is separated from radiating patch so spurious feed radiation is less. Therefore generation of higher order modes are less and cross-polarization is less. Its fabrication is difficult because of proper management of position of feedline is difficult. Bandwidth of proximity coupled technique is high (approximate 13%) as compare to other techniques.

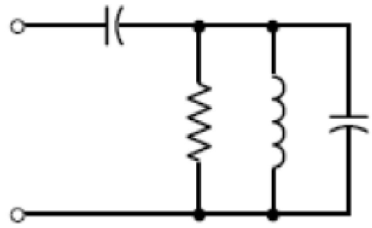


Figure 3.9: Equivalent circuit of Proximity-Coupled Feed.

3.4 Rectangular Patch Analysis

The rectangular patch antenna is the most widely used antenna configuration [11] [34]. It is very easy to analyze this type of antenna by using both the transmission-line and cavity models, which are almost accurate for thin substrates. The rectangular microstrip patch antenna can be analysed using two famous techniques or models known as *the transmission line model* and *the cavity model.*

3.4.1 Transmission-Line Model

Transmission line model is one of the easiest one for the analysis of rectangular microstrip patch antenna. It provides very basic picture or equivalent model for the patch antennas.

This model usually makes use of the concept of the transmission line. In this model the patch antennas analysis is carried out by assuming the microstrip antenna structure as an arrangement having a transmission line which is feeding some power in two separate symmetrical loads [40]. This is shown in the Figure3.10. The resistive component of the load is nothing but the radiation losses [40].

In case of resonance or when the antenna is operated in its resonance frequency, the imaginary part of the input impedance of the patch cancels each other. Thus the input impedance is purely real or resistive so that complete absorption of power takes place coming from the feed line.

The point where the transmission line or feed line is connected to the radiated element, in order to supply microwave signals, is called the *driving point* of the antenna. And the impedance associated with that point is called the *driving point impedance* or generally input impedance. This input impedance can be easily calculated with the help of this transmission line model. The most famous form in which the driving point impedance is represented is when it is in terms if admittances.

$$Y_{in} = Y_0 \frac{Y_L + jY_0 tan(\beta L)}{Y_0 + jY_L tan(\beta L)} \tag{3.1}$$

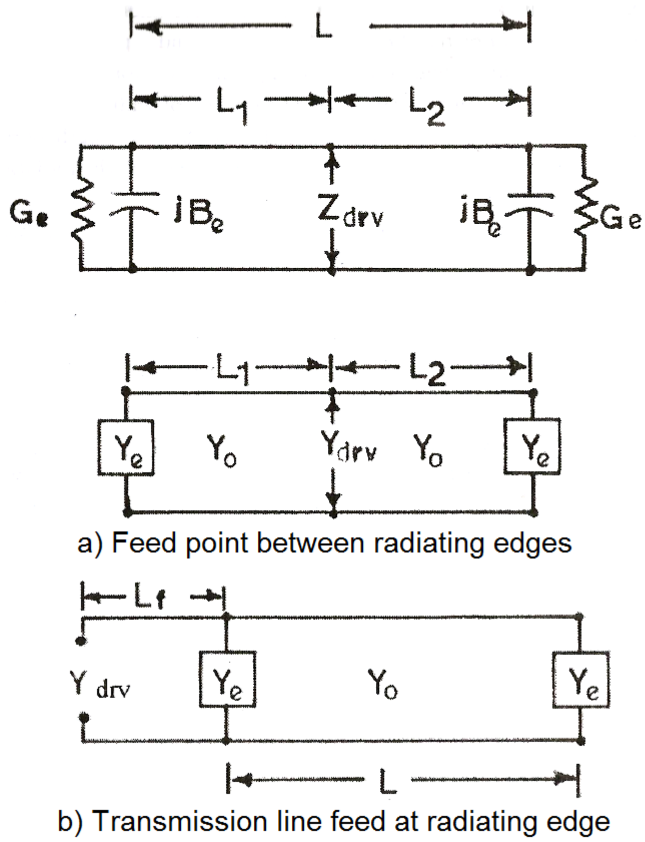


Figure 3.10: The transmission line model of a rectangular microstrip patch antenna.

Thus the input admittance of the antenna is the admittance which is located at the end of transmission line. This line has a chracatreistic admittance of Y_0 having Y_L as the load admittance. So we can visualize that this transmission line of characteristic admittance of

Y_0 is feeding complex load having admittance depended on frequencies. It should also be noted that the Y_e represents the radiation loss and is known as *Edge admittance*. The driving point admitance is given by

$$Y_{drv} = \frac{1}{Z_{drv}} \tag{3.2}$$

Using equation (previous), the driving point admittance $Y_{drv} = 1/Z_{drv}$ at a driving point between the two radiating edges is given by

$$Y_{drv} = Y_0 \left[\frac{Y_e + jY_0 tan(\beta L_1)}{Y_0 + jY_e tan(\beta L_1)} + \frac{Y_e + jY_0 tan(\beta L_2)}{Y_0 + jY_e tan(\beta L_2)} \right] \tag{3.3}$$

The edge admittance Y_e can be expressed as edge conductance G_e and edge susceptance B_e. The transmission line having characteristics admittance Y_0 separates the two loads.

$$Y_e = G_e + jB_e \tag{3.4}$$

A.*Fringing Effect*

The fields at the edges of the patch experience the fringing effects due to the smaller dimensions of the patch and the inputed higher frequency. Fringing is predominant at higher or microwave frequencies near to discontinuous edges of the device. The fringing is also depended upon the height of the substrate. The field lines are shown in the Figure3.11. As we can see that the maximum percent of the line reside in the substrate but also some considerable amount of field also present in air. The filed mostly confined in the substrate because W/h≫1 and the dielectric constant of the substrate $\varepsilon_r \gg 1$. Due to the effect of feeding the behaviour of th microstrip line is not only dependent on its physical dimensions but also the air surrounding it, making it look a little wider. So the phenomenon effective dielectric constant ε_{reff} is introduced in analysis. It is given by

W/h>1

$$\boxed{\varepsilon_{\text{reff}} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left[1 + 12\frac{h}{W}\right]^{-1/2}} \tag{3.5}$$

The effective length of the antenna:

$$\frac{\Delta L}{h} = 0.412 \frac{(\varepsilon_{\text{reff}} + 0.3)\left(\frac{W}{h} + 0.264\right)}{(\varepsilon_{\text{reff}} - 0.258)\left(\frac{W}{h} + 0.8\right)} \tag{3.6}$$

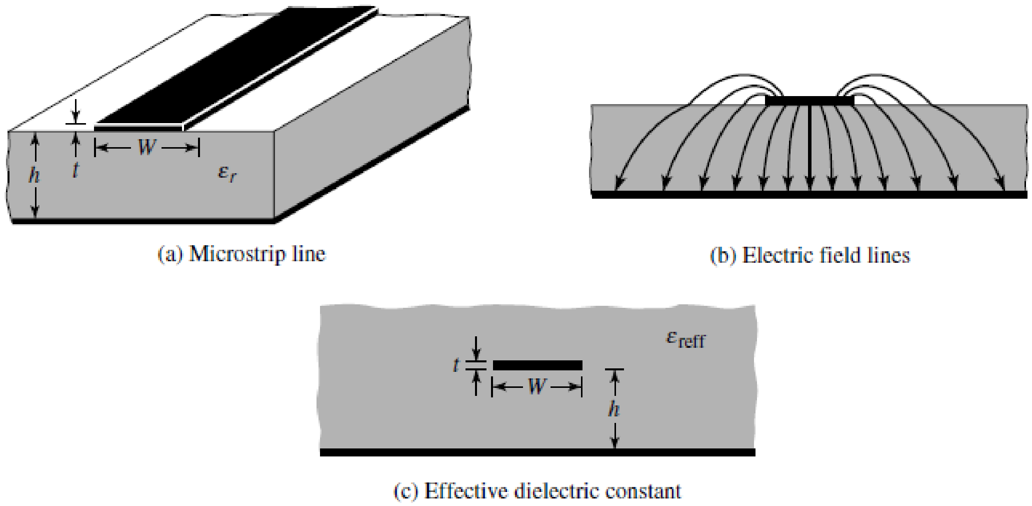


Figure 3.11: Microstrip line and its electric field lines.

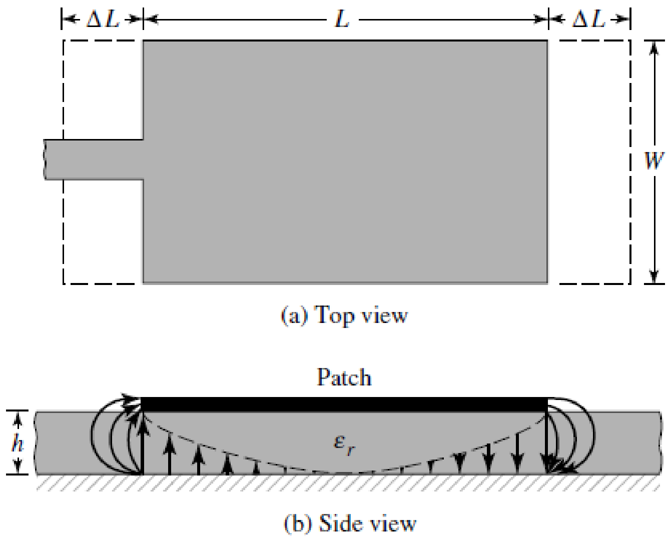


Figure 3.12: Physical and effective lengths of rectangular microstrip patch.

The radiating element generally known as the patch looks greater than its physical dimension due the effect of fringing fields. Thus for further analysis the length of the patch is extendend on either side by delta L which is given by

$$L_{\text{eff}} = L + 2\Delta L \tag{3.7}$$

The resonant frequency at which the input impedance is purely real is given by

$$(f_r)_{010} = \frac{1}{2L\sqrt{\varepsilon_r}\sqrt{\mu_0\varepsilon_0}} \tag{3.8}$$

$$= \frac{v_0}{2L\sqrt{\varepsilon_r}} \tag{3.9}$$

The above equation can be slightly modified if we consider the effect of fringing fields and including edge effects.

$$(f_{rc})_{010} = \frac{1}{2L_{\text{eff}}\sqrt{\varepsilon_{\text{reff}}}\sqrt{\mu_0\varepsilon_0}} \tag{3.10}$$

$$= \frac{1}{2(L+2\Delta L)\sqrt{\varepsilon_{\text{eff}}}\sqrt{\mu_0\varepsilon_0}} \tag{3.11}$$

$$= q\frac{1}{2L\sqrt{\varepsilon_r}\sqrt{\mu_0\varepsilon_0}} \tag{3.12}$$

$$= q\frac{v_0}{2L\sqrt{\varepsilon_r}} \tag{3.13}$$

where

$$q = \frac{(f_{rc})_{010}}{(f_r)_{010}} \tag{3.14}$$

The actual length of the patch can now be determined by solving Eq.3.10 for L, or

$$L = \frac{1}{2f_r\sqrt{\varepsilon_{\text{reff}}}\sqrt{\mu_0\varepsilon_0}} - 2\Delta L \tag{3.15}$$

3.4.2 Cavity Model

Although the transmission line is widely used due to its simplicity and lucidity, it often avoided in some accurate analysis because of its disadvantages. Some of them are listed below:

1) The transmission line model works good for finding the input impedance for the thicker substrate. But it is inaccurate when the substrates used are thin. For thinner substrate the calculated and the actual results for this model shows a huge gap.

2) It doesn't give information of the internally excited modes which are not aligned to the feeding line. The mode analysis sometimes is desired for detailed analysis of the antenna.

3) The transmission line model carry out calculations by assuming the current flow in a single direction. But practically the current can flow everywhere in any direction over the entire area of the rectangular element.

In the cavity model analysis the patch antenna is assumed as a cavity surrounded by the conducting walls above and below. And it is also surrounded by the magnetic walls for the open circuit case, so that the accurate calculation of normalised fields takes place which exists within the dielectric.

When the radiating element is given the microwave power from the microstrip line, the upper plane as well as lower plane consists of the charge distribution which is created as a result of the supplied power. The attractive and repulsive mechanism controls these distributions of charges. The force of attraction takes place between the lower end charges of the patch with the opposite charges present in the ground plane. As a result the charge concentration is maintained at the bottom of the radiating element. On the other hand the force of repulsion takes place between the like charges at the bottom of the radiating element which forces the charges to be present at the edges and the top. The whole mechanism is shown in the Figure3.13.

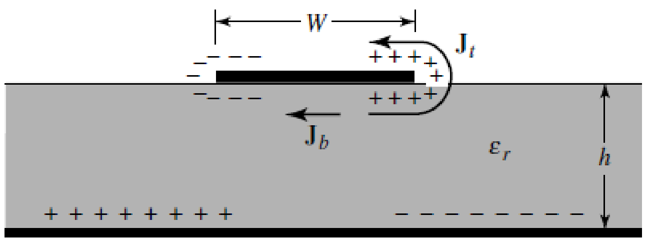


Figure 3.13: Charge distribution and current density creation on microstrip patch.

The current density J_b and J_t thus created at both the surface of the patch due to the above discussed movement of charge. In general the attractive mechanism is more as compared to the repulsive one, as the height to width ratio is very small. Due to this at the edges and at the top surface of the patch, the current flow exists.

But it must be noticed here is that, the current flow may be decreased due to the increase in height to width ratio. In this case at the top edge of the patch the current would be negligible failing to create any magnetic field components. Thus the four walls or the conducting surface should be considered as perfect magnetic surfaces which do not affect the magnetic field, which in turn avoids any disturbances of electric field below the patch. The hight to width ratio will be small in every case, so the best approximation can be made that the four sidewalls are magnetic conducting.

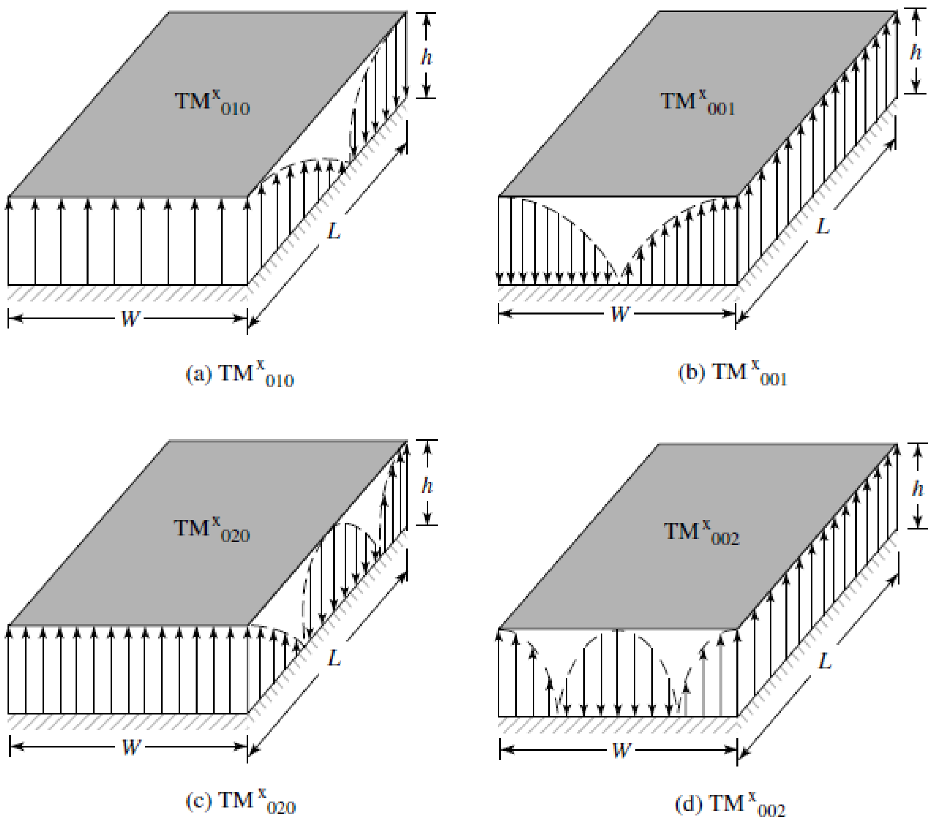


Figure 3.14: Field configurations for rectangular microstrip patch.

A. **Field Configurations (modes)-**TM^x

The field configurations within the cavity can be found using the vector potential approach

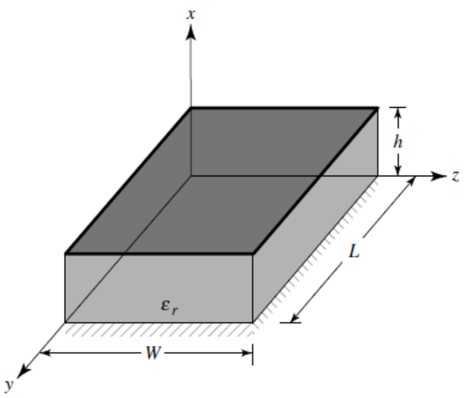


Figure 3.15: Rectangular microstrip patch geometry.

The wavenumbers k_x,k_y,k_z are equal to

$$\left.\begin{aligned} k_x &= \left(\frac{m\pi}{h}\right),\ m = 0,1,2,.... \\ k_y &= \left(\frac{n\pi}{L}\right),\ n = 0,1,2,.... \\ k_z &= \left(\frac{p\pi}{W}\right),\ p = 0,1,2,.... \end{aligned}\right\} m = n = p \neq 0 \tag{3.16}$$

The resonant frequencies for the cavity can be given by

$$(f_r)_{mnp} = \frac{1}{2\pi\sqrt{\mu\varepsilon}}\sqrt{\left(\frac{m\pi}{h}\right)^2\left(\frac{n\pi}{L}\right)^2\left(\frac{p\pi}{W}\right)^2} \tag{3.17}$$

the electric and magnetic fields within the cavity are written as

$$\left.\begin{aligned} E_x &= -j\frac{(k^2-k_x^2)}{\omega\mu\varepsilon}A_{mnp}cos(k_xx^{'})cos(k_yy^{'})cos(k_zz^{'}) \\ E_y &= -j\frac{(k_xk_y)}{\omega\mu\varepsilon}A_{mnp}sin(k_xx^{'})sin(k_yy^{'})cos(k_zz^{'}) \\ E_z &= -j\frac{(k_xk_z)}{\omega\mu\varepsilon}A_{mnp}sin(k_xx^{'})cos(k_yy^{'})sin(k_zz^{'}) \\ H_x &= 0 \\ H_y &= -\frac{k_x}{\mu}A_{mnp}cos(k_xx^{'})cos(k_yy^{'})sin(k_zz^{'}) \\ E_z &= \frac{k_y}{\mu}A_{mnp}cos(k_xx^{'})sin(k_yy^{'})cos(k_zz^{'}) \end{aligned}\right\} \tag{3.18}$$

3.5 Advantages of Microstrip Patch Antennas

Size and profile: The overall volume of the patch antenna in its simple form is comparatively very small than the other conventional antennas. The single layered patch antennas are less than $0.05\lambda_0$ (Free space wavelength) and multi layered one have a thickness of about $0.1\lambda_0$. Thus it can be easily mounted close to the ground plane and can be performed similar functions as that of a monopole antenna. Thus the space accommodated by the patch antenna is smaller than wire or even horn antennas. Due to its lesser thickness it is a perfect candidate to be used at the skins of various objects such as airplane or missile.

