A Compact Hexaband Frequency Reconfigurable Antenna For Wireless Applications

A Project report submitted in partial fulfilment of the requirements for the award of the degree of

BACHELOR OF TECHNOLOGY
IN
ELECTRONICS AND COMMUNICATION ENGINEERING

Submitted by

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ANIL NEERUKONDA INSTITUTE OF TECHNOLOGY AND SCIENCES
(UGC AUTONOMOUS)
(*Permanently Affiliated to AU, Approved by AICTE and Accredited by NBA & NAAC*)
Sangivalasa, bheemili mandal, visakhapatnam dist.(A.P)
2022-2023

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CERTIFICATE

This is to certify that the project report entitled"**A COMPACT HEXABAND FREQUENCY RECONFIGURABLE ANTENNA FOR WIRELESS APPLICATIONS**" submitted by **Mogadala Teja (319126512036), Mohammad Zaheer (319126512037), M. Usha Jyothi (319126512035), M. Srivardhan Varma (319126512038)** in partial fulfilment of the requirements for the award of the degree of **Bachelor of Technology** in **Electronics & Communication Engineering** of Anil Neerukonda Institute of technology and Sciences(A), Visakhapatnam is a record of bonafide work carried out under my guidance and supervision.

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ACKNOWLEDGEMENT

We would like to express our deep gratitude to our project guide **Dr. K. Sreelakshmi, Asst. Prof**, Department of Electronics and Communication Engineering, ANITS, for her guidance with unsurpassed knowledge and immense encouragement. We are grateful to **Dr. B. Jagadeesh**, Head of the Department, Electronics and Communication Engineering, for providing us with the required facilities for the completion of the project work.

We are very much thankful to the **Principal and Management, ANITS, Sangivalasa,** for their encouragement and cooperation to carry out this work.

We express our thanks to all **teaching faculty** of Department of ECE, whose suggestions during reviews helped us in accomplishment of our project. We would like to thank **all non-teaching staff** of the Department of ECE, ANITS for providing great assistance in accomplishment of our project.

We would like to thank our parents, friends, and classmates for their encouragement throughout our project period. At last but not the least, we thank everyone for supporting us directly or indirectly in completing this project successfully.

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ABSTRACT

Antennas are an important core element of any communication system for transceiving signals in the form of electromagnetic radiation but sometimes their inability to adjust to new operating scenarios can limit system performance. Traditionally, antenna design and performance are optimized for fixed frequency, radiation and polarization. However, modern electronic and wireless cellular communication technologies necessitate compact and multifunctional antennas that are suitable for adapting in changing operating scenarios. Making antennas reconfigurable so that their behaviour can adapt with changing system requirements or environmental conditions can ameliorate or eliminate these restrictions and provide additional levels of functionality for any system. Reconfigurability can affect one or more antenna parameters such as frequency, radiation pattern, and polarization. Antenna reconfiguration can be done with physical or mechanical modification, by electrical control by switching or tuning elements, by change of material properties, and via an optical switching scheme. The integration of multiple radios with reconfigurable antennas maximizes connectivity without resorting to multiple antenna components. The ability of reconfigurable antennas to change their functionality on demand allows them to dynamically cater for multiple wireless services without increasing the real estate required to accommodate multiple antennas. Currently, multiband antennas, which are designed to address more than one band/service at a time, are the most practical and affordable single wireless module solution, even though dedicated single-band antennas would provide superior performance. However, multiband antennas face serious challenges as more and more wireless services are packed into ever smaller devices. Most multiband antenna solutions require very expensive stringent filters to improve their out of band rejection. Frequency-reconfigurable antennas, on the other hand, have inherent bandpass characteristics and generally have excellent out-of-band rejection without of filters.