Ease of manufacturing, integration and are cheap: The microstrip patch antenna can be fabricated using printed circuit technology. So the bulk manufacturing of the microstrip patch antenna can take place which can result into lower price rates of these antennas. However the same manufacturing cost of the other antennas is higher. Moreover the microstrip patch antenna can be easily integrated with their feed network, which is not possible in case of wire antennas or waveguide based antennas. Thus these antennas can be manufacture with ease consisting active devices of the terminal creating one board solution. In the recent years it has been found that, the fabrication process of these antennas is greatly simplified as compared to other antennas, this is because the whole arrangement consist of sheets of dielectric and conductors and nothing more. Thus the developing cost is low. In addition to this if the operating frequency is lower than 1GHz the standard FR-4 materials can be used which is inexpensive and easily available.

Arrays can be implemented more easily: The gain of the microstrip antennas is low in order of 8dBi. Thus in the application where higher gain is requires, single antenna is not sufficient. Thus arraying of the antennas is used. Since the antennas are manufacturing using planar printed circuit technology it is very convenient and easy to form the array in the same process in the same time. Also in patch arrays the single feeding is also possible which can supply all the array elements. The coupling between feeding and the array elements can be done in several ways such as by probes, slots, etc.

Efficiency: The microstrip patch antennas are known as the efficient radiators. This is because they come in the category of the resonant antennas. The resonant antennas are comparatively more efficient than the non resonant counterparts. The losses associated with the microstrip patch antenna can be listed as conductor loss, dielectric loss and surface wave loss. All these losses are solely dependent on the material being used which can lead to better efficiency. The type feeding employed will be very important in determining efficiency. The direct contact feeding technique is more efficient and gives better results.

3.6 Disadvantage of Microstrip Patch Antennas

Narrow Bandwidth: The bandwidth of the microstrip patch antenna is very narrow i.e of the order of couple of the center frequency. This is due to the fact that these antennas are resonant type antennas which show resonance over small range of frequencies and also it has small thickness typically smaller than 0.05 λ_0. This demerit acts as a hindrance for the patch antennas to be used in several applications. However several techniques have been devised to enhance the bandwidth of the antenna.

Excitation of the surface waves: The microstrip patch antennas generally excite surface waves, due to the presence of dielectric substrate material. This surface wave excitation can cause decreased efficiency. These waves are also gets couples to several elements of the antenna and feed network. The surface waves reduces the isolation between different polarisation feed networks, which greatly affects the overall performance of the antenna. For this also, methods have been implemented to reduce the surface waves for improving the efficiency.

Radiation performance: As we have seen that the radiation performance of the patch antennas are well behaved and also obtaining the dual polarization is relatively simple as compared to other antennas. But there are certain applications where this antenna is not suitable for the requirements of the system. For example sidelobe levels of 50 dB is required for an array, it will be very difficult for the patch antennas to meet this specification.

3.7 Applications of Microstrip Patch Antenna

The microstrip antennas are widely used due to its robust design, satisfactory performance, ease of manufacturing [10], etc. The microstrip patch antennas finds application in defence system especially in missiles, aircraft and in rockets [24]. It is also famous for Satellite related applications [24] [12] [14], in biomedical engineering, etc.

Microstrip antennas has been greatly exploited in government related application and now it is spreading its feathers in commercial filed. This is just because of its easily availability of manufacturing elements such as substrates. In the years to come it is expected that it will replace most of the existing other working antennas. The different areas of application is discussed below:

1. ***Mobile and satellite communication systems:*** As we know in the mobile has become the necessity of every human being and is used in our day to day life. The most desired property of this system is its portability. Thus it requires antenna having low profile [24], light weight, low cost [15] [12]. These all requirements is successfully fulfilled by the Microstrip patch antenna [14]. It has benn designed in various shapes and configuration [12] for use in mobile communication technology.
   Satellite communication system often suffers the problem of polarization mismatch. For this the signals must be circularly polarised so that it can be received efficiently by the receiver. It makes use of Microstrip patch antenna for circular polarisation [14], as circular polarization can be easily achieved by using square or circular patch with one or two feed points.

2. ***Global Positioning System applications:*** It has been found that the microstrip patch

antennas with high dielectric permittivity substrate are used for GPS. These antennas are use in circular polarization mode and are quite expensive for its positioning purpose. It is specially installed in vehicles and other movable objects at the receiving ends.

3. ***Radio Frequency Identification (RFID):*** Radio Frequency Identification usually makes use of frequencies in the range of 30 Hz to 5.8 GHz. This technique is used in many areas of mobile communication, manufacturing, logistics, etc. Basically RFID system is a tag or transponder and a transceiver or reader.

4. ***Worldwide Interoperability for Microwave Access (WiMax):*** Wimax comes under IEEE 802.16 standrd. It has a range of about 30 miles and the data rate of about 70Mbps. The microstrip patch antennas which are used in these applications consist of three resonant modes at 2.7 GHz, 3.3 GHz and 5.3 GHz.

5. ***In Radio Detection and Ranging Equipments (RADAR):*** Radar is used to find any target by maching use of an echo concept. It usually detects an echo coming from the target to detect it. The microstrip antennas of light weight, low profile are the first choice of the RADAR systems. Moreover it is also helping the defence systems to supply RADARs more quickly due to the bulk manufacturing of the microstrip antennas [15].

3.8 Introduction of Reconfigurable Antennas

The antennas plays a significant role in many wireless communication system [18] and also used widely in defence systems [2]. The antennas are made reconfigurable so that they should be operated according to the demands of a particular system [24], to improve the existing functionality, or adapt to the environmental conditions. Out of the other reconfigurable antennas, frequency reconfigurable antennas has found numerous applications.

For the designing of any communicating equipment present in today's world, reconfigurable antennas have become the first choice of the designer. The reconfigurable antennas can come in as a single element or a group of radiating element especially known as *arrays*.

The reconfigurability can be defined as "the ability to change a particular characteristics of an existing design through the means of electrical, mechanical or even optical switches". The reconfigurable antennas has gained much attention in the past years [35] for providing spectrum efficiency and reduction of the overall system's size and cost. The change in the existing characteristics is achieved by redistributing the electric currents. Thus it changes the radiated electromagnetic fields from the apertures.

3.9 Reconfiguration Techniques

According to context of antennas, reconfigurability is the virtue to change a particular radiator's fundamental operating characteristics through electrical, optical, physical, material change [24].

As discussed earlier the reconfigurability is the ability to change a particular characteristics of an existing design through the means of electrical, mechanical or even optical switches. These techniques are classified as:

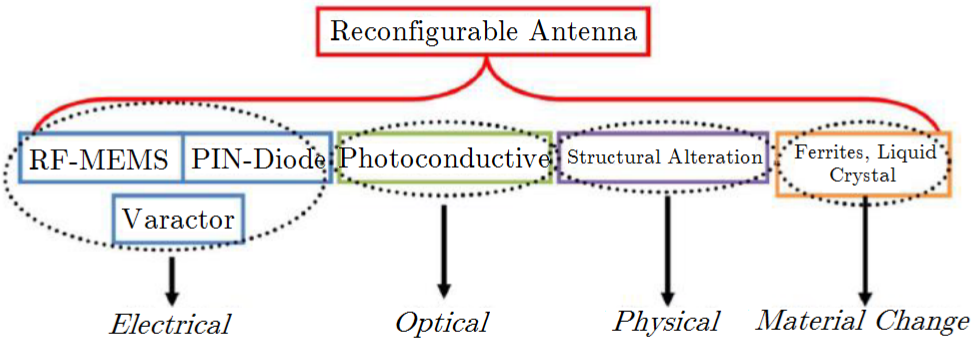


Figure 3.16: Types of reconfigurable antennas.

1. ***Electrically reconfigurable antennas:*** These types of antennas are made to change their performance based on the alteration of electrical current's path. These reconfigurable antennas makes use of electrically operated switches which are quite popular at microwave frequencies. These are PIN diodes [16] [35], varactor diodes [21] [25], etc.

2. ***Optically reconfigurable antennas:*** These antennas are made reconfigurable by the use of optical switches [33]. Optical communication system concept is then come into picture. Since we are aware about the advantages of using optically operated systems, it finds application here also. The non contacting operation of the switches makes the antenna more reliable. It makes use of photoconductive switching elements, photo transistors, etc.

3. ***Physically reconfigurable antennas:*** These antennas are also known as a mechanically reconfigurable antennas. Here the reconfigurability is achieved by altering the physical dimensions of particular antenna.

4. Finally, there are also antennas available which demands material changes which makes use of ferrites or liquid crystals [9].

3.10 Challenges for Designing Reconfigurable Antennas

When designing reconfigurable antennas, RF engineer must address three challenging questions.

1)Which reconfigurable property (e.g., frequency, radiation pattern, or polarization) needs to be modified?

2)How are the different radiating elements of the antenna structure reconfigured to achieve the required property?

3)Which reconfiguration technique minimizes negative effects on the antenna radiation/impedance characteristics?

3.11 Concept of Reconfigurability

The reconfigurability concept can be better understood by considering single element design and array design.

The *single element* design consist of a cellular phones, portable wireless communicating equipment or a laptop computer. The antenna used in such type of devices are basically microstrip antennas which may or may not consist of multiple frequency capabilities. Diversity concept may also be used for increasing the portability of reception, but only a single antenna is used for transmission. Due to the limited power, size and cost considerations, the portable device transmission to the access points is the delicate part of the communication system. In addition to this the condition may arise that these devices are to be used in harsh environmental conditions. The reconfigurability technique may act as a boon in such situations which offers several advantages. This is because the ability of reconfigurable antennas to switch in between the frequencies may be utilised to filter out the signals which are interfering, or the antennas can be tuned to different environment as desired. On the other hand, radiation pattern reconfigurability technique will be very much help full to the antenna so that the radiation pattern can be redirected to the base station and thus use less transmitted power.

However due to the addition of reconfigurability, several undesired changes can occur in the existing design. These are listed as

1) The antenna design becomes complex which will be very difficult to manufacture and installed.

2) Additional circuitry responsible for switching is needed.

3) Several characteristics changes which are not desired.

3.12 Classification of reconfigurable antennas based on the parameter of the antenna to be switched

Reconfigurable antennas can be classified into four different categories.

1. ***Frequency reconfigurable antennas***

   In these types of antennas the operating frequency of the radiating element is hopped [18] between different operating frequency bands. These are also called as *frequency agile antennas* [29] [33].

2. ***Polarization reconfigurable antennas***

   As the name implies these types of antennas may change their state of polarisation depending upon their requirement. For example at some cases antenna radiates in vertical polarization mode and in other case in horizontal polarization mode [23].

3. ***Radiation pattern reconfigurable antennas***

   The antenna radiation pattern may change in these cases. The change may take the form of altering the number of side lobes, nulls, beamwidth of the antennas, etc. [24].

3.13 Methods for achieving Frequency Reconfigurability

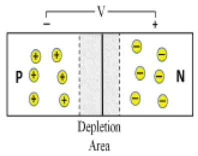
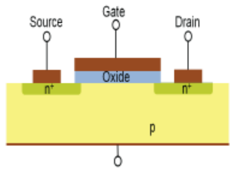
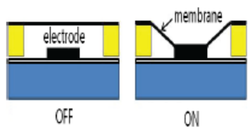
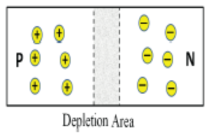
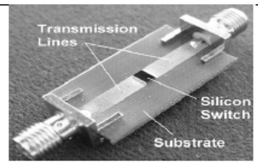
The frequency reconfigurable antennas are subdivided into two categories

i) Continuous frequency reconfigurable antennas ii) Switched transitional reconfigurable antennas

In *continuous frequency reconfigurable antennas* the variation in the operating frequency or the transition in between the frequency takes place smoothly. In *switched transitional reconfigurable antennas*, the sudden variation of frequency takes place with the help of different switching element.
These antennas has some operating principle, but they differ from the different switching techniques used. In theory it is proven that the effective length of the antenna is closely associated with the frequency of operation. Thus effective length variation also opens a door for frequency reconfigurability [19]. Number of techniques ahs been devised to change the effective length of the antenna having some merits and demerit.

3.13.1 Using Switches

The operating frequency of the antenna can be changed by changing its effective length. The length can be altered by attaching or detaching several parts of the antenna with the use of switches such as PIN [22] [16], RF-MEMS [35] [4] [16] Figure3.17 shows the example of a dipole antenna with photoconductive switch. In this dipole reconfigurable antenna, the switch is operated by an optical ray supplied by laser diode. So when both the switches are closed the operating frequency is 2.16 GHz, and when both the switches are open then the operating frequency is 3.15 GHz.

Device	Diagram	Description and Operation	Pros	Cons
p-i-n diodes		It has highly doped p-type and n-type regions separated by a wide lightly-doped intrinsic region. At high frequencies, when forward biased it acts like a low resistance and open circuit when reverse biased. [44].	• Low ON state loss. • Low OFF state capacitance. • Reasonable linearity. • Mature technology	• High dc power consumption. • Complex biasing.
FETs		Increasing the gate voltage allows current to flow between the source and drain. [44].	• Low ON state loss. • Low OFF state capacitance. • Low dc power consumption. • Good linearity. • Widely available in the 2.4 and 5 GHz bands	• Ultra-wideband SPST switches are not commercially available yet.
MEMs		Tiny mechanical switches made on a substrate. An electrostatic force pulls the beam down when a voltage is applied [44].	• Very Low ON state loss. • Very low OFF state capacitance. • Highly linear.	• Slow switching speed. • High actuation voltage (20–90 V). • Low reliability.
Varactors		It is a diode with a thin depletion layer and the capacitance is inversely proportional to the square root of the applied voltage [44].	• Continuous tunable operation. • Low dc power consumption	• Highly non-linear. • Analogue bias voltage required.
Optical switches		When silicon is illuminated by light, it changes from an insulator state to a near conducting state [23].	• Avoidance of biasing lines that could disturb the antenna performance.	• Not easy to integrate in some wireless devices.

Pros and cons of switching devices in reconfigurable antennas.

Non Linearity in Switching Devices:

The switching process in the reconfigurable antennas is the most delicate process as compared to other ones. It works well when the switches shows linear behaviour to the input signals. However slight nonlinearity in the switching devices may cause considerable undesired changes at the output. Reconfigurable antennas can be severely affected by such non linear behaviour of the switches. If the non linear system is inputted by a signal $x(t) = Acos(\omega t)$ the output can be represented by

$$y(t) = \sum_{i=0}^{\infty} B_i A^i cos^i(\omega t) \tag{3.19}$$

The third order term can be expressed as

$$B_3 A^3 cos^3(\omega t) = \frac{3}{4} B_3 A^3 cos^3(\omega t) + \frac{1}{4} B_3 A^3 cos^3(3\omega t) \tag{3.20}$$

It can be observed that the third order component is depended on the cube of the input signal. Thus it results in the gain compression of the system. In a similar way, when two tones with frequencies f_1 and f_2 are in the passband of a non linear system, they will generate third-order terms, with cubic dependence on the input signal magnitude, located at $2f_2 - f1$ and $2f_1 - f_2$ and these terms will cause intermodulation distortion.

In varactor diodes there is non linear relation between input reverse voltage and its capacitance. This in turn gives rise to the intermodulation distortion.

Also in case of PIN diodes, in te middle intrinsic region there is conductivity modulation of the charges during ON state and capacitance modulation in the OFF state. This is also a non linear process making the PIN diode also a non liner divices. The non linear relationship between the drain current (Ids) and the drain source voltage (Vds) in the FET switches also creates some distortion. Thus making FET switches unsuitable to be used in these types of antennas. But MEMs switches on the other hand have shown linearity in many areas of application. In MEMs metal to metal physical contact shows nearly linear behaviour with contact resistance of 1-2Ω. This is the reason why these types of switching devices have shown much popularity in the past decade.

Reliability of the switching devices:

The reliability of the device is directly related to the probability of the switching devices to perform switching for specified conditions for a predetermined operating time. The examples of the reliable switching devices are PIN diodes, varactor diodes, FET devices, etc. But due to the mechanical failure of the moving parts MEMs switches usually lacks reliability. Various techniques have been devised in the recent years to improve the linearity of the switching devices.

For instance, Panagamuwa et al. changed the effective length of a monopole antenna using optical switches, which helped to eliminate some of the switch and bias line effects that can occur with other kinds of switches. In this case, a balanced dipole fabricated on high-resistivity silicon was equipped with two silicon photoconducting switches, as shown in Figure3.17.

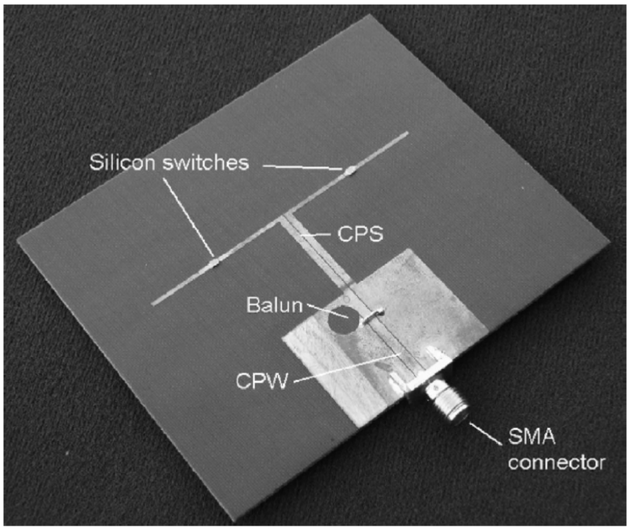


Figure 3.17: Photograph of an optically switched dipole antenna.

Light from infrared laser diodes guided with fiber-optic cables was used to control the switches. With both switches closed, the antenna operated at a lower frequency of 2.16

GHz, and with both switches open, the antenna operated at 3.15 GHz.

3.13.2 Variable Reactive Loading

This technique share the similar concept of frequency reconfigurability. All the parameters are same, but it differs from previous technology by the types of switches used. The switches are such that it gives the result of smooth or continuous frequency reconfigurability.The effective length is changed smoothly with the help of reactive element. Figure3.18 shows an example of variable reactive loading which has used RF-MEMS capacitors. The capacitors are mounted on a patch with CPW stubs and given the DC supply of 12V.

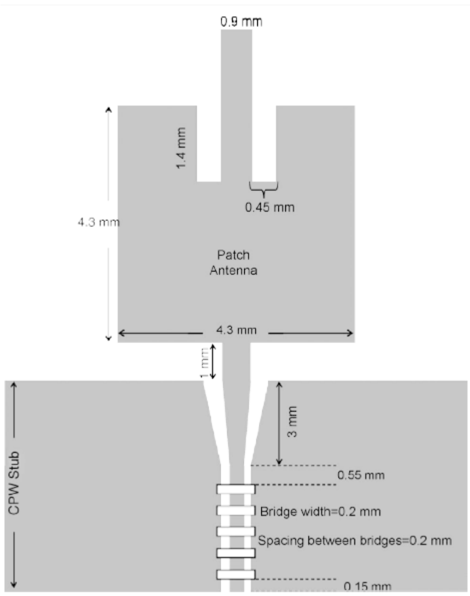


Figure 3.18: Frequency tunable microstrip patch antenna with RF-MEMS capacitors and CPW tuning stub.

3.13.3 Structural / Mechanical Changes

Larger shifts in the frequency bands can be achieved by employing the mechanical alteration rather than electrical one. This includes both switched or continuous reconfigurability.

Here the challenge is to design such type of radiator which can be altered mechanically without affecting the other dimensions of the antenna.The example of continuous frequency change is shown in the Figure3.19. It consist of a patch antenna mounted in such a way that the distance between it and the substrate can be mechanically varied. Here initially the patch antenna of 26 GHz is designed. It was having thin layer of magnetic material. The patch is slightly moved away from the substrate. By applying the DC magnetic field the process known as plastic deformation takes place at the boundaries in the points where the feed line is attached.

This varies the patch position at slight angles above the substrate. This change in angle causes the change in operating frequency. Small angles change the frequency without affecting the radiation characteristics. On the other hand large angles results in the shift in frequencies with noticeable change in radiation pattern.

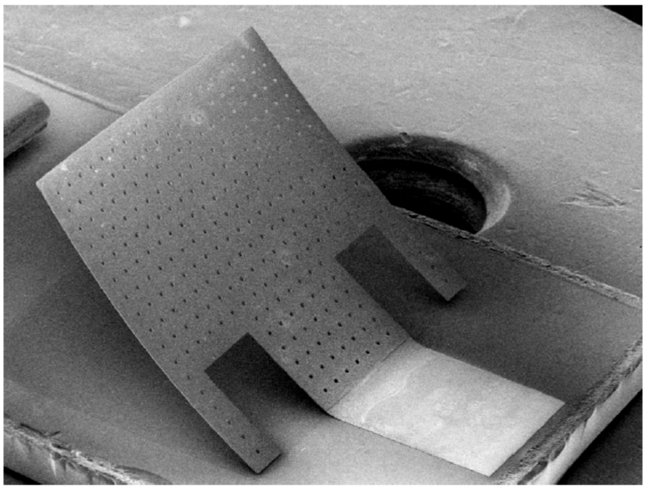


Figure 3.19: Photograph of magnetically actuated reconfigurable microstrip antenna.

3.13.4 Material Changes

The change in the material characteristics of the substrate used can also cause significant change to tune the antenna at different operating frequency. It can be easily altered by the application of external means. Reviewing the concept of material science, the relative permittivity of the ferroelectric materials is greatly affected by the application of external electric field. On the other hand the relative permeability of the ferrites is greatly affected by the application of external magnetic field. The effective length of the antenna is very much affected by these material changes. And thus shift in the frequency is obtained, as the operating frequency is directly related to the electrical length.

3.14 Methods for Achieving Polarization Reconfigurability

The performance of the communication system can be greatly improved by applying the *diversity* concept. Many diversity techniques are available for improving the communication link. This provides avoidance of interfering signals from the desired signals in varying environmental conditions. This is practically possible by the use of polarization reconfigurability of the antenna.

The polarization reconfigurability can be achieved by changing the convensional current flow on the antennas radiating element. This is achieved by changing the antenna geometry, basic material properties, feed positions, etc. If we use polarization reconfigurability, the antenna is practically shifted from one polarization state to other polarization state. This includes linear, right circular and left circular polarization states.

Though the implementation is quite different as that of frequency reconfigurability, the two shares almost the same concept and procedure to obtain reconfigurability. The mechanism for obtaining the change in geometry, material is almost same as in frequency reconfigurability.

3.15 Methods for Achieving Radiation Pattern Reconfigurability

The behaviour of the electrical current and their rate of change on a radiating element directly affect the radiation pattern distribution. Thus altering the behaviour of the currents to achieve Radiation pattern reconfigurability without giving rise to frequency reconfigurability is a difficult task.

A designer must be aware of what kind of source current required along with their magnitude and phase, so that he can design antennas with a particular radiation pattern. Once the behaviour of the current is studied, a baseline antenna can be designed or selected and it is afterwards altered to obtain the variation in the distribution of currents.

The later task of the designer is to manage not to change the operating frequency while obtaining pattern reconfigurability, since the currents also have some effects on the operating frequency. This is one of the critical task. In some design the designer keeps the input of the feeding arrangement quite isolated from the are to be reconfigured, so that frequency reconfigurability is avoided.

3.16 Advantages of Reconfigurable Antennas

1) Ability to support more than one wireless standard minimizes cost, minimizes volume requirement, simplifies integration, good isolation between different wireless standards.
2) Lower front end processing no need of front end filtering, good out-of-band rejection.
3) Best candidate for software-defined ratio capability to adapt and learn, automated via a microcontroller or a field programmable gate array (FPGA).
4) Multifunctional capabilities changes functionality as the mission changes, act as a single element or as an array, provide narrow band and wideband operation.

3.17 Limitations of Reconfigurable Antennas

1)Design of biasing network for activation/deactivation of the switching elements with add complexity to the antenna structure
2)Increased in the required power consumption due to the incorporation of active components which augments the system cost
3)Generation of harmonics and inter modulation products
4)Need for fast tuning in the antenna radiation characteristics to assure a correct functioning of the system.

3.18 Applications of Reconfigurable Antennas

1. ***Frequency Reconfigurable Antenna for a Cognitive Radio System:***
   The cognitive radios make use of frequency reconfigurable antennas [33] [1]. While operating in a particular frequency bands, sometimes the signal degrades due to the harsh environmental conditions. This radio then continuously monitors for the frequency which is unused. Thus obtaining better performance and minimises the interference with other frequency bands.

2. ***Pattern Reconfigurable Antenna for MIMO Systems:***
   Multiple antennas are employed in the MIMO system at both the transmitting and receiving ends. With the use of reconfigurable antennas various information can be sent simultaneously. Thus it increases the spectral efficiency.

3. ***Reconfigurable Antennas for Satellite Applications:***
   In applications of dynamic space, for serving better to the new coverage zone, it is quite essential to change or switch the existing radiation pattern of the antenna.

The satellite communication system greatly makes use of polarization reconfigurable antennas [33] to change their state of polarization according to the need of particular receiving stations. It is also used to reduce the fading concept. Thus the operation in higher data rate is possible [15].

CHAPTER **4**

Bandwidth and Efficiency Improvement of Microstrip Patch Antenna

The bandwidth enhancement techniques is classified as:

1) Intrinsic techniques of enhancement of bandwidth

2) External matching techniques

3) Non contact fed patches

Intrinsic techniques: It also has two subdivisions for bandwidth enhancement

i) Thick substrate material must be used ii) The lower dielectric constant substrate must be used

The above two techniques hen employed, bandwidth enhancement can be obtained up to 10%. Due to the use of thicker substrate materials, the feed line becomes more inductive which has some significant effect on the impedance. The input impedance locus thus becomes inductive. But these types of procedures is basically not suitable for edge type of feeding, to enhance the bandwidth. This is because the feeding structure can give rise to unwanted radiation. By increasing substrate thickness and also using substrate of less dielectric constant, the structure of feed line widens. Thus the overall radiation of the patch is reduced a little which is more noticeable at higher frequencies.

4.1 External matching structures

The external matching structures are used to enhance the bandwidth of the existing narrow-band of the order of 15%. But this in turn will solely depend upon the feeding structure and the nature of the substrate material. In several cases the antenna impedance acts as load impedance for the input feed line. The stubs are then used to match this impedance with the characteristic impedance of the feed line for complete power transfer to take place. Usually the impedance of the transmission line used is close to 50 ohms. The input impedance of the antenna though frequency depended, is then adjusted to 50 ohms at that particular operating frequency.

4.2 Non-contacts fed patches

The direct or contact feed structures introduce discontinuity in the current distribution on the radiating element. Thus Non contact fed techniques are suitable for enhancing the bandwidth. In the research it is found that the aperture coupled technique has given rise to wider bandwidth as compared to the proximity feeding counterpart. This is because the aperture technique consists of more than one radiator.

4.2.1 Horizontally coupled parasitic patches

If the parasitic elements are installed along with the main radiating element which is known as driven element, the bandwidth can be enhanced. The parasitic elements are not given any supply. Only there are placed near to the driven element. The field gets coupled to the surface of these elements causing currents to flow.

This is because if we use different patch geometries responsible for different resonant frequency, then along with the frequency of radiator, these frequencies also get radiated. Due to this the number of operating frequencies increases which in turn increases the bandwidth. The geometry of the patch is shown in the Figure4.1.

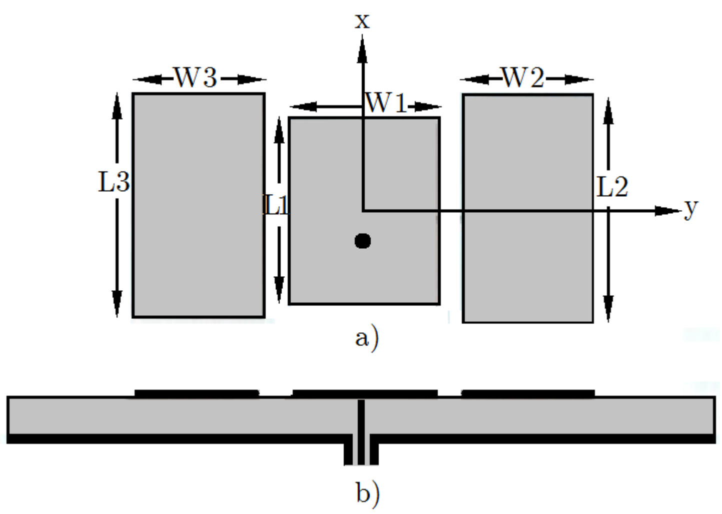


Figure 4.1: Horizontally coupled parasitic patches.

The gap between the driven element and the parasitic one plays very important role as it couples the power from driven element to parasitic elements. Hence it reduces the radius of resonant loop in the impedance locus.

4.3 Role of substrates

The other parameter which can change the impedance matching behaviour over the large range of frequencies, is the substrate used in the planar structures. It has been observed that the substrate having small dielectric constant enhances the bandwidth. The other techniques such as employing both the higher and lower dielectric substrate also have shown increment in the bandwidth. The use of lower dielectric substrate along with the foam has also resulted into wideband characteristics.

4.4 Efficiency improvements in the microstrip patch antennas

The efficiency of the microstrip patch antenna is greatly dependent upon the generation of the surface wave. The surface wave generation is the main cause of depriving the efficiency of the antenna. Thus the efficiency can be greatly improved if we reduce the formation of the surface wave. To understand this it is necessary to have background about the surface wave.

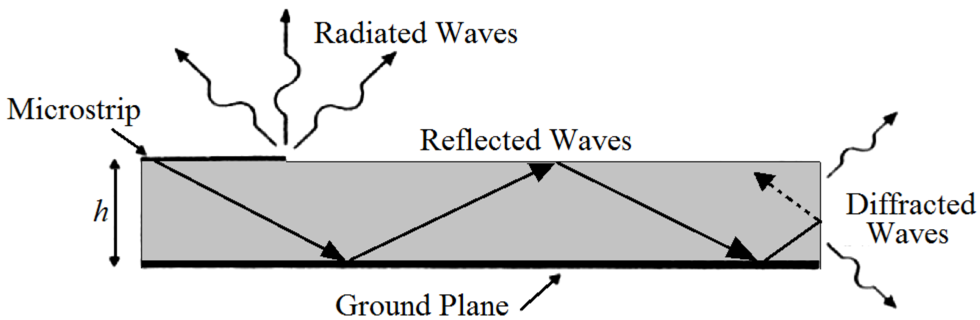


Figure 4.2: Consequences of surface waves.

Surface waves: These are the waves which are supported by the ground plane. These waves spread out or travel in a cylindrical way just around the feed or the excitation point. Its strength decreases with the distance of propagation. Thes wave while travelling also gets reflected by the ground plane and meet the ground substrate and at dielectric to air boundary.

Thus these waves get trapped in the substrate of dielectric and thus cause sufficient distortion to the desired signal to be radiated. This is because these waves takes up part of energy from the desired signal. The effect of the surface wave would be negligible if we use the ground plane of very large size. But in practice the ground plane is of finite size and thus gives rise to these waves unwontedly. While travelling, surface waves follow a zig-zag path until it reaches an edge or corner. After reaching the corner they get reflected and also diffracted by the edges as shown in Figure4.2. These diffracted waves gives rise to the additional radiation, thus degrading the antenna performance by producing ripples in the radiation pattern in the unwanted directions.

The surface waves can be reduced by decreasing the value of substrate thickness and also reducing the permittivity value. Thus less energy is coupled to the surface wave causing reduction in its value.

4.5 Motivation and Research Challenges

The motivation behind using the microstrip patch antenna along with the reconfigurable properties is straight forward. The capability of the antenna to operate multifunctionaly and avoiding the use of multiple antennas for specific different applications , provides the reduction in the system complexity and additional degree of operational freedom which helps in the the enhancement of the system performance. With the implementation of the reconfigurable techniques the antenna can be made to operate in the desired band with the help of switches such as RF-MEMS, PIN diodes, etc., which further helps the system to achieve its goal. Reconfigurable antennas are the main area of interest for the present researchers due to its enumerable merits. Howwever it also has some drawbaks, but its merits outweighs its demerits. The other motivations can be summarised as follows:

1. The antenna requirements for Satellite and RADAR communication or even smart wireless systems are not implemented in full scale yet. It is expected that the reconfigurable antennas will replace the conventional antennas in the coming years. Thus we can also expect that it will definetly find application in Satellite and RADAR communications for the reduction of system complexity.

2. The reconfigurable antennas that have been devised by the earlier researchers for wireless communication has wideband and narrowband functionality which can be switched between two or maximum three bands. The switchable capability in the standard microwave frequency band such as X, Ku and K band is not actually carried out by many researchers. This also is the reason behind the motivation to make qaud band reconfigurable antennas able to switch in between standard microwave frequency bands.

3. In the reasearch carried out on reconfigurable antennas by the several researchers, the switching assembly is generally near to the patch or in the patch. Almost none of the researchers have worked on the design having swiches near to the strip line. The main advantage of installing switches near to the strip line is that it can further be modified to the array antenna fed by the common microstrip line without disturbing the switching arrangements. This motivates to apply uinique switching arranements near to the feed line.

CHAPTER 5

Wideband Antenna Design

5.1 Design of a simple rectangular patch antenna which acts as a basic structure for the desired antenna.

5.1.1 Antenna Design Discussion and parameter calculations:

The structure which forms the base of my project is discussed in this section. Initially a simple rectangular patch antenna has been designed as shown in the Figure5.1.The design consist of a FR-4 substrate having dimensions 30x35x1.6 mm3. The FR-4 substrate has dielectric constant ε_r=4.3 and loss tangent of about 0.02. On this substrate a rectangular patch of dimensions 15x14.5mm is formed. Also at the backside of the substrate a full ground is formed. The patch is fed by a 50 ohm quarter wavelength transmission line. This type of feeding is known as microstrip line feeding technique. The dimensions of the antenna is calculated by considering the transmission line model of the rectangular patch antenna.

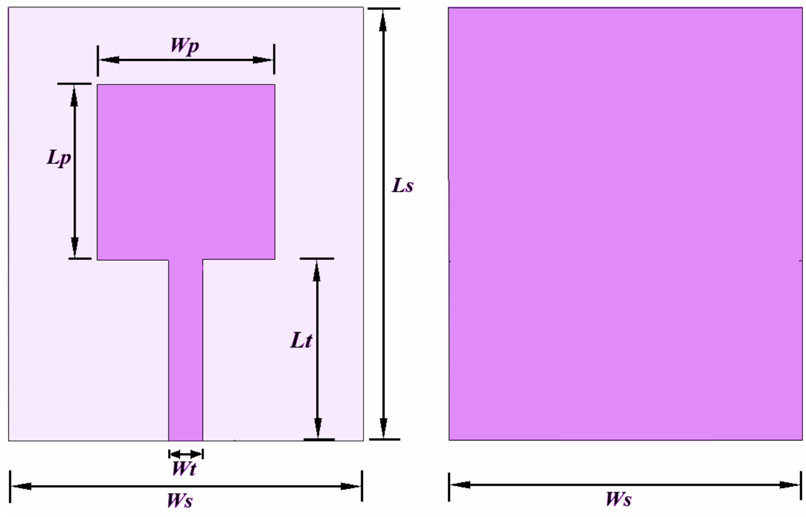


Figure 5.1: Design of the antenna of 6 GHz.

Table 5.1: Design parameter dimensions of antenna having 6 GHz resonant frequency.

Parameters	Values(mm)
Ws	30
Ls	36.7
Wp	15.35
Lp	11.45
Lt	15.5
Wt	2.9

Calculation:

Given: f=6 GHz, Dielectric Constant ε_r=4.3, Loss tangent δ=0.02, h=1.6mm

The width of the patch can be calculated by :-

$$W_p = \frac{c}{2f_0\sqrt{\frac{\varepsilon_r+1}{2}}}$$

$$= \frac{3\times 10^8}{2\times 6\times 10^9\times\sqrt{\frac{4.3+1}{2}}} = 15.35\ mm.$$

The effective dielectric constant then will be:-

$$\varepsilon_{reff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left[\frac{1}{\sqrt{1 + 12\left(\frac{h}{W_p}\right)}}\right]$$

$$= \frac{4.3 + 1}{2} + \frac{4.3 - 1}{2}\left[\frac{1}{\sqrt{1 + 12\left(\frac{1.6}{15.35}\right)}}\right] = 3.75\ mm.$$

The length of the patch is found out by:-

$$L_p = \frac{c}{2f_0\sqrt{\varepsilon_{reff}}} - 0.824h\left(\frac{(\varepsilon_{reff} + 0.3)\left(\frac{W_p}{h} + 0.264\right)}{(\varepsilon_{eff} - 0.258)\left(\frac{W_p}{h} + 0.8\right)}\right)$$

$$= \frac{3 \times 10^8}{2 \times 6 \times 10^9\sqrt{3.75}} - 0.824 \times 1.6\left(\frac{(3.75 + 0.3)\left(\frac{15.35}{1.6} + 0.264\right)}{(3.75 - 0.258)\left(\frac{15.35}{1.6} + 0.8\right)}\right)$$

$$= 11.45\ mm.$$

5.1.2 Simulation Results Discussions:

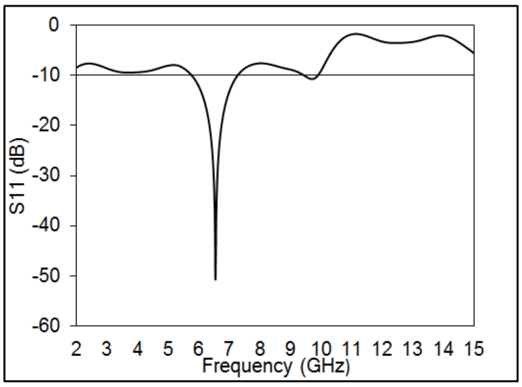


Figure 5.2: S11 plot of the proposed antenna.