In this article the design and analysis of a compact hexa-band antenna employing the

PIN diode to realize frequency reconfigurable characteristics is presented. The presented antenna is backed by aground plane and printed on top of a 1.6 mm thicker FR4 substrate. The antenna size is very compact (24 mm × 19 mm × 1.6 mm), and can be readily incorporated with many other RF front-end circuits. The presented antenna consists of a rectangular microstrip patch antenna, F-shaped monopole, Z shaped monopole, two T shaped monopoles and inverted L-shaped monopole. The investigated antenna realizes hexa/Triple band characteristics by turning ON/OFF the PIN diode positioned between the F shaped monopole and metal strip. While in OFF state, the investigated antenna covers 6 unique frequencies 2.3 GHz (LTE Band 30), 2.5 GHz (LTE Band 53), 3.35 GHz (LTE Band 52), 4.4 GHz (Radio altimeter), 5.3 GHz (U-NII-2A) and 5.6 GHz (U-NII-2C) and in ON state, the antenna covers 3 unique frequencies 4.35 GHz (Radio altimeter), 5.25GHz (U-NII-1 & U-NII-2A), and 5.65GHz (U-NII-2C) for wireless applications. The investigated antenna exhibits very small frequency ratios between two consecutive bands of the value of 1.086/1.34/1.31/1.20/1.05, respectively. The proposed design's simulated and measured results are compared, and they demonstrate good agreement.

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CHAPTER 3 INVESTIGATION OF ROLE OF RECONFIGURABLE ANTENNAS IN WIRELESS CELLULAR COMMUNICATION

CHAPTER 4 A COMPACT HEXA-BAND FREQUENCY RECONFIGURABLE ANTENNA FOR WIRELESS COMMUNICATION

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LIST OF ABBREVIATIONS

GSM – global system mobile communication
PCS – personal communication system
UMTS – Universal Mobile Telecommunication System
LTE – Long term Evolution
Wi-Max – Worldwide Interoperability for Microwave Access
Wi-fi – Wireless Fidelity
RFID – Radio Frequency Identification
MIMO – Multiple Input Multiple Output
MEMS – Micro-electromechanical System
UNII – Unlicensed National Information Infrastructure
GPS – Global Positioning System
WLAN – Wireless Local Area Network
DGS – Defected Ground Service
PWA - Personal Wireless Applications
ITS - Intelligent Transportation Systems
CPW – Coplanar Waveguide
MPA - Microstrip Patch Antenna
VNA - Vector Network Analyser
PCB – Printed Circuit Board
TEM - Transverse Electromagnetic Mode
VHF – Very High Frequency
UHF – Ultra High Frequency
AUT – Antenna Under Test
DCS – Distributed Control System
GACS _ Grounded Asymmetric Coplanar Strip
VSWR – Voltage Stand Waving Ratio

BW – Bandwidth

RHCP - Right Hand Circularly Polarized

LHCP - Left Hand Circularly Polarized

HPBW – Half Power Beamwidth

FNBW – First-Null Beamwidth

PIN – Positive Intrinsic Negative

HFSS - High Frequency Structure Simulation Software

LOS - Line Of Sight

LIST OF SYMBOLS

λ - wavelength

λmax - maximum wavelength in the bandwidth

λmin - minimum wavelength in the bandwidth

εr - relative permittivity

εmax - maximum relative permittivity

εmin - minimum relative permittivity

f - frequency

ϕ - azimuth angle

εeff - effective dielectric constant

C - Circumference of helix

A - Pitch angle

D - Diameter of helix

D - Diameter of conductor

S - Spacing between two turns

N - Number of turns

A - Axial length

L - length of one turn

L - spacing of helix from ground plane

W - Width of the Micro-strip Patch Element

T - Thickness of Patch

H - Height of the Dielectric Substrate

S11 - Reflection Coefficient

P - power

E - electrical field component vector

H - magnetic field component vector

K - antenna radiation efficiency

Chapter 1

Introduction

1.1 Introduction

The most critical and important part of any wireless communication system is the antenna. The antenna was born when Heinrich Hertz first proved the presence of electromagnetic waves more than 113 years earlier. According to the Institute of Electrical and Electronics Engineers (IEEE std. 145-1993), the term aerial or antenna is defined as "a means of receiving or radiating radio waves". It can be described as a structure that is related to the transition of a region between free space and guided wave [1], or vice versa. The resonant condition is achieved by the antenna when the antenna dimension is a fraction of the wavelength at its frequency of resonance. This implies that the antenna size increases with a decrease in its resonant frequency. Antennas are generally classified as travelling wave, wire, reflector, log periodic, microstrip, aperture, fractal, conformal and wearable antennas [2]. However, several inherent benefits and drawbacks are retained by individual antenna groups, depending upon these characteristics their suitability for a specific application is determined.