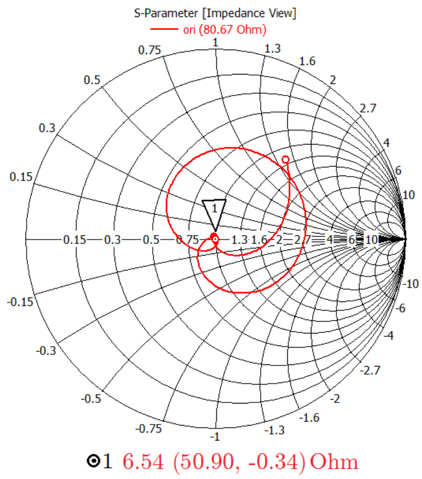


Figure 5.3: Smith chart of the proposed antenna.

The results are simulate using CST microwave studio [43]. The S11 and the associated smith chart plot of the designed antenna is illustrated in the Figure5.2 and Figure5.3 respectively. The impedance matching is achieved perfectly at the resonant frequency 6.5 GHz with return loss of about -50db.

The smith chart shows the matching property of the designed antenna with the transmission. The smith chart is the plot of the normalised input impedance of the antenna. It is plotted for the frequency ranging from 2 to 15 GHz. But at resonance frequency the real part of the antenna impedance is equal to the characteristic impedance of the transmission line which is of 50 ohm. And the associated imaginary part becomes negligible at that frequency.

This shows that the antenna is perfectly matched at that frequency. Thus the maximum power is transferred to the antenna with minimum refection. And also the voltage standing wave ratio (VSWR) is close to unity. This antenna's patch geometry is further modified to get wideband characteristics. Which in turn will be modified to get the desired multiband reconfigurable characteristics.

5.2 Design of a wideband antenna as a modification of simple rectangular path antenna.

5.2.1 Achieving wideband antenna characteristics

One of the major limitations of conventional microstrip patch antenna is that its bandwidth is quite narrow of the order of 15-50% of the centre frequency. The researchers have worked over this limitation and now several methods have been devised to overcome this main demerit of the patch antenna. These methods include varying the size of patch or by varying height, volume of the antenna. Or even by changing the type of feeding mechanism used. In the past decade many bandwidth enhancement schemes have been developed.

For improving the operating bandwidth of the antenna, several techniques have been suggested. First the patch can be modified in different shapes. For example patch may be having bevel or smooth bottom for obtaining better impedance matching. Secondly different types of slots having different shapes can be employed in the radiating element for the impedance matching improvement, especially at higher frequencies.

Thirdly, partial grounding technique or feed gap between patch and the ground plane may be used for enhancing the bandwidth. Fourthly, at the bottom of the rectangular or square patch if two notches are cut, will also improve the bandwidth since they greatly influences the coupling between the radiator and the ground plane. Finally by employing different types of feeding techniques the bandwidth can be enhanced. By the optimization of the feed point, the antenna impedance can be widened further. This is because by changing the feed point the input impedance of the antenna can also be changed.

5.2.2 Reduction of ground plane effect on antenna performance

For the designing of the UWB antennas the geometry of the patch and the ground greatly influences the characteristics of antennas. Slight modification can play a big role in the final outcome. The assembly of the patch and the ground plane initially forms as an unbalanced design.

The currents which are fed by the microstrip line is spread both on the patch as well as on the ground plane. The ground plane thus unwantedly radiates little bit. Thus printed or planar ultrawideband antenna's performance is affected mostly by the size of the ground plane. So by reducing the ground and making it patial ground, the unwanted radiation is reduced significantly, giving better impedance matching at the wider range of frequency.

5.2.3 Design discussion of the wideband antenna

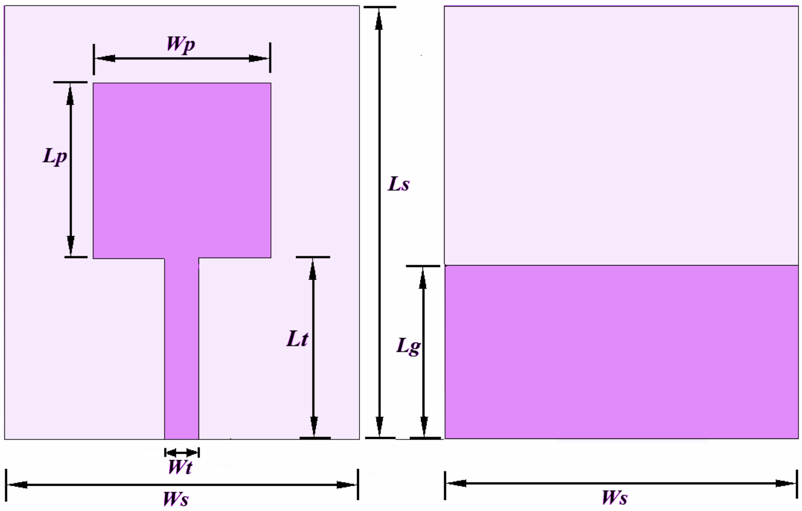


Figure 5.4: Design of the wideband antenna.

Table 5.2: Design parameter dimensions of wideband antenna.

Parameters	**Values(mm)**	**Parameters**	**Values(mm)**
Ws	30	*Ls*	36.7
Wp	15.35	*Lp*	11.45
Lt	15.5	*Wt*	2.9
Lg	15.2		

5.2.4 Observation from simulated S11 plot

The S11 plot of the previous antenna along with the S11 plot of the wideband antenna with variation of the length of the ground plane is shown in Fibure5.5. With the full ground the corner frequency at -10 dB return loss of that antenna is f1=6.20 GHz and f2=7GHz i.e percentage bandwidth is about 12.12%, with the resonant frequency 6.5GHz having return loss -51.2dB.

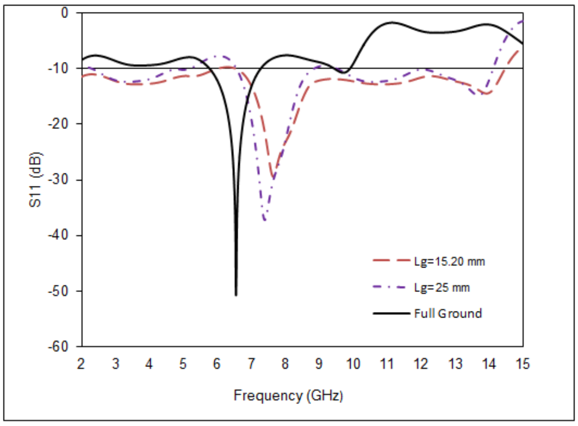


Figure 5.5: S11 plot of the proposed antenna.

After the reduction of the length of the ground with Lg=20, the corner frequencies have changed to f1=6.9 GHz to 9 GHz with 25.70% percentage bandwidth. This structure resonates at 7.4 GHz with return loss -38.5dB. It can be observed that the return loss is increased at the resonant frequency and the bandwidth has been enhanced with the use of partial ground. The bandwidth has been enhanced due to the impedance matching in the frequency range 6.9 GHz to 9 GHz. Further parametric analysis is carried out with Lg=15.2 .The associated return loss is shown. It can be observed that the corner frequency is drastically changed to f1=7 GHz to 14.6 GHz with the percentage bandwidth of about 70.4%. again we can say that the return loss of that particular resonant frequency has been increased further. Also the bandwidth is greatly increased due to impedance matching over large frequency range. The ground plane dimensions were found to be very important parameters in the antenna design, because of strong dependence of bandwidth on ground plane size. It was found that the introduction of partial ground plane have greatly improved the value of VSWR in the operating frequency. The ground length also affected the VSWR value. This phenomenon can be explained when the ground plane is treated as a part of the antenna. When the ground plane size is large, the current flow on the top edge of the ground plane is increases. This corresponds to an increase of the inductance of the antenna if it is treated as a resonating circuit, which causes the first resonance mode either up-shifted or down-shifted in the spectrum. Also, this change of inductance causes the frequencies of the higher harmonics to be unevenly shifted. Therefore, the size of the ground plane makes some resonances become not so closely spaced across the spectrum and reduces the overlapping between them. Thus, the impedance matching becomes worse (return loss $\geq -10dB$) in ultra-wide frequency band.

With this value of Lg=15.2 . We get the maximum enhancement in the bandwidth.

CHAPTER 6

Multiband Antenna Design

6.1 Introduction of defective ground.

We have discussed the effect of partial ground in the previous section. The parametric study of the length of the ground plane is discused in the previous section. The length of the ground plane is being finalised which has given desired results. But this only gives the wideband characteristic to the antenna. But the design did not stop upto this. It must be first converted to the multiband antenna for reconfigurability. Multiband antennas are the antennas which operates efficiently in all its resonant frequencies.

Several researchers have devised different shapes of the radiating element. Most of the researchers have worked on the patch for obtaining the multiband behaviour. But in my design the changes are made in the ground plane. To make the behaviour of the antenna closer to the multiband behaviour I have introduced the defective ground to the existing partial ground. As shown the changes is only made in the ground structure. The defective ground also has a slot in the middle.

6.1.1 Antenna Design

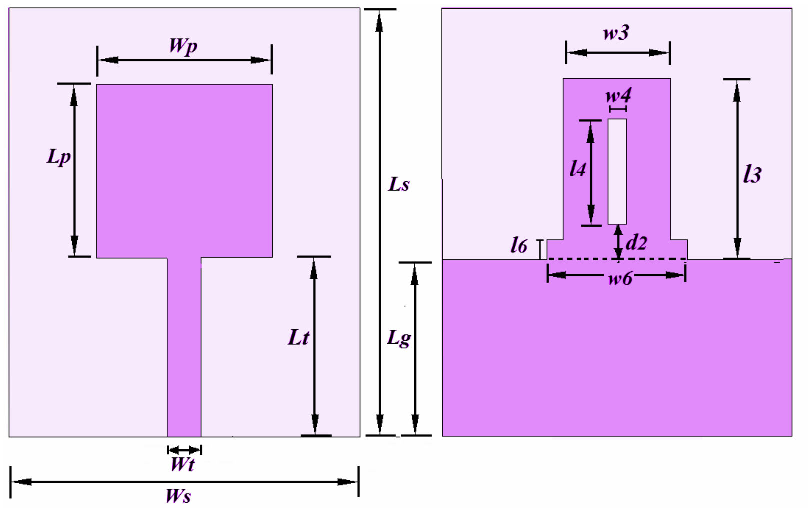


Figure 6.1: Antenna with defective ground.

Table 6.1: Design parameter dimensions of antenna with defective ground.

Parameters	**Values(mm)**	**Parameters**	**Values(mm)**
Ws	30	*Ls*	36.7
Wp	15	*Lp*	14.3
Lt	15.5	*Wt*	2.9
Lg	15.2	*l3*	15.8
w3	9.2	*l4*	9
w4	1.6	*d2*	3
l6	1.7	*w6*	12

6.1.2 Simulation results

To enhance the bandwidth and reduce the ground plane effect further, the top edge of the partial ground plane is reshaped to form a symmetrical rectangular shape top edge by cutting of rectangular shape slot as shown in Figure6.1).

This technique alter the distance between the ground plane and lower part of planar monopole antenna and tune the capacitive coupling between them resulting in wider operating bandwidth. The optimized dimension of the rectangular shape slot is 9x1.6mm. From the return loss curve shown in Figure6.2 it is seen that the modified ground plane with rectangular shape top edge has a little effect on lower edge frequency while it significantly influence the upper edge frequency of the operating band as expected.

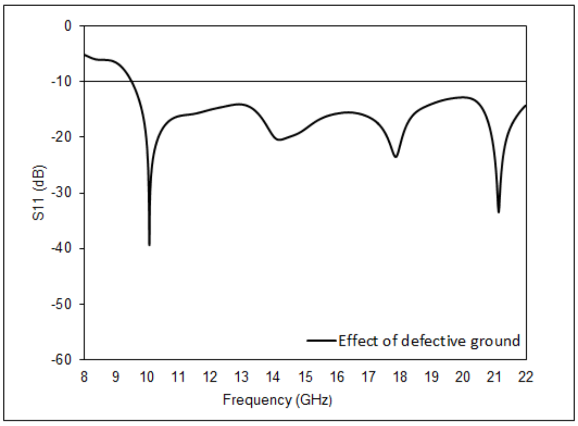


Figure 6.2: S11 plot of the anenna with defective ground.

It is also observed that, introduction of rectangular shaped slots not only widens the bandwidth but also reduces the return loss. The insertion of slots in the top edge of the ground plane increases the gap between the radiating patch and the ground plane and as a result the impedance bandwidth increases further due to extra electromagnetic coupling in between radiating element and the ground plane. Compared to the result associated with the initial design, the antenna with modified rectangular shape ground plane can increase the bandwidth by 13.47% as depicted in Figure6.2.

It is seen that compared to partial ground plane without any slot and with a rectangular slot, the antenna with rectangular shape ground plane exhibit less capacitive load to the antenna especially at higher frequencies of the operating band, which means the impedance match is getting better, thus leading to a wider operating bandwidth as illustrated in Figure6.2.

6.2 Introduction of slot in the radiating patch for the creation of multiband characteristics

6.2.1 Antenna Design

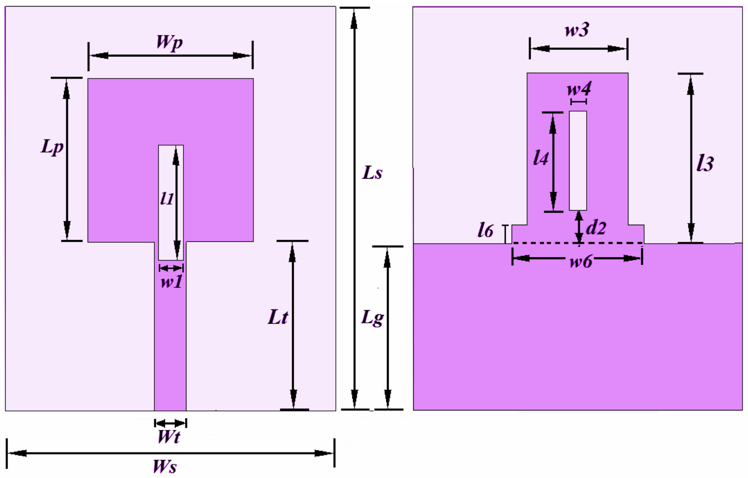


Figure 6.3: Design of the antenna with rectangular slot.

Table 6.2: Design parameter dimensions of the antenna.

Parameters	Values(mm)	Parameters	Values(mm)
Ws	30	*Ls*	36.7
Wp	15	*Lp*	14.3
Lt	15.5	*Wt*	2.9
l1	15.4	*w1*	2.2
Lg	15.2	*l3*	15.8
w3	9.2	*l4*	9
w4	1.6	*d2*	3
l6	1.7	*w6*	12

After designing the antenna for the wideband characteristics my next aim was to make this antenna a multiband one. So for this the introduction of notch frequency is must. The widely used technique for this kind of purpose is by embedding a narrow slot in the radiating patch. This changes the regular current flow on the patch. Researchers have used different shapes of slot in their work. But most widely used is a rectangular shaped slot which is also used in my project. By cutting a single and multiband half wavelength rectangular shaped slots in the radiating patch, single and multiband notch functions have been generated.

Thus due to this reason the slot l1xw1 has been introduced in the patch. In this section we will discuss the effect of introducing the slot and its importance in achieving the notch frequency in between first and second operating frequency bands.

6.2.2 Simulated Results

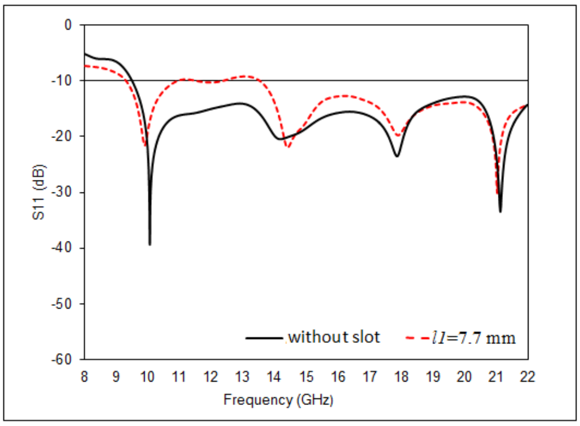


Figure 6.4: S11 plot showwing the formation of notch.

The S11 plot after the introduction of the rectangular slot on the patch is shown in the Figure6.4. It can be seen that the slot has its significant effect on the first notch and a negligible effect on the remaining notch frequencies. The length of the slot $l1$ can be calculated by the formula given below

6.3 Introduction of slot *l2* in the existing patch design.

6.3.1 Antenna Design

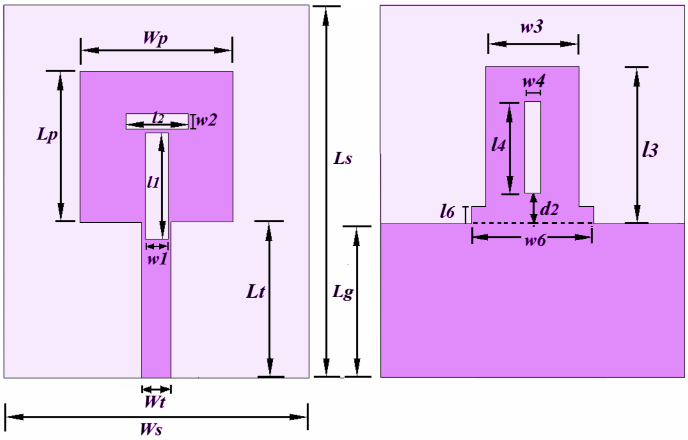


Figure 6.5: design of the antenna with the introduction of slot *l2*

Table 6.3: Design parameter dimensions of the antenna.

Parameters	**Values(mm)**	**Parameters**	**Values(mm)**
Ws	30	*Ls*	36.7
Wp	15	*Lp*	14.3
Lt	15.5	*Wt*	2.9
l1	15.4	*w1*	2.2
l2	6.1	*w2*	3
Lg	15.2	*l3*	15.8
w3	9.2	*l4*	9
w4	1.6	*d2*	3
l6	1.7	*w6*	12

In the previous design, due to the inclusion of slot $l1 \times w1$, only the first notch is created. But to have the multiband criteria other natch establishment is also essential. Thus the further modification of the patch is necessary. As it can be shown in the Figure6.5, the second slot $l2 \times w2$ is introduced in the existing geometry of the patch. It will be cleared by observing the S11 plot, that this slot is responsible for second notch creation.

6.3.2 Simulation Results

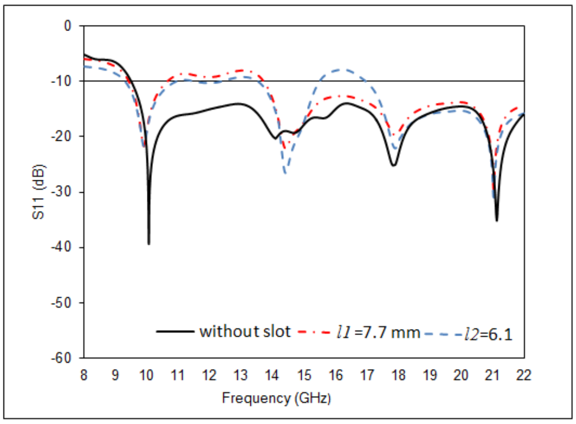


Figure 6.6: S11 plot showing formation of the second notch.

The simulated S11 plot is shown in Figure6.6. Note that the $l2 = 0$ corresponds to the patch without any slot created whose S11 is shown by the solid line. And also as discussed earlier the $l1 = 7.7mm$ plot creates the first notch as shown by the dash and dot line. Now the third graph shows the effect of slot $l2 \times w2$. This is shown by the dashed line. We can observe that this slot is responsible for the formation of the second notch. But it has negligible effect on the other notch frequencies. So we can say that slot $l2 \times w2$ is mainly responsible for this notch creation. All this methods are widely used to reject a fixed frequency bands. This happens due to the fact that at the notch frequency due to the slot $l2 \times w2$, maximum mismatch occurs thus increasing the return loss and the most of the power is reflected back.

6.4 Introduction of slot $l7 \times w1$ in the previous design

6.4.1 Antenna Design

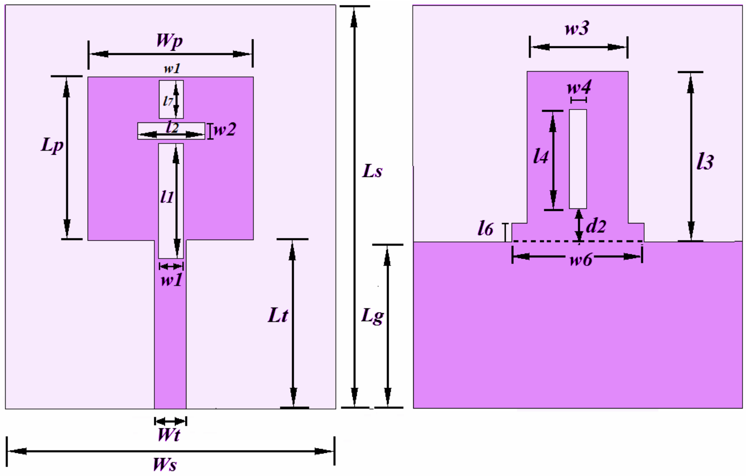


Figure 6.7: Antenna design having upper slot *l7xw1*

Table 6.4: Design parameter dimensions of the antenna.

Parameters	Values(mm)	Parameters	Values(mm)
Ws	30	*Ls*	36.7
Wp	15	*Lp*	14.3
Lt	15.5	*Wt*	2.9
l1	15.4	*w1*	2.2
l2	6.1	*w2*	3
Lg	15.2	*l3*	15.8
w3	9.2	*l4*	9
w4	1.6	*l7*	3.6
d2	3	*w6*	12
l6	1.7		

Up till now the two notch is created with the two individual slots, solely responsible for their respective notch creation. However the third notch is to be needed to completely isolate the third and the fourth band. This is done by the inclusion of the third slot $l7 \times w1$. This is positioned above the $l2 \times w2$ slot. In the following section it will be shown that this slot is responsible for third notch creation. However up till now the remaining antenna geometry is still undisturbed.

6.4.2 Simulated results

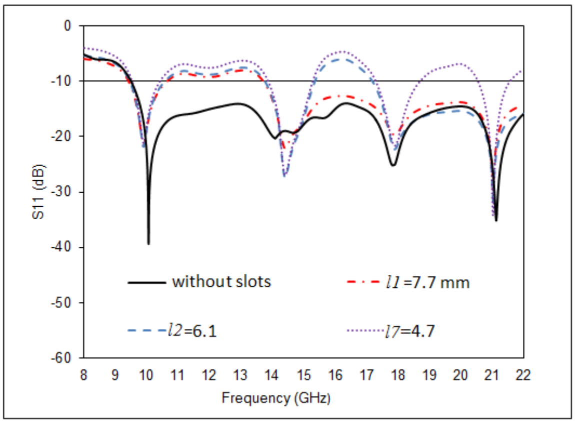


Figure 6.8: S11 plot showing formation of the third notch.

The S11 plot of the patch along with the three slots is shown in the Figure6.8. This S11 plot clearly shows the effect of each and every slot separately. We have discuused the effect of previous slots in the preceding sections. The slot $l7 \times w1$ has been introduced into the patch geometry along with the existing two slots. Clearly it can be observed that the slot $l7 \times w1$ crates the third notch between the third and the fourth bands. This can be observed from the dotted graph in the Figure6.8. So the whole assembly of patch along with the three patch has made the antenna a quad band antenna with the return loss in the range of -30 to -40 dB. We can say that the multiband behaviour is mainly obtained by the introduction three slot in the plane rectangular patch.

6.5 Increment in the width w2 and its effect on S11 plot

6.5.1 Antenna Design

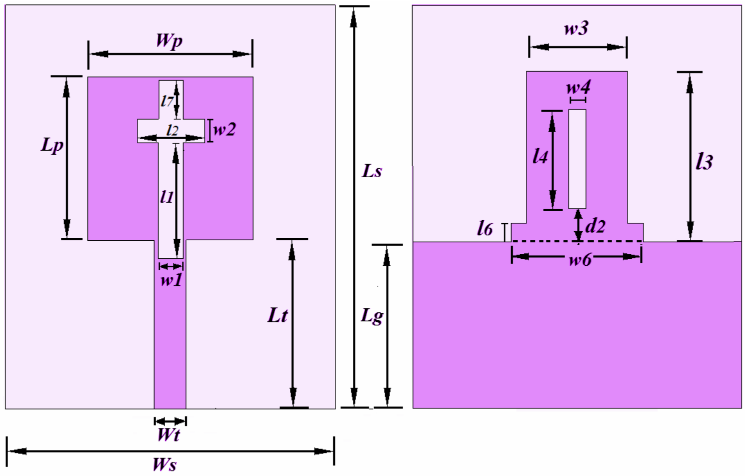


Figure 6.9: Design of the antenna with cross slot.

Table 6.5: Design parameter dimensions of the antenna.

Parameters	Values(mm)	Parameters	Values(mm)
Ws	30	*Ls*	36.7
Wp	15	*Lp*	14.3
Lt	15.5	*Wt*	2.9
l1	15.4	*w1*	2.2
l2	6.1	*w2*	3
Lg	15.2	*l3*	15.8
w3	9.2	*l4*	9
w4	1.6	*l7*	3.6
d2	3	*w6*	12
l6	1.7		

The three slot effect has been discussed in the preceding sections along with their effect in the S11 plots. In this section we will discuss about the effect in the increment of the width *w*2 of the middle slot. As it can be seen from Figure6.9 that due to the increment in the width the three slots are merged with each other to form the cross shaped slot. The effect of increment is discussed in the below section.

6.5.2 Simulated Results

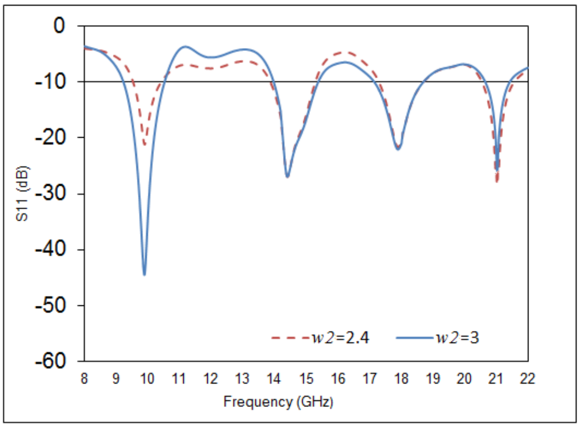


Figure 6.10: S11 plot of the antenna with cross slot.

The S11 plot of the arrangement is shown in the Figure6.10 with initial and final values of *w*2. It can be observed that it mainly affect the first resonance frequency and also the first notch frequency. Due to the increment in the *w*2 the return loss of the first resonant has increased a lot. So we can say better impedance matching has taken place for the first band. Also the first notch frequency has been shifted upwards which shows better isolation between the first and the second band. This increment in the width *w*2 has hardly affected any of the other resonant frequency and also the other notch frequencies. In the later section we will discuss the improving in the return loss characteristics for the other remaining bands with slight change in the patch geometry.

6.6 Introduction of the corner cuts at the three edges

6.6.1 Antenna Design

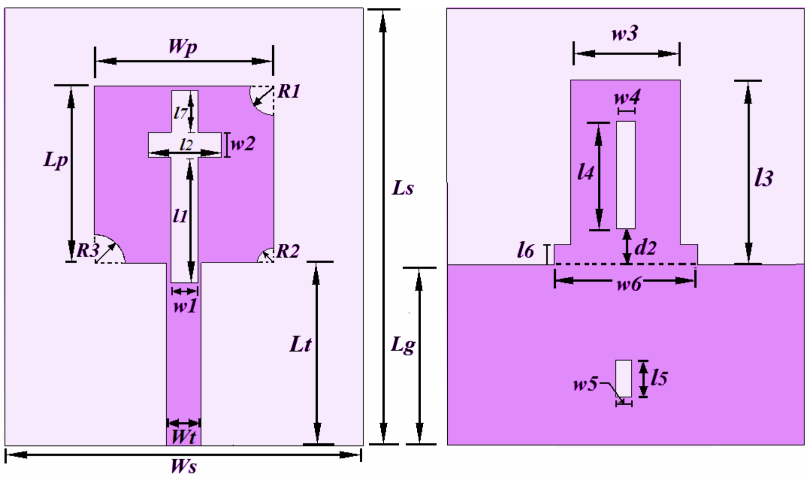


Figure 6.11: Antenna design with corner cuts

Table 6.6: Design parameter dimensions of antenna with corner cuts.

Parameters	Values(mm)	Parameters	Values(mm)
Ws	30	*Ls*	36.7
Wp	15	*Lp*	14.3
Lt	15.5	*Wt*	2.9
l1	15.4	*w1*	2.2
l2	6.1	*w2*	3
Lg	15.2	*l3*	15.8
w3	9.2	*l4*	9
w4	1.6	*l7*	3.6
d2	3	*l5*	3.5
w5	1.5	*w6*	12
l6	1.7	*R1*	2
R2	1.4	*R3*	2.6

In the last section we almost achieved the multiband behaviour of the antenna. The return loss for the first band is quit appreciable and perfectly matched with the feeding line. However the other bands have the return loss in the range -20 dB to -30 dB. In order to reduce the return loss for the remaining three bands some modification in the patch is done. We can see that the three edges has been cut circularly with three different values of radius. We can say these cuts as a corner cuts at three edges. Also I have introduced a small slot $w5 \times l5$ at the ground plane just beneath the transmission line which shows a specific purpose.

6.6.2 Simulated Results

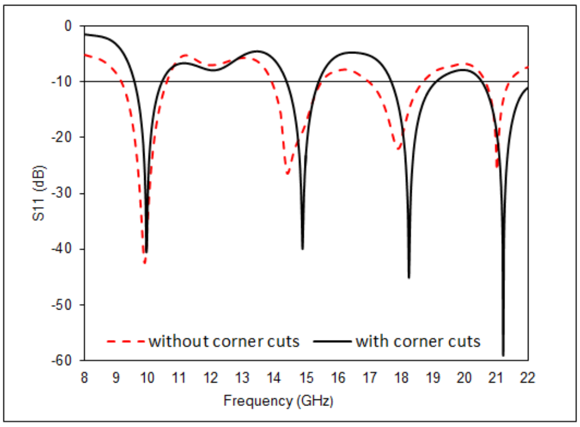


Figure 6.12: S11 improvement by the introduction of corner cuts.

Due to the three corner cuts the impedance matching is greatly improved for the last three bands. Due to this the return loss is decreased a lot and it is in the range -40 dB to -60 dB. The effect of the corner cuts is significant for the last band as the return loss is greatly reduced from -25 dB to -60 dB.

Other thing which need to be considered here is that due to the encroachment of the slot $l1 \times w1$ into the feed line the main characteristic impedance of the feed line slightly deviates from its nominal value of 50 ohms. In order to make the value of the feed line impedance again of 50 Ω a small rectangular slot beneath the feed line at the ground plane is introduced. It can be observed from the smith chart that the feed line impedance has been made 50.03 Ω.

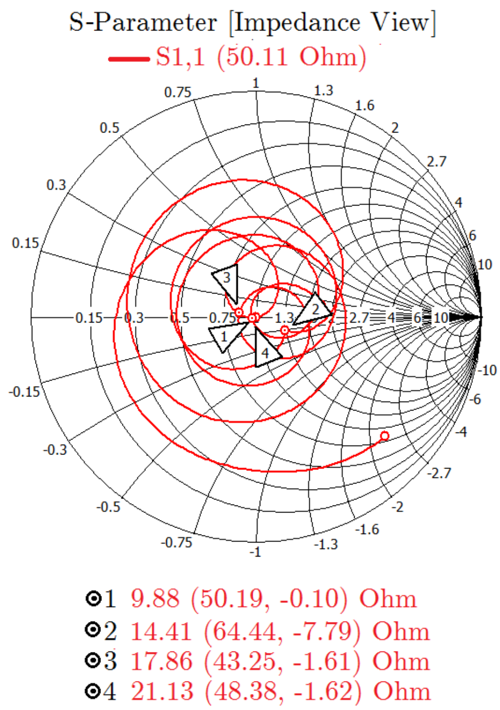


Figure 6.13: Smith Chart of the antenna before inclusion of corner cuts.

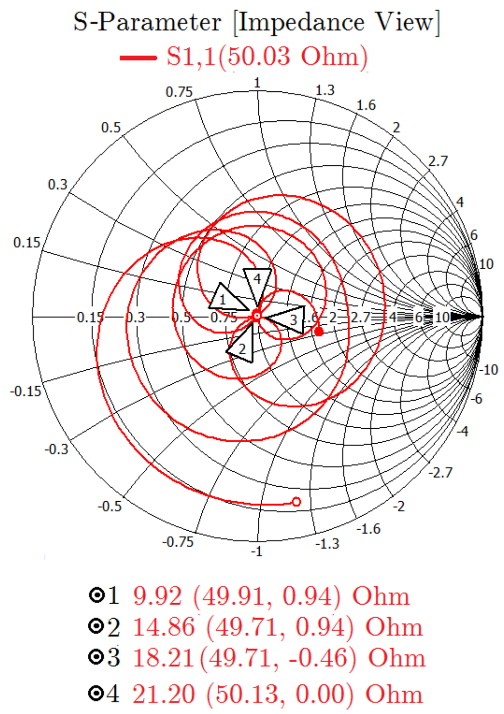


Figure 6.14: Smith Chart of the antenna after inclusion of corner cuts.

From the literature we know that the smith chart is quite useful for analysing the impedance matching characteristics of the device. The smith chart usually shows the plot of normalised input impedance of the antenna. If the plot crosses the (1, 0) point, this indicates that the input impedance is equal to the characteristics impedance of the feed line with imaginary part equal to zero at resonant frequencies. If the plot does not crosses this point at the desired resonant frequency, we can say that the impedance is not properly matched at that frequency and the return loss is very high. This will have incomplete power transmission to the load which here in our case is the Patch antenna. So efforts is to be made to make the plot to cross the point (1, 0) at that resonant frequency. The smith chart of with corner cuts and without corner cuts is shown on the Figure6.13 and Figure6.14. We can see from the smith chart a), that input impedance of the antenna for the first band is closer to 50 Ohms and is perfectly matched to the feed line. But for the other three bands the input impedance is not closer to 50 Ohms which causes some mismatch with feed line. So we can observe from the chart that there is some capacitive effect for the three bands and also the real part is not exactly 50 Ohms.

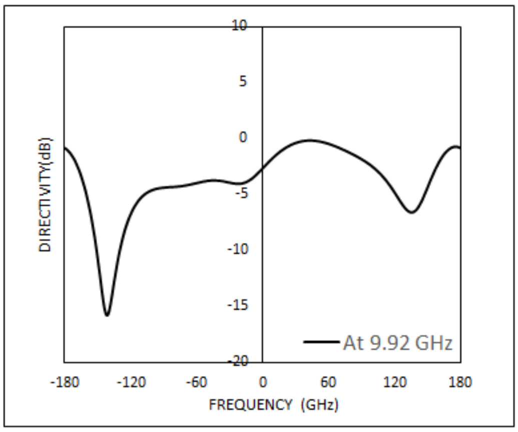


Figure 6.15: Directivity plot at 9.94 GHz

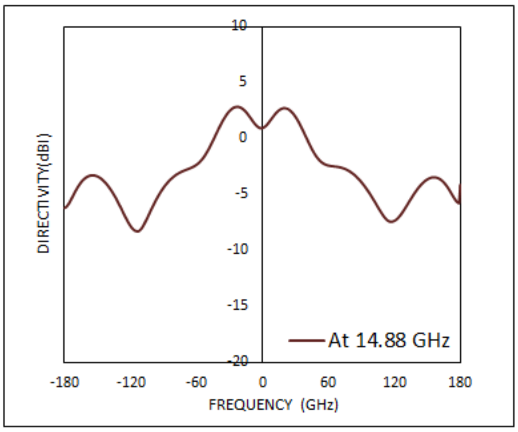


Figure 6.16: Directivity plot at 14.88 GHz

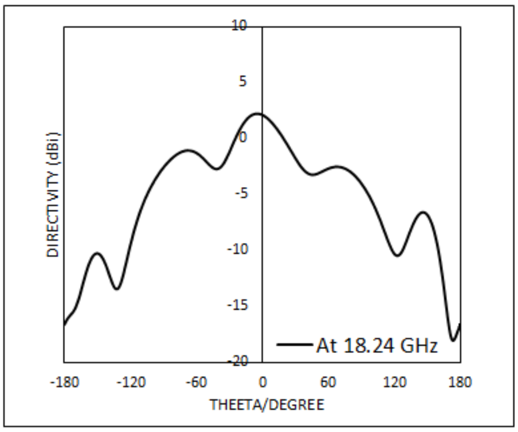


Figure 6.17: Directivity plot at 18.34 GHz.

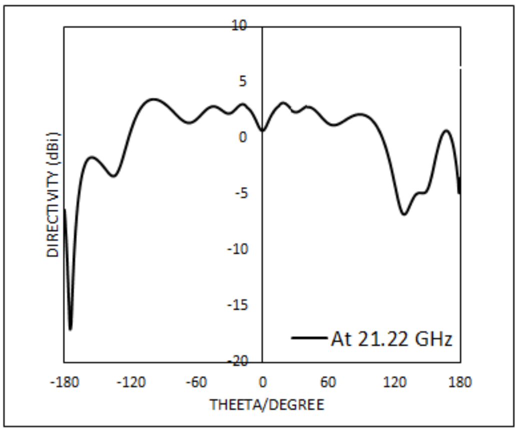


Figure 6.18: Directivity plot at 21.22 GHz.

After the introduction of the corner cuts of different radius of R1, R3, and R3 some inductive effects is introduced in the antenna impedance. This inductive effect cancels the capacitive effect to make the imaginary part approximately equal to zero at the resonant frequencies of respective bands, making the imaginary part approximately zero. Also the corner cuts have the effect on the real of the impedance making it closer to 50 Ohms. Thus all the four bands are completely matched with feed line of 50 Ohm impedance with minimum return loss.