The exponential growth in wireless cellular communication has resulted in a huge demand for mobile devices operating using various standards like GPS, GSM850, DCS, GSM900, PCS, UMTS, LTE and 5G. Besides, mobile devices with smaller form factors are demanded by the end-user. Research on compact and multiband antennas is initiated by these two specifications. The evolution of mobile communication standards [3] is depicted in Figure. 1.1.

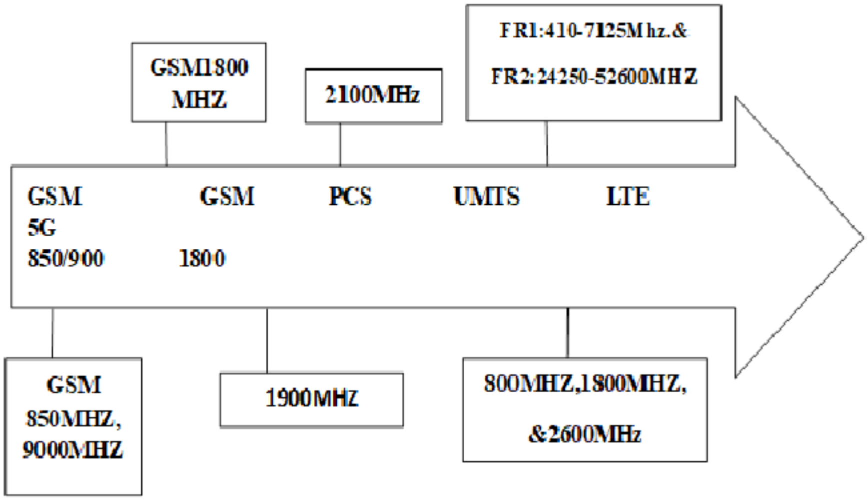


Figure 1.1 The evolution of the standards in mobile communication

In the past, spiral and monopole antennas operating in a single frequency band are used in mobile phones and they are located outside the mobile devices. Current mobile devices or laptop dongles may nearly have “10‟ operating frequency bands, and all of these bands must be implemented in one device only. The main restrictions in designing a single antenna for each operating band in mobile phones are location, space, packaging, EMI/EMC, RF interference, performance, and cost. The solution to this is to have a handheld device fitted with a quad band, pentaband, or hexa-band antenna.

Figure. 1.2 is an example of a personal digital assistant (PDA) device, which needs not only to operate at different mobile networks but also support WLAN as well as the WiMAX and Bluetooth wireless modules. This requires more than one multiband antenna fitted on the mobile device. Some modules need three antennas for MIMO (Multiple Input and Multiple Output), but most of them need two antennas for diversity

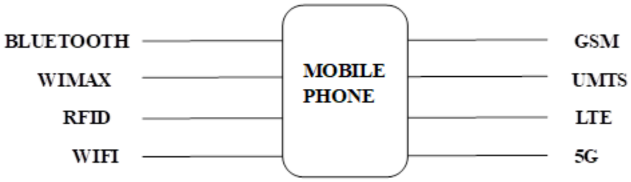


Figure 1.2 Example of different standards that need to be supported by a future mobile phone.

1.2 Motivation

However, the fact is that the available volume for antenna design keeps decreasing as it is desirable to have a wireless device, especially portable devices, as compact as possible. So, even with multiband antennas, the mobile device may run out of space for antennas. The situation is worse for small form factor devices. Hence, the antennas from various wireless modules must be placed side by side, which can lead to poor isolation among antennas and may also result in a failed connection, when several antennas operate concurrently. This is mainly due to the closely spaced antennas and the poor out-of-band rejection capability of multiband antennas.