The Figure6.15, Figure6.16, Figure6.17 and Figure6.18 shows the directivity plot of the quadband antenna at four resonant frequencies. We can observe that the antenna radiates well in the desired direction with maximum directivity in that direction and relatively less in the other direction. We can clearly observe that at lower band number of side lobes is less. In the middle band the sidelobes gets increased. And finally at the higher band large number sidelobes are formed. This is common in all the multiband antennas. The main thing we need to consider here is that the directivity is maximum in the required direction.

CHAPTER 7

A Quad-Band Frequency Reconfigurable Antenna with Shorted Stubs for Microwave Applications

7.1 Inroduction

Up till now the quad band antenna was designed successfully with the desired return loss. The return loss as low as -60 dB is obtained which is very good. The designed discussed in the last section was a perfect candidate for variety of applications where the antenna is operated in all the three bands simultaneously. It also provides sufficient isolation between the adjacent bands to avoid any interference in between the bands. However due to the increase in demand for more compact antennas which shows multifunctional properties has increased in the past decade. Due to the advancement in the wireless technology a single device can be operated in several frequency bands. For this reconfigurable antennas are the need of the day.

Situation arises where the antenna sometimes needed to be operated in single bands or multiple bands, depending on the application. If the system requires to be operated in single band, then the antenna should be inactive for the remaining bands so as to minimize power wastage. For this case the antenna should operate as single band antenna.

If system requires multiple frequency bands to be received, then the same antenna should used for this case acting as a multiband antenna. Using the same antenna for different application reduces the size of the system. This property is very much desired in the present era of communication. The reconfigurable antennas is finding importance in this area. Several researchers are working in the field of the reconfigurable antenna as these types of antenna is highly demanded in the present world. Thus the quadband antenna is converted into a reconfigurable antenna by the application of rectangular parasitic elements which is positioned near to the feeding line. Stepwise analysis has been carried out showing the passing of a particular frequency band and the rejection of the other bands.

7.2 Antenna operation in the first band

Various reconfigurability techniques has been devised by the researcher for the switching in between the bands. But in this project I have used the concept of band filtering. Microwave filter kind of structure is made over the existing design of the patch. To operate antenna in single band the input is passed first to this filter. We know in simulation software almost infinite amount of frequency component is inputted via the input port. In time domain it looks like an impulse shape. This signal is then passed to an adjustable (switchable) filter that will pass a particular range of frequencies. These frequency is then radiated by the antenna.

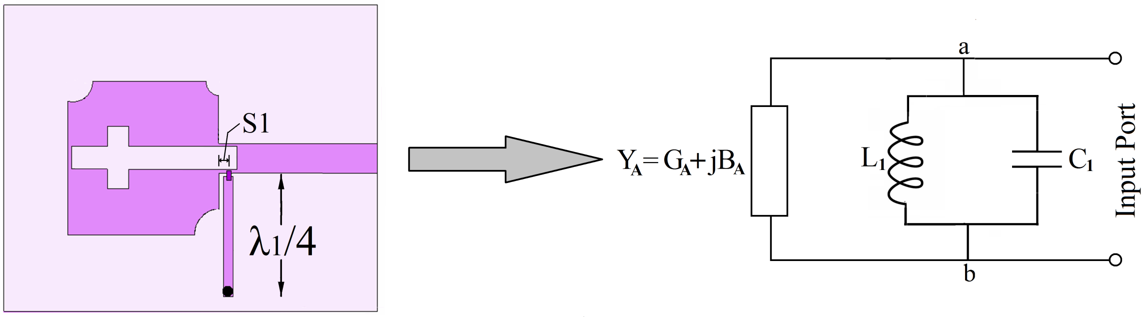


Figure 7.1: Equivalent circuit for operation in the first band.

The deign of the antenna and its equivalent circuit is shown in Figure7.5. The parasitic elements acts like a shorted stubs which is used to match the input impedance if the antenna to the characteristic impedance of the transmission line, for a particular frequency. The length of the stubs play a very important role in determining which frequency is to be passed. It is calculated as $\lambda_1/4$ where λ_1 is associated with resonant frequency of the band1. The antenna acts as a load in this case with admittance Ya. And the stub is equivalent to the LC network, which acts as a band pass filter. Let us assume that the characteristic impedance be rael i.e Z_0. So the associated admittance will also be real i.e G_0.

The admittance between a and b is given by:

$$Y_{abS1}(due\ to\ load\ Y_A) = Y_0 \left[\frac{Y_A + jY_0 tan\beta_1 S_1}{Y_0 + jY_A tan\beta_1 S_1} \right]$$
$$= G_{abS1} + jB_{abS1}$$
$$Y_{ab}(due\ to\ the\ stub) = j(B_C - B_L)$$

where β_1 is the phase constant associated by λ_1 and is given by $\beta_1 = \frac{2\pi}{\lambda_1}$. Now combining these two effects to find the total admittance at point a and b we get,

$$Y_{ab} = G_{abS1} + jB_{abS1} + j(B_C - B_L)$$

So for maximum power transfer to load with no reflection,

$$Y_{ab} = G_0 + j0$$

$$G_{abS1} + j(B_{abS1} + B_C - B_L) = G_0 + j0$$

Thus equating real and imaginary parts, we get

$$G_{abS1} = G_0 \text{ and } B_{abS1} + B_C - B_L = 0$$

So we can see that for the particular band to be passed, all the imaginary components must be zero. So for a particular band say band1 the length of the stub is adjusted in such a way that L_1C_1 network is formed which cancelles the effect of imaginary component of the load.

And the load impedance equal to the characteristic impedance of the feed line so that maximum power transfer takes place for that particular band and not for the other band.

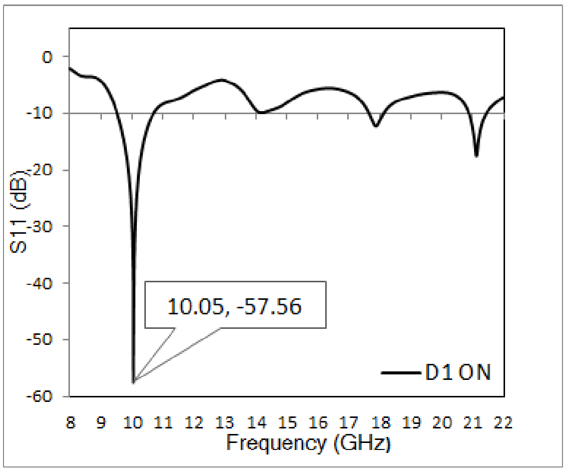


Figure 7.2: S11 plot for the antenna operation in first band.

When D1 is ON, the $\lambda_1/4$ rectangular parasitic element gets connected to the line. And this assembly acts as a band pass filter to the input signal which only passes the band 1. Thus the antenna is successfully operated in this band. The related S11 plot is shown above. It can be observed that the resonant frequency is little bit disturbed which is due to the parasitic element introduced. This much shift is accepted.

7.3 Antenna operation in the second band

Similar rectangular element is designed on the other side of the line. But in this case it will be responsible for the passing of the second band. This rectangular element acts as stub for the impedance matching between the load which in our case is the antenna and the characteristic impedance.

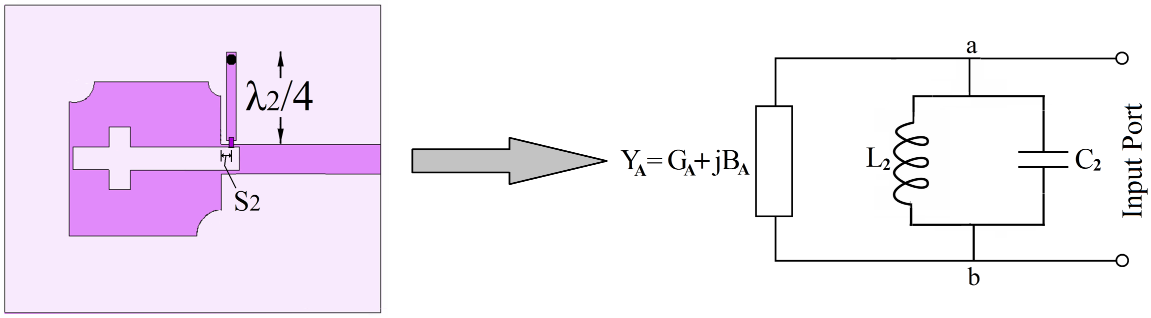


Figure 7.3: Equivalent circuit for operation in the second band.

Matching takes place only for the second band in this case. The length of the stubs is taken as $\lambda_2/4$. The stubs is acting as a L_2C_2 network which is a band pass filter for band 2. This is because we know that capacitive and inductive susceptance are frequency dependent. Consider the maximum power transfer theorem, the load admittance must be equal to the characteristic admittance G_0 of the load, which is a real quantity.

$$\begin{aligned} Y_{abS2}(due\ to\ load\ Y_A) &= Y_0\left[\frac{Y_A + jY_0 tan\beta_2 S_2}{Y_0 + jY_A tan\beta_2 S_2}\right] \\ &= G_{abS2} + jB_{abS2} \\ Y_{ab}(due\ to\ the\ stub) &= j(B_C - B_L) \end{aligned}$$

where β_2 is the phase constant associated by λ_2 and is given by $\beta_2 = \frac{2\pi}{\lambda_2}$. Now combining these two effects to find the total admittance at point a and b we get,

$$Y_{ab} = G_{abS2} + jB_{abS2} + j(B_C - B_L)$$

So for maximum power transfer to load with no reflection,

$$Y_{ab} = G_0 + j0$$

$$G_{abS2} + j(B_{abS2} + B_C - B_L) = G_0 + j0$$

Thus equating real and imaginary parts, we get

$$G_{abS2} = G_0 \; and \; B_{abS2} + B_C - B_L = 0$$

So the inductive and capacitive susceptance exactly cancels the imaginary part of the load at that particular resonant frequency for maximum power to take place.

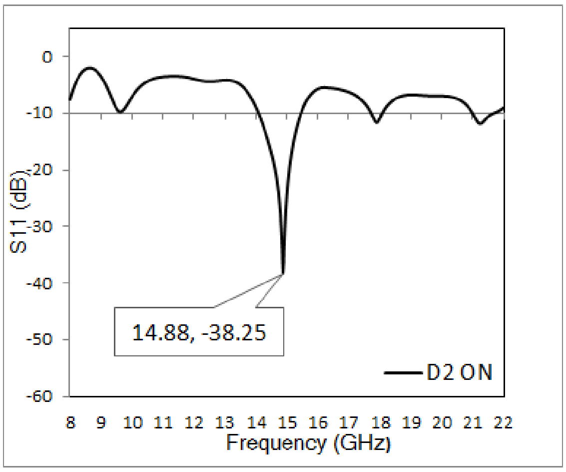


Figure 7.4: S11 plot for the antenna operation in second band.

When the switch D2 is ON, the $\lambda_2/4$ slot is connected to the line which acts like a band pass filter for the second band. So the antenna faithfully operates in the second frequency band. The return loss obtained is near to -40 dB which is quite desirable also the resonant frequency is slightly changed.

7.4 Antenna operation in the third band

Same procedure is adopted for the third band. Here the length of the rectangular parasitic element is taken as $\lambda_3/4$. We can see that the length of the element decreases as the operating frequency is increased. The stub is positioned at a distance of S3. The equivalent circuit for the antenna is shown in Figure7.7.

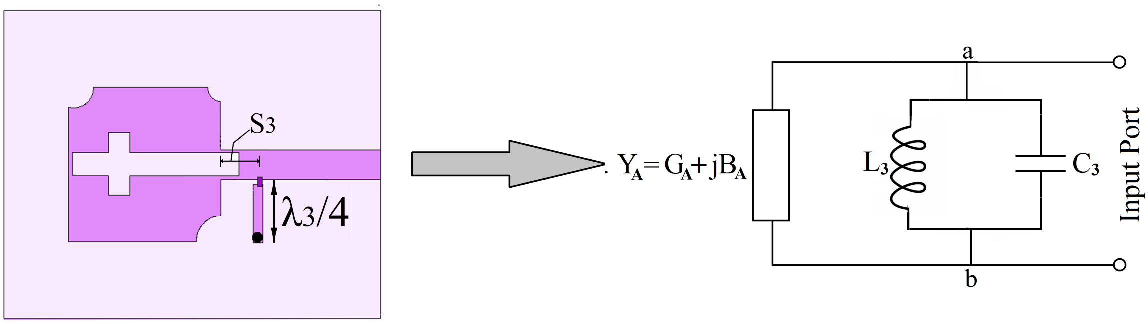


Figure 7.5: Equivalent circuit for operation in the third band.

The L_3C_3 network corresponds the stub $\lambda_3/4$ acting as a bandpass filter the third band. This networks cancels the effect of reactive component of the load at that particular third resonant frequency. This can be understood from the following analysis.

Consider the maximum power transfer theorem, the load admittance must be equal to the characteristic admittance G_0 of the load, which is a real quantity.
So for maximum power to take place,

$$Y_{abS3}(due\ to\ load\ Y_A) = Y_0 \left[\frac{Y_A + jY_0 tan\beta_3 S_3}{Y_0 + jY_A tan\beta_3 S_3}\right]$$

$$= G_{abs3} + jB_{abs3}$$

$$Y_{ab}(due\ to\ the\ stub) = j(B_C - B_L)$$

where β_3 is the phase constant associated by λ_3 and is given by $\beta_3 = \frac{2\pi}{\lambda_3}$. Now combining these two effects to find the total admittance at point a and b we get,

$$Y_{ab} = G_{abS3} + jB_{abS3} + j(B_C - B_L)$$

So for maximum power transfer to load with no reflection,

$$Y_{ab} = G_0 + j0$$

$$G_{abS3} + j(B_{abS3} + B_C - B_L) = G_0 + j0$$

Thus equating real and imaginary parts, we get

$$G_{abS3} = G_0 \; and \; B_{abS3} + B_C - B_L = 0$$

Thus the stub $\lambda_3/4$ is used for impedance matching between the load and the characteristic impedance of the feed line.

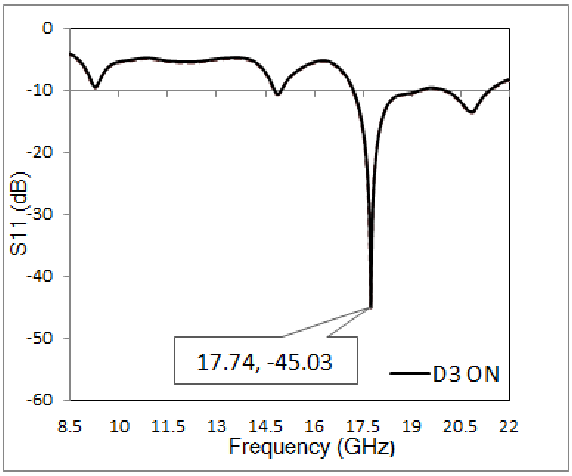


Figure 7.6: S11 plot for the antenna operation in third band.

When the switch D3 is on the associated $\lambda_3/4$ stub is connected to the feed line. This acts as a band pass filter for the third band and the antenna is successfully operated in this band. The return loss again here is -40 dB.

Note that the position of the rectangular parasitic element or so called stubs is determined by the parametric analyisis.

7.5 Antenna operation in the fourth band

Similarly the previous procedure is adopted for the fourth band. Here the length of the rectangular parasitic element is taken as $\lambda_4/4$. The stub is positioned at a distance of S4. The equivalent circuit for the antenna is shown in Figure7.7.

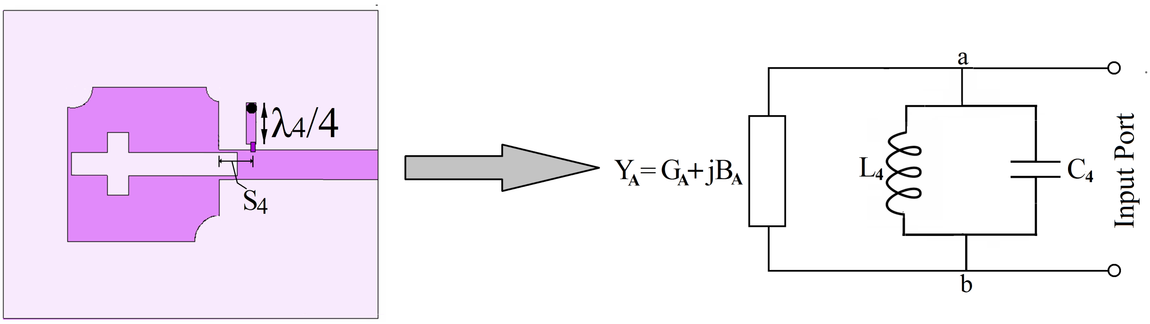


Figure 7.7: Equivalent circuit for operation in the third band.

The L_4C_4 network corresponds the stub $\lambda_4/4$ acting as a bandpass filter the third band. This networks cancels the effect of reactive component of the load at that particular third resonant frequency. This can be understood from the following analysis.

Consider the maximum power transfer theorem, the load admittance must be equal to the characteristic admittance G_0 of the load, which is a real quantity.

So for maximum power to take place,

$$Y_{abS4}(due\ to\ load\ Y_A) = Y_0\left[\frac{Y_A + jY_0 tan\beta_4 S_4}{Y_0 + jY_A tan\beta_4 S_4}\right]$$

$$= G_{abs4} + jB_{abs4}$$

$$Y_{ab}(due\ to\ the\ stub) = j(B_C - B_L)$$

where β_4 is the phase constant associated by λ_4 and is given by $\beta_4 = \frac{2\pi}{\lambda_4}$. Now combining these two effects to find the total admittance at point a and b we get,

$$Y_{ab} = G_{abS4} + jB_{abS4} + j(B_C - B_L)$$

So for maximum power transfer to load with no reflection,

$$Y_{ab} = G_0 + j0$$

$$G_{abS4} + j(B_{abS4} + B_C - B_L) = G_0 + j0$$

Thus equating real and imaginary parts, we get

$$G_{abS4} = G_0 \text{ and } B_{abS4} + B_C - B_L = 0$$

Thus the stub $\lambda_4/4$ is used for impedance matching between the load and the characteristic impedance of the feed line.

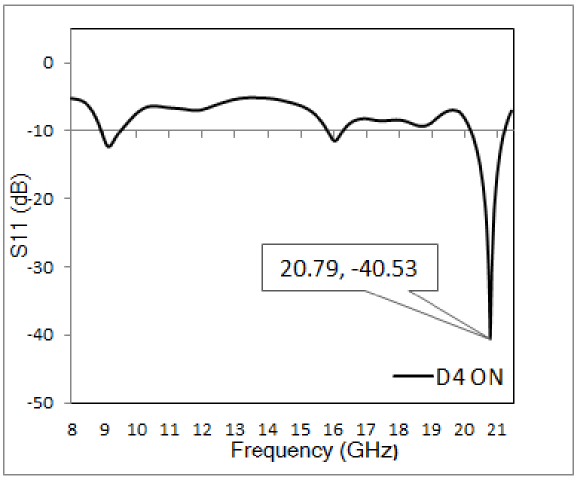


Figure 7.8: S11 plot for the antenna operation in fourth band.

When the switch D4 is on the associated $\lambda_4/4$ stub is connected to the feed line. This acts as a band pass filter for the third band and the antenna is successfully operated in this band. The return loss again here is -40 dB.

Note that the position of the rectangular parasitic element or so called stubs is determined by the parametric analyisis.