To increase their out-of-band rejection capability, multiband antennas need very costly stringent filters. As opposed to reconfigurable antennas, fixed multiband antennas are inflexible in adapting to the new services, although they are commonly used in various devices and systems. The word fixed means that the radiation patterns, operating frequencies, and polarization are fixed based on the specifications of the designer and the antenna performance cannot be changed, once the antenna is fabricated and installed in the device. For example, a new device must be developed by manufacturers of mobile phones if any service such as 4G or Long-Term Evolution (LTE) allocates a new band. Therefore, new techniques for designing compact and multiband antennas need to be investigated, which is the key motivation of this thesis work.

One technique to alleviate such challenges is to use a frequency reconfigurable antenna, this technique is further studied in this thesis work and has been successfully applied to the design of proposed printed multiband antenna. Frequency reconfigurable antennas, on the other hand, have inherent bandpass characteristics and generally have excellent out-of-band rejection without filters [4]. In current modern-day applications, where versatility and adaptability have become key factors in designing an antenna, fixed multiband antenna structures operating over a defined bandwidth are losing interest. For these reasons, coupled with low-cost implementations and advanced simulation environments, reconfigurable antennas have been gaining enormous popularity over the years for their applications in wireless cellular communications, electronic surveillance, and countermeasures. Advancements in CMOS-MEMS technologies and implementations in RF/microwave switches have provided antennas with the ability to dynamically adapt to changing application demands, yielding the concept of reconfigurable antennas.

1.3 Aim and Objective of the Thesis

The main aim of this thesis is to design reconfigurable multiband antennas using rigid substrate for wireless cellular communication. To achieve the above aim, the following objectives are carried out.

1. Investigation of the role of antenna in wireless communication.
2. Investigation of the role of reconfigurable antenna in wireless communication.
3. Design of a compact hexa-band frequency reconfigurable antenna for wireless applications. The investigated antenna covers 6 unique frequencies 2.36 GHz (LTE Band 30), 2.56 GHz (LTE Band 69), 3.48 GHz (LTE Band 22), 4.3GHz (Radio altimeter), 5.26 GHz (U-NII-2A) and 5.68 GHz (U-NII-2C) for wireless communications.