7.6 Proposed antenna design

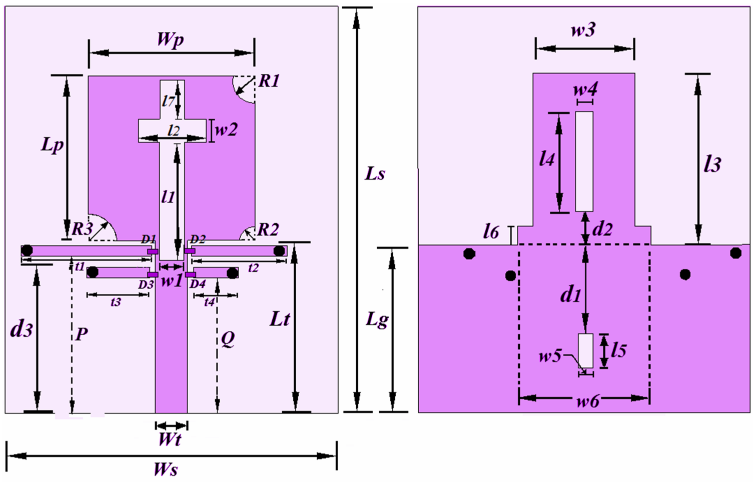


Figure 7.9: Design of final proposed Quad Band Reconfigurable antenna.

Table 7.1: Design parameter dimensions of of Quad Band Reconfigurable antenna.

Parameters	Values(mm)	Parameters	Values(mm)
Ws	30	*Ls*	36.7
Wp	15	*Lp*	14.3
Lt	15.5	*Wt*	2.9
l1	15.4	*w1*	2.2
l2	6.1	*w2*	3
Lg	15.2	*l3*	15.8
w3	9.2	*l4*	9
w4	1.6	*d1*	8
d2	3	*l5*	3.5
w5	1.5	*w6*	12
l6	1.7	*f1*	5.7
f2	1.1	*f3*	4
R1	2	*R2*	1.4
R3	2.6	*d3*	13.8
f4	1	*P*	14.5
Q	12.5	*H*	1.6

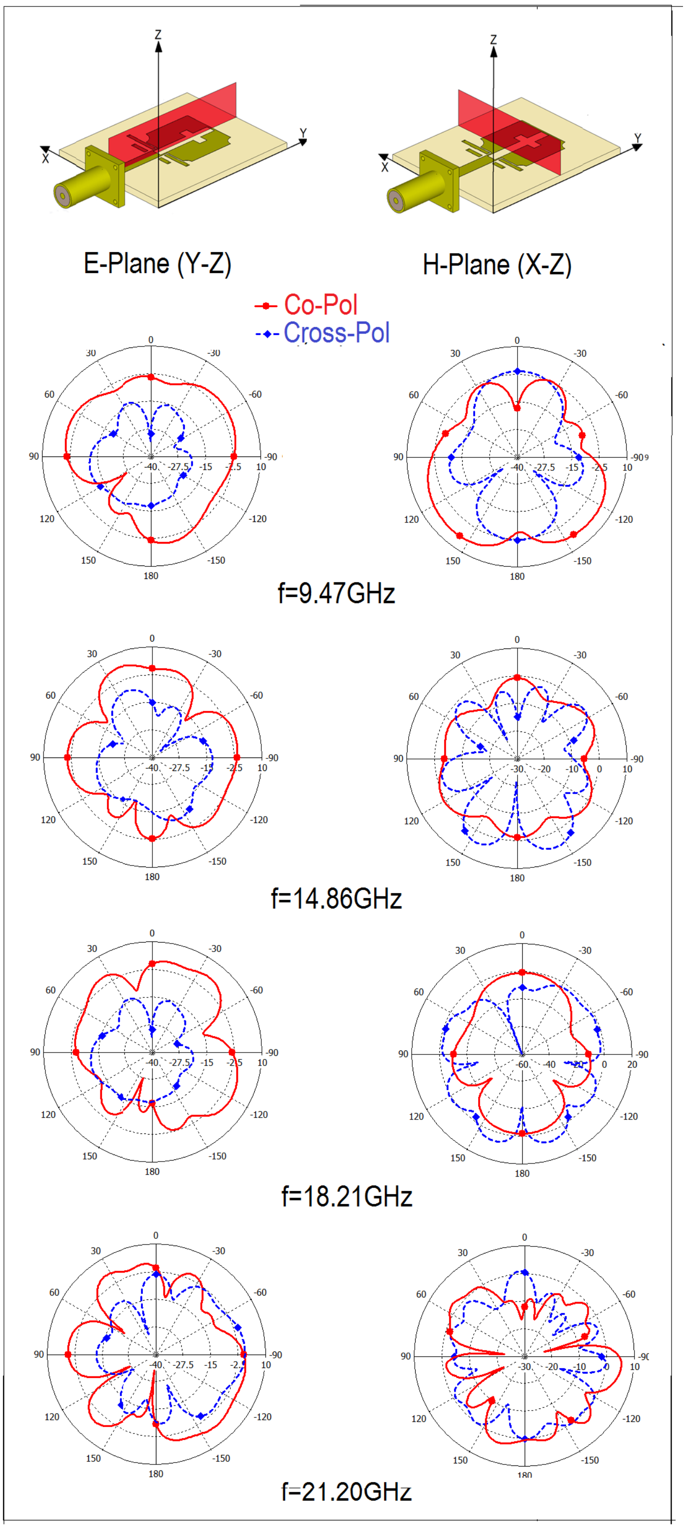


Figure 7.10: Co and Cross polarisation of Quad Band Reconfigurable antenna.

The final design of the antenna is shown in Figure7.9. All the four discussed cases has been summarized here. We can see that the parasitic element gets connected to the feed line whenever desired with help of switches.

The Co and Cross polarisation is also plotted in Figure7.10 for the Quad Band Reconfigurable antenna. Suppose the antenna is designed to operate in the vertical polarisation. So for this antenna the vertical polarisation is called the *Co-polarisation*. However due to some spurious radiation, some orthogonal polarisation componets also gets radiated which in the present case is the horizontal polarisation which usually undesired. This type of polarisation is called as *Cross polarisation*. This cross polarisation component interferes with the co-polarisation component to distort the signal. So to keep the distortion minimum the value of the cross polarisation must be less as compared to the co polarisation component.

7.7 Alternative design of Quad band Reconfigurable Antenna

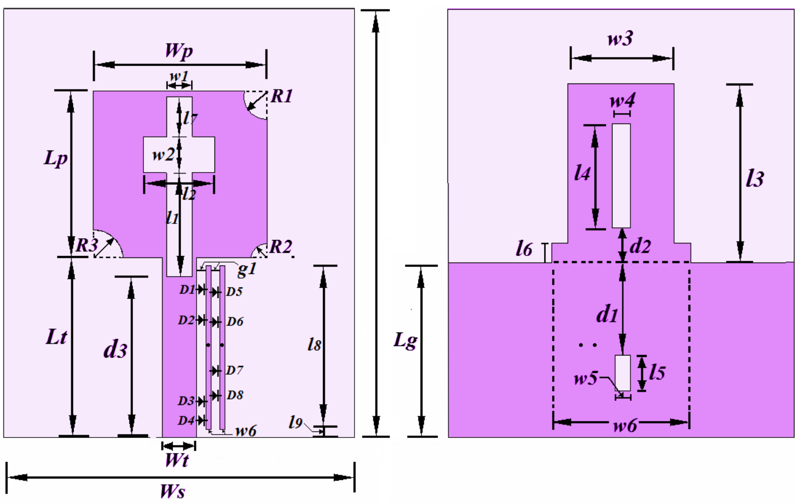


Figure 7.11: A design of the proposed atenna.

So far we have discussed the design of the quad band reconfigurable antenna using four parasitic elements shorted to ground. This section illustrates another design of the similar type of characteristics. Figure 7.11 shows the configuration of the antenna. We can see that the arrangement and the geometry of the patch are similar to the previous discussed antenna. Only difference in this case is in the switching arrangements. Here two parallel copper strips near to the feeding line is formed which are shorted to ground at the middle. Switches D1 to D7 are connected to these two lines. By different switching combinations single band can be passed from microstrip line to the antenna or radiating element.

7.8 Operation of the modified antenna

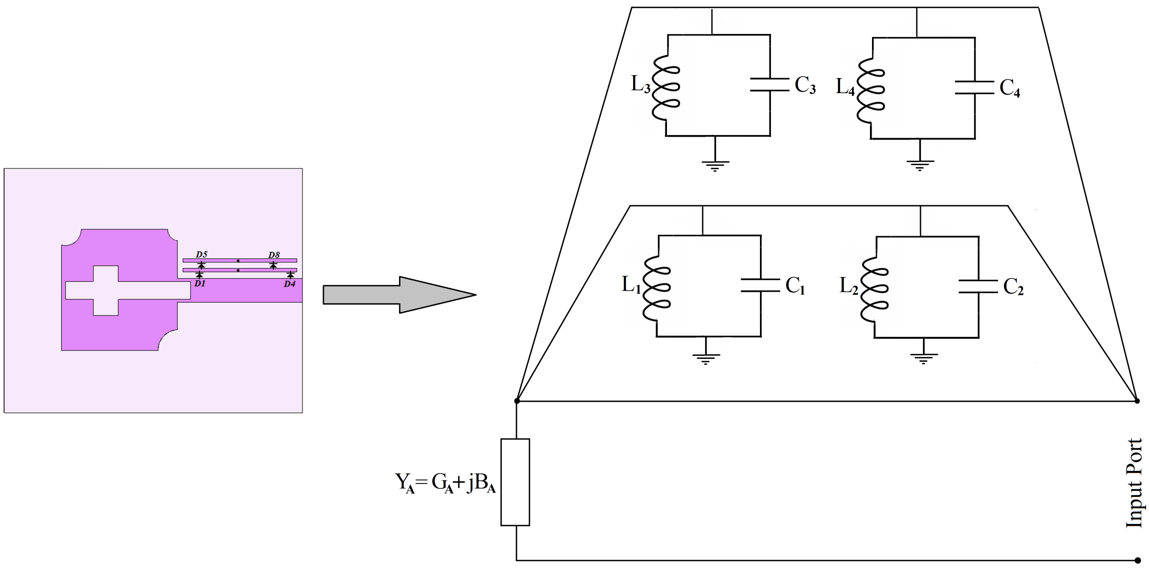


Figure 7.12: Equivalent circuit of the antenna.

To understand the operation of the antenna, first the equivalent circuit is to be understood properly. The arrangement of the two lines is done in such a way that it behaves as a four LC networks. For this, the switches D1, D4, D5 and D8 are always in ON condition. The radiating element acts as a load having admittance Y_A. The four LC networks associated with four resonant frequencies are shown in the Figure 7.12.

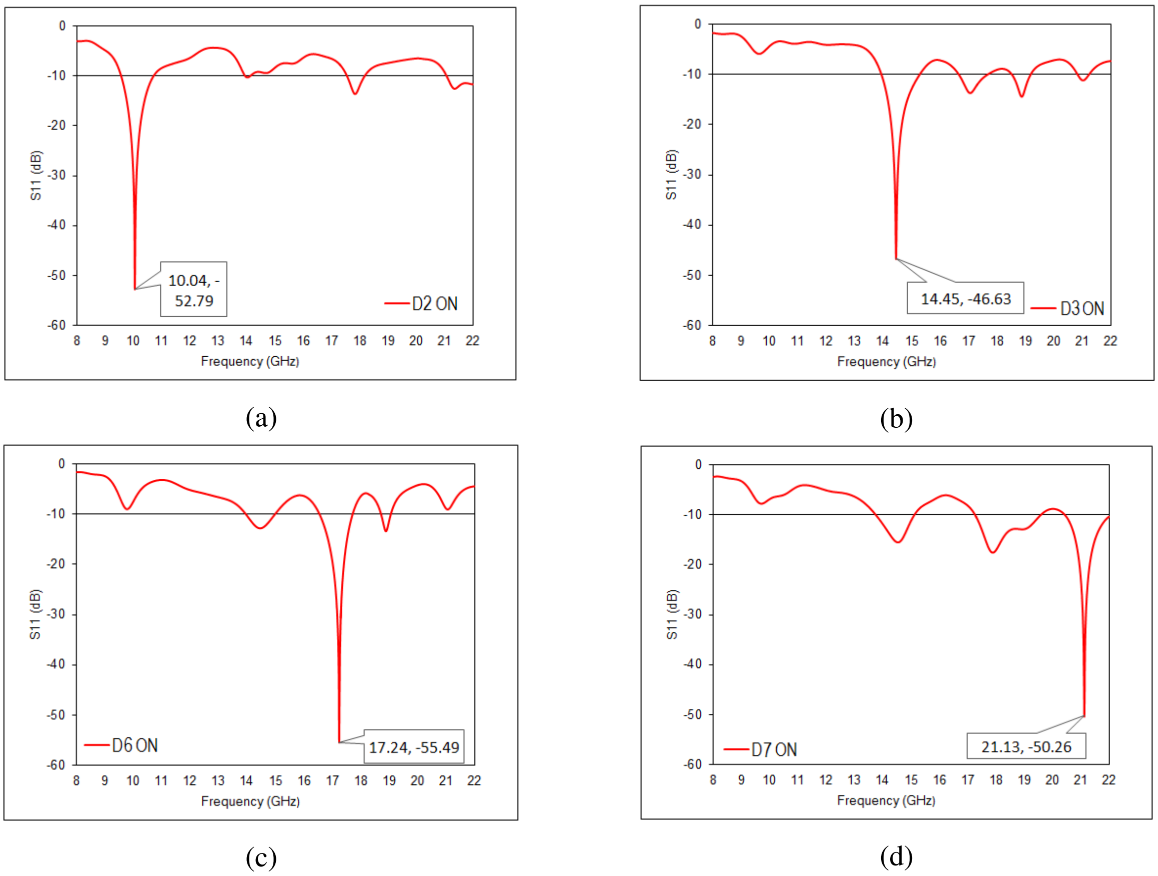


Figure 7.13: Single band operation of the antenna.

The operation of the antenna can be understood by considering D1, D4, D5 and D8 always ON. When the switch D2 is ON, the L_1C_1 network so formed is associated with the first resonant frequency. Which mens it cancels the imaginary part of the load at this particular resonant frequency. This network does not behave similarly to the other three bands and thus it does not able to cancel the imaginary part of the load at these frequencies.

Thus it does not passes the other resonant frequencies except the first one.

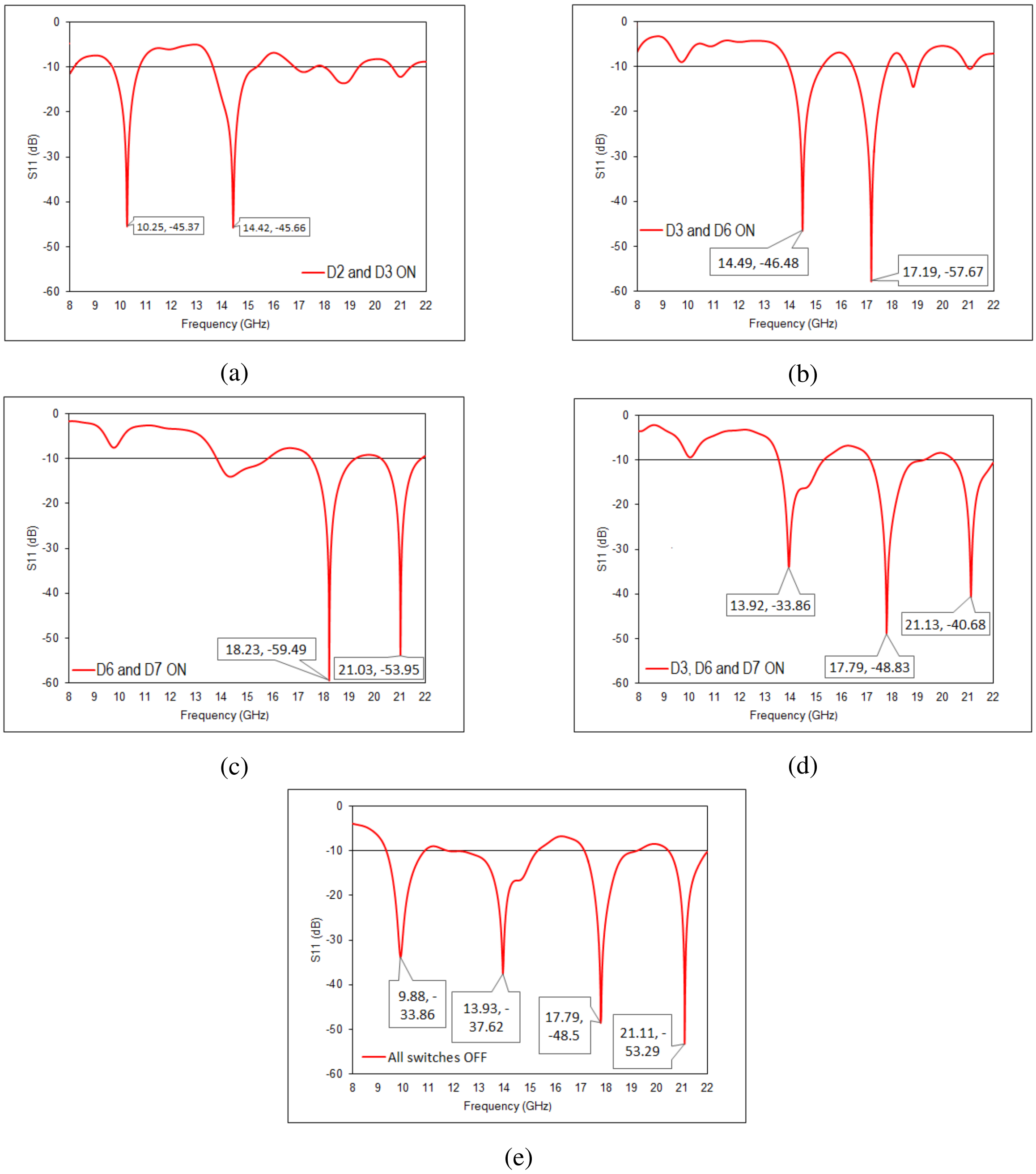


Figure 7.14: Multiband operation of the antenna.

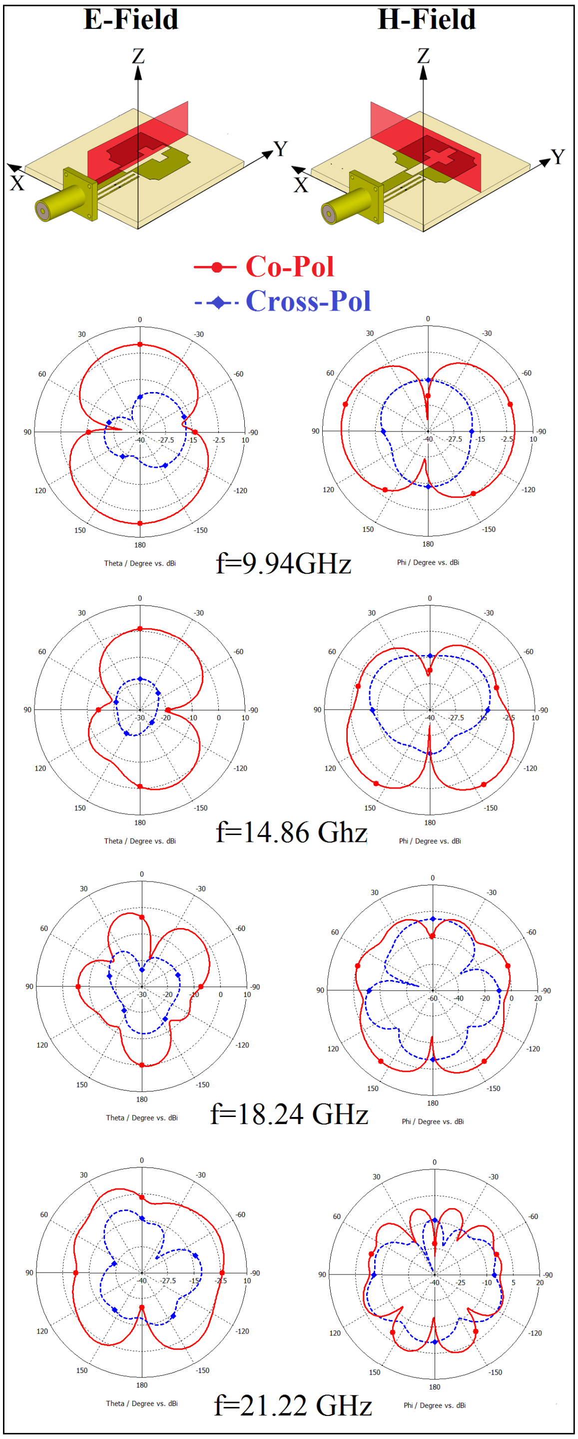


Figure 7.15: Co-polarization and Cross-polarization of the antenna at four resonant frequencies.

Similarly when the switch D3 is ON the L_2C_2 network so formed have the characteristics associated to the second band only except the other three bands. Thus here only second band is passed and thus gets radiated by the antenna. For the other two cases also i.e. D6 for L_3C_3 and D7 for L_4C_4 associated with the third and fourth resonant frequencies respectively. The antenna in these cases acts as a single band antenna in each case, radiating in only single band at a time. However we can convert it to double or triple band antenna by simultaneously switching ON the two diodes or three diodes respectively. This can be observed from Figures 7.14a,7.14b,7.14c and 7.14d. The only drawback in this type of design is that the number of switches used is more here.

The Co and Cross polarisation of this modified antenna is plotted in Figure7.15 for the Quad Band Reconfigurable antenna. Suppose the antenna is designed to operate in the vertical polarisation. So for this antenna the vertical polarisation is called the *Co-polarisation*. However due to some spurious radiation, some orthogonal polarisation componets also gets radiated which in the present case is the horizontal polarisation which usually undesired. This type of polarisation is called as *Cross polarisation*. This cross polarisation component interferes with the co-polarisation component to distort the signal. So to keep the distortion minimum the value of the cross polarisation must be less as compared to the co polarisation component.

We can conclude from the above discussion that initial quad band design uses four parasitic elements but here in this case the parasitic elements used are only two. Moreover the number of shorting pins is four in the earlier case which is twice the number used here. As the number of shorting pins increases the spurious radiation also gets increases which is undesired. So the use of shorting pins should be minimised. This modified design has the advantage over the initial design of having lesser number of shorting pins.

Also from Figure7.15 we can see that the cross-polarization component is very much reduced as compared to the co-polarization component. This is also can be considered as an advantage of the modified design of having lesser value of cross polarization component.

CHAPTER 8

Conclusions and Scope of Future Work

8.1 Conclusion

In the previous sections, detailed study of the design of the antenna was discussed. The design discussions on each and every aspect has been carried out in this text. Initially how a 6 GHz antenna is deigned was seen and its characteristics was simulated. Later this design was converted to an Wideband design. This was obtained by only by removing the part of the ground plane this ground plane was given the name *partial ground*.

But the design was not limited to the Wideband one. It is then converted into a Quad Band antenna by the introduction of defective ground structure in the ground plane and also by the introduction of the cross slot. The antenna showed minimum return losses at the three bands namely X, Ku and K bands. This antenna gave perfect impedance matching property in all the four resonant frequency and their associated bands. Since this Quad band antenna was limited only for certain applications, it was decided to better convert it into a switchable or reconfigurable antenna.

A unique technique of achieving reconfigurability has been employed. The use of parasitic elements which are shorted to ground made the antenna a reconfigurable one. A single parasitic element is capable of band pass filtering a single band at a time. These elements are connected to the feed line with help of switches such as PIN diode which are usable at microwave frequencies. A point should be noted that the discussion in this text is only on the design of the antenna, but not the type of switching employed. We can assume that it is a generalised design having possibilities of incorporating all types of switching techniques such as electrical or optical techniques.

However by the use of such elements the original characteristics has been little bit disturbed. The resonant frequencies of the antenna was little bit shifted. These shift is quite negligible and hence should not be taken into consideration. Also the return losses has been slightly increased.

Also an alternative design of the antenna having similar reconfigurable chracteristic has been designed which shows nealy same characteristics as that of previous one.

In the whole project work the basics related to the antennas was studied in depth. In this text also all the concept has been discuused. In the design of the Quad Band reconfigurable antenna also, the function of each and every cuts and slots was discussed and analysed. Wherever needed the parametric analysis has been carried out. Thus finally the end product was as desired giving better results.

8.2 Scope for Future Work

Although the antenna designed has all the desired properties and application, there is always a scope for further improvement.

The proposed design consist of the substrate made up of FR-4 material. This material is selected because it is easily available and cheap. However FR-4 material shows good behaviour upto 10 GHz frequency, but its performance degrades there after. It is not recommended at higher frequencies. Thus this antenna can be modified with the use of substrate made up of materials such as RT Duroid, Rogers 4350, etc. which are capable of operating efficiently at higer frequencies.

The unique feature of this project is that the switching takes place in the feeding line area which is away from patch geometry. This allows us to extend this project towards implementing reconfigurable array antennas. Only a power divider network is needed to supply power to the array element. Switching will take place near to the feeding arrangement which will not disturb the array. The advantage of using array configuration is that we will get better gain and efficiency. The gain of this proposed design is quite low. So this array configuration will enhance the gain of this antenna.

Other technique to enhance the gain of this antenna is to use *Frequency Selective Surface (FSS)*. The Frequency Selective Surface (FSS) are the periodic structures of small elements which are arranged in 2D. These are totaly passive elements without any power supplied to them. These surfaces acts as reflector for some frequencies but it is almost transparent to other frequencies. If these surfaces are designed according to the desired resonant frequencies of the antenna and if it is placed at the back of the antenna with some specific distance from the antenna, it will reflect the fields associated with the three resonant frequencies. These field add up with the existing fields of the antenna giving better directivity and gain. Note that these surface acts similar to reflectors in the parabolic antenna case.

References

[1] Z. Faiza, M. T. Ali, S. Subahir and A.L.Yusof, "Design of Reconfigurable Dual-Band E-Shaped Microstrip Patch Antenna", *International Conference on Computer and Communication Engineering (ICCCE 2012)*, 2012.

[2] Huda A. Majid, Mohamad Kamal Abdul Rahim, Mohamad Rijal Hamid, Noor Asniza Murad, and Mohd Faizal Ismail, "Frequency-Reconfigurable Microstrip Patch-Slot Antenna", *IEEE Antenna and Wireless Propagation Letters*, vol. 12, 2013.

[3] H. A. Majid, M. K. A. Rahim, M. R. Hamid, M. F. Ismail and M. R. SaniâĂŹ "Frequency Reconfigurable Microstrip Patch Antenna", *IEEE Asia-Pacific Conference on Applied Electromagnetics (APACE 2012)*, 2012.

[4] Nooshin Valizade Shahmirzadi and Homayoon Oraizi, "Design of reconfigurable coplanar waveguide fed planar antenna for multiband multi-inputâĂŞmulti-output applications", *IET Microw. Antennas Propag.*, 2016, vol. 10, Iss. 14.

[5] Ojaroudi, M., Yzdanifard, S., Ojaroudi, N. and Sadeghzadeh, R.A.: "Band-notched small square-ring antenna with a pair of T-shaped strips protruded inside the square ring for UWB applications", *IEEE Antennas Wirel. Propag. Lett.*, 2011, 10, pp. 227-230

[6] Fateh Lal Lohar, Abhinav Deshpande, Ravi Kumar Maddila and M.M.Sharma , "A Design of Five Band Microstrip Antenna for Radar and Satellite Communications", *International Conference on Optical and Wireless Technologies (OWT 2017)*, MNIT Jaipur, Jaipur-India, March 18-19, 2017.

[7] Lui, W.J., Cheng, C.H., Cheng, Y., et al: "Frequency notched ultra wideband microstrip slot antenna with a fractal tuning stub", *Electron. Lett.*, 2005, 6, (41), pp. 294-296.

[8] Su, S.-W., Wong and K.-L., Chang, F.-S.: "Compact printed ultra wideband slot antenna with a band notched operation", *Microw. Opt. Technol. Lett.*, 2005, 45, pp. 128-130.

[9] Ros Marie C Cleetus and T.Sudha, "Design and Analysis of a Frequency and Pattern Reconfigurable Microstrip Patch Antenna for Wireless Applications", *2013 International Conference on Control Communication and Computing (ICCC).*

[10] M. Borhani, P. Rezaei, and A. Valizade, "Design of a Reconfigurable Miniaturized MicrostripAntenna for Switchable Multiband Systems", *IEEE Antennas and wireless propagation letters*, vol. 15, 2016.

[11] Nghia Nguyen-Trong, Leonard Hall, and Christophe Fumeaux, "A Frequency- and Polarization-Reconfigurable Stub-Loaded Microstrip Patch Antenna", *IEEE transaction on antenna and propagation*, vol. 63, NO. 11, November 2015.

[12] Nghia Nguyen-Trong, Leonard Hall and Christophe Fumeaux, "A Frequency- and Pattern-Reconfigurable Center-Shorted Microstrip Antenna", *IEEE Antennas and wireless propagation letters*, vol. 15, 2016.

[13] Abhinav Deshpande, Fateh Lal Lohar, Ravi Kumar Maddila, I. B. Sharma and M.M.Sharma, "Tri Band Microstrip Patch Antenna for C, X and Ku Band Applications", *International Conference on Optical and Wireless Technologies (OWT 2017)*, MNIT Jaipur, Jaipur-India, March 18-19, 2017.

[14] ZHANG Pengfei, LIU Shizhong, CHEN Rongrong and HUANG Xinglin, "A Reconfigurable Microstrip Patch Antenna with Frequency and Circular Polarization Diversities", *Chinese Journal of Electronics*, vol.25, No.2, Mar. 2016.

[15] Azzeddin Naghar, Otman Aghzout, Ana Alejos, Manuel Sanchez, Azzeddin Naghar, Mohamed Essaaidi and Francisco Falcone, "Ultra Wideband and tri-band Antennas for satellite applications at C-, X-, and Ku bands", 2014 *IEEE*.

[16] Anamiya Bhattacharya and Rajeev Jyoti, "Frequency Reconfigurable Patch Antenna Using PIN Diode at X-Band", *2015 IEEE 2nd International Conference on Recent Trends in Information Systems (ReTIS).*

[17] Hoang Thi Phuong Thao, Vu Thanh Luan and Vu Van Yem, "Design of compact frequency reconfigurable planar invert-F antenna for green wireless communications", *IET Commun.*, 2016, Vol. 10, Iss. 18.

[18] Abhinav Deshpande, Fateh Lal Lohar, Ravi Kumar Maddila, I. B. Sharma and M.M.Sharma, Tri Band Reconfigurable Microstrip Patch Antenna Using Shorted Strip Technique", *ICMARS-2017, 12th International Conference on Microwave, Antenna, Propagation and Remote Sensing*, Jodhpur-India, February 15-17, 2017.

[19] P.-Y. Qin, A. Weily, Y. Guo, T. Bird, and C.-H. Liang, "Frequency reconfigurable quasi-yagi folded dipole antenna," Antennas and Propagation, *IEEE Transactions*, vol. 58, no. 8, pp. 2742-2747, Aug 2010.

[20] Y. Zhou, R. Adve, and S. Hum, "Design and evaluation of pattern reconfigurable antennas for mimo applications", Antennas and Propagation, *IEEE Transactions* , vol. 62, no. 3, pp. 1084-1092, March 2014.

[21] Q. Liu and P. Hall, "Varactor-loaded left handed loop antenna with reconfigurable radiation patterns," in Antennas and Propagation Society International Symposium, 2009. *APSURSI '09. IEEE*, June 2009, pp. 1-4.

[22] N. Ramli, M. T. Ali, A. L. Yusof, S. Muhamud - Kayat, and A. A. A. Aziz, "PIN Diode Switches for Frequency-Reconfigurable Stacked Patch Microstrip Array Antenna using Aperture-Coupled Technique", *Asia-Pacific Microwave Conference Proceedings*, 2013.

[23] Jeen-Sheen Row and Jia-Fu Tsai, "Frequency-Reconfigurable Microstrip Patch Antennas with Circular Polarization", *IEEE Antenna and Wireless Propagation Letters*, vol. 13, 2014.

[24] Fateh Lal Lohar, Abhinav Deshpande, Ravi Kumar Maddila and M.M.Sharma, "A Quad Band Frequency Reconfigurable Monopole Antenna with Shorted Stubs for Microwave Applications", *3rd URSI Regional Conference on Radio Science (URSI-RCRS)*, 1-4 March,2017.

[25] D. V. Thiel, "Switched parasitic antennas and controlled reactance parasitic antennas: a systems comparison," in *Antennas and Propagation Society International Symposium*, 2004. IEEE, vol. 3, June 2004, pp. 3211-3214 Vol.3.

[26] M. J. Ammann and Z. N. Chen, "Wideband monopole antennas for multi-band wireless systems," *IEEE Antennas Propag. Mag.*, vol. 45, no. 2, pp. 146-150, Apr. 2003.

[27] J. Evans, "An investigation of planar monopole antennas for modern portable applications," *Dublin Institute of Technology*, 2007.

[28] Fateh Lal Lohar, Abhinav Deshpande, Ravi Kumar Maddila and M.M.Sharma , "Switchable Five Frequency Band Microstrip Antenna (MSA) Using Shorted ParasiticElements", *ICMARS-2017, 12th International Conference on Microwave, Antenna, Propagation and Remote Sensing*, Jodhpur-India, February 15-17, 2017.

[29] A. Mansoul, and H. Kimouche, "A Simple Frequency Reconfigurable Microstrip Patch Antenna for Wireless Communications", *8th International Workshop on Systems, Signal Processing and their Applications*, 2013.

[30] D. Kumar, T. Singh, R. Dwivedi, and S. Verma, "A Compact Monopole CPW-Fed Dual Band Notched Square-Ring Antenna for UWB Applications," in *2012 Fourth International Conference on Computational Intelligence and Communication Networks (CICN)*, 2012, pp. 57-60.

[31] J. Liang, C. C. Chiau, X. Chen, and C. G. Parini, "Study of a printed circular disc monopole antenna for UWB systems," *IEEE Trans. Antennas Propag.*, vol. 53, no. 11, pp. 3500-3504, Nov. 2005.

[32] T. Manabe, Y. Miura, and T. Ihara, "Effects of antenna directivity and polarization on indoor multipath propagation characteristics at 60 GHz," *IEEE J. Sel. Areas Commun.*, vol. 14, no. 3, pp. 441-448, Apr. 1996.

[33] Shing-Lung Steven Yang, Ahmed A. Kishk, and Kai-Fong Lee, "Frequency Reconfigurable U-Slot Microstrip Patch Antenna", *Antenna and Wireless Propagation Letters*, vol. 7, 2008.

[34] S.Muhamud Kayat, M. T. Ali and M.K.M.Salleh, "A Reconfigurable Microstrip Antenna with a Slotted Patch at Dual Frequency", *8th International Symposium on Wireless Communication Systems*, 2011.

[35] Harish Rajagopalan, Joshua M. Kovitz, and Yahya Rahmat-Samii, "MEMS Reconfigurable Optimized E-Shaped Patch Antenna Design for Cognitive Radio", *IEEE transaction on antenna and propagation*, vol. 62, NO. 3, March 2014.

[36] Lei Ge and Kwai-Man Luk, "Frequency-Reconfigurable Low-Profile Circular Monopolar Patch Antenna", *IEEE transaction on antenna and propagation*, vol. 62, NO. 7, July 2014.

[37] D. Chatterjee, "Design and Comparison of Dual Coaxial and edge feed Square Micro Strip Patch Antenna for Wind Profiling Radar Applications at 430 Mhz"*IOSR J. Eng.*, vol. 3, no. 4, pp. 24-33, 2013.

[38] J. Traister, "Design Guidelines for Surface Mount Technology". *Elsevier*, 2012.

[39] C. A. Balanis, *Antenna Theory Analysis and Design*. John Wiley and Sons, Inc., 2005.

[40] Randy Bancroft, *Microstrip and Printed Antenna Design*. SciTech Publishing Inc., 2nd Revised edition edition (15 December 2008).

[41] John D. Kraus, *Antennas*, McGraw-Hill book company, Second edition 1988.

[42] David M. Pozar, *Microwave Engineering*, Fourth Edition 2012.

[43] CST Microwave Studio, User's Manual, 2017, `www.cst.com`.

Author's Publications

Conference Proceedings

1. Fateh Lal Lohar, Abhinav Deshpande, Ravi Kumar Maddila and M.M.Sharma , "Quad-band frequency reconfigurable monopole antenna with shorted stubs for Microwave Applications", *Microwave Applications, International Union Of Radio Science (URSI-RCRS 2017)*, Tirupati-India, March 1-4, 2017.

2. Fateh Lal Lohar, Abhinav Deshpande, Ravi Kumar Maddila and M.M.Sharma , "Switchable Five Frequency Band Microstrip Antenna (MSA) Using Shorted ParasiticElements", *ICMARS-2017, 12th International Conference on Microwave, Antenna, Propagation and Remote Sensing*, Jodhpur-India, February 15-17, 2017.

3. Fateh Lal Lohar, Abhinav Deshpande, Ravi Kumar Maddila and M.M.Sharma , "A Design of Five Band Microstrip Antenna for Radar and Satellite Communications", *International Conference on Optical and Wireless Technologies (OWT 2017)*, MNIT Jaipur, Jaipur-India, March 18-19, 2017.

4. Abhinav Deshpande, Fateh Lal Lohar, Ravi Kumar Maddila, I. B. Sharma and M.M.Sharma, "Tri Band Reconfigurable Microstrip Patch Antenna Using Shorted Strip Technique", *ICMARS-2017, 12th International Conference on Microwave, Antenna, Propagation and Remote Sensing*, Jodhpur-India, February 15-17, 2017.

5. Abhinav Deshpande, Fateh Lal Lohar, Ravi Kumar Maddila, I. B. Sharma and M.M.Sharma, "Tri Band Microstrip Patch Antenna for C, X and Ku Band Applications", *International Conference on Optical and Wireless Technologies (OWT 2017)*, MNIT Jaipur, Jaipur-India, March 18-19, 2017.