1.4 Literature Survey

With the rapid development of wireless communication, current transceiver systems tend to provide different kinds of services, including telephony, data, multimedia, internet access, GPS and Bluetooth, among others. Antennas operating at single frequency band can be used for one service only. This results in usage of more antennas for applications seeking multiple radios. More number of antennas result in large space consumption, interference between adjacent antenna elements, huge installation cost and complex hardware platform. To overcome this drawback, compact multiband antennas are required [6]. These antenna acts as an alternative for two or more separate antennas thus miniaturizing operating equipment's. To meet the demand for multiband operation, one of useful approaches is to design a broadband antenna or even ultrawideband antennas to cover all applications. However, the latter could not be suitable where communications are not required at certain frequencies, and hence, there is a necessity to avoid interfering oscillations. In this case, multiband antennas are desired in order to keep away from emitting or receiving any interference [7]. Many researchers have made large efforts to design such kind of antennas, which can be used for multiband operations. A compact-size quad-band microstrip patch antenna is proposed for the fifth generation (5G) mobile handsets in [8], a metamaterial-inspired miniaturized quadband antenna is designed and discussed with a transmission line model to study the theory of miniaturization and multiband in [9], a novel compact patch antenna with Defected Ground structure (DGS) operating for wireless applications is proposed and investigated in [10], a compact hexagonal nested loop fractal antenna with L shaped slot on the ground plane is presented for multiband applications in [11], a new design approach is presented for achieving a miniaturized quad-band microstrip patch antenna (MPA) suitable to be used for 915-MHz (UHF band), 2.45 and 5.8 GHz (ISM band), and 3.5-GHz (WiMAX band) in [12], a novel asymmetric coplanar waveguide-fed quad-band hybrid antenna for wireless applications is proposed in [13], a four-band slot antenna for the global positioning system (GPS), worldwide interoperability for microwave access (WiMAX), and wireless area network (WLAN) is presented in [14], a novel low-profile monopole antenna fabricated on flexible substrate based on a pentangle-loop radiator is presented and investigated in [15], a compact rectangular patch with dual-ring SRR (split-ring resonator) is presented in [16], a single-layer pentaband antenna with very small frequency ratio for urban vehicular communication application has been presented in [17], a novel shape penta-band microstrip patch antenna is presented in [18], a rectangular microstrip antenna containing an array of narrow L-slots and inverted Lslots is described for multifrequency operation in [19], a pentaband antenna is presented based on the conducting copper material printed on an FR4 substrate for the applications operating in the Gigahertz frequencies in [20], a miniaturized coplanar waveguide (CPW) fed rectangular nested loop antenna is proposed for penta band wireless applications in [21], a novel shaped hexa-band microstrip patch antenna (MPA) is presented in [22], a vertex-fed hexa-band frequency reconfigurable antenna for wireless applications [23] a compact Hexa-band Bio-inspired antenna is presented in [24], a novel multiband microstrip patch antenna with small frequency ratio is designed and analyzed in [25]. However, these multiband antennas [8-25] transmit all resonances regardless of user needs, i.e., they lack reconfigurability. Alternatively, it is not possible to tune a multiband antenna at the required frequency. Hence, employing frequency reconfigurability to existing multiband antennas can enhance the functioning of them. To address these constraints, researchers have designed a feasible solution: reconfigurable antennas. Reconfigurable antennas can exhibit reconfiguration properties within the appropriate radiation, frequency of operation, polarization, and combined factor ranges. Furthermore, the frequency reconfigurable antenna provides excellent out-of-band noise rejection which immensely reduces filtering demands of the front-end circuitry [26]. Various reconfigurable antennas with distinct switching have been tested; they include a thorough procedural investigation of a highly compact reconfigurable quad-band monopole antenna providing multiband operation at 1.85 GHz (GSM 1900 MHz), 2.42 GHz Bluetooth/IMTE, 3.4 GHz (Wi-MAX) and 5.3 GHz wireless LAN (WLAN) for personal wireless applications (PWA) is presented in [27], a tri-Band frequency reconfigurable antenna for

LTE (Long Term Evolution)/Wi-Fi (Wireless Fidelity)/ITS (Intelligent Transportation Systems) applications is presented in [28], a low-profile, compact size, inexpensive, and easily integrable frequency reconfigurable antenna system is proposed in [29], a compact size (31 × 27 × 1.6 mm^3) multiband compound reconfigurable antenna having both frequency reconfigurability and pattern reconfigurability is presented in [30], a low-profile printed antenna that offers pattern and frequency reconfiguration functionalities printed on FR-4 substrate with a size of 46 × 32 × 1.6 mm^3 is proposed in [31], a low-profile, compact hexa-band pattern reconfigurable antenna is presented in [32], a compact multiband, multimode frequency reconfigurable antenna for heterogeneous wireless applications [33], design and analysis of an octagonal shaped split ring resonator based multiband antenna fed at vertex for wireless applications with frequency-band reconfigurable characteristics is presented in [34] and a novel design of compact low cost quad band reconfigurable antenna resulting in frequency switching capabilities, is presented in [35]. Although these antennas [27-35] are reconfigurable, they either have large dimensions, complex structures, fails cost–efficient design as they use expensive substrate materials and multiple active components or provide a limited number of resonances.

1.5 Technical Approach

The following approach is employed to accomplish the objectives of this thesis. The first one is identifying the methods and technologies of reconfigurability, scope, and limitations of current approaches to generate new concepts and realize better reconfigurable antenna designs. The frequency reconfiguration of the antenna is achieved by adding RF PIN diode switches to the radiating structure. The PIN diode switch is popular in microwave circuit applications due to its fast-switching times and relatively high current handling capabilities. Switching speeds of less than 100 ns are typical.

The flow chart of the overall approach employed is shown in Figure. 1.3. First, the desired antenna specifications are considered for the required application. After that, the antenna design is done by using HFSS simulation software. The evolution process is considered in the next step to optimize the designed antenna to get the required band of frequencies. After the simulation, if the results meet the desired goal, then the antenna is fabricated, otherwise, the optimization process is repeated until the desired goal is achieved. After the fabrication of the antenna, the performance is measured by vector network analyser (VNA) for reflection coefficient (S_{11}) and anechoic chamber for radiation pattern measurement. The final step is to validate the simulated and measured results of the proposed antenna.

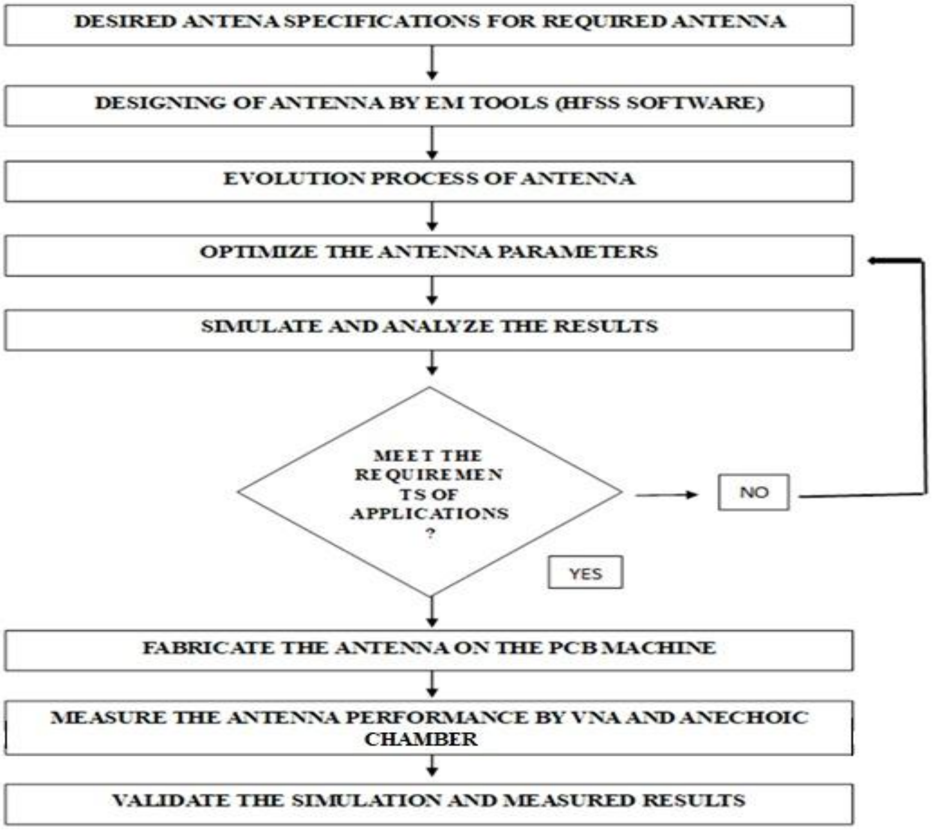


Figure 1.3 Methodology

1.6 Applications of the Thesis

The applications of this research work are as follows:
Reconfigurability and compactness of investigated hexa-band antenna make the antenna relevant to integrate into the devices with smaller form factors, such as smartphones, laptops, or other compact devices to provide services in LTE Band 30/LTE Band 69/LTE Band 22/Radio altimeter/U-NII frequency bands.

1.7 Organization of Thesis

This thesis comprises 5 chapters including the introduction and conclusions. Chapter 2demonstrates the types of antennas such as wire, folded dipole, yagi-uda, helical, horn logperiodic rectangular micro-strip patch antenna. The main parameters which we have used to describe the properties of an antenna are reflection coefficient, gain, radiation pattern, bandwidth, polarization, etc. The classification of antennas are done. Chapter 3 demonstrates the design and development process of a reconfigurable antennas and related concepts. The techniques such as electrical, mechanical, optical, and material changes that contribute significantly to achieving antenna reconfigurability, are also investigated in detail. Chapter 4 deals with the design of a compact GACS-fed frequency reconfigurable hexa-band antenna that deploys single PIN diodes to achieve frequency reconfiguration operating over the LTE Band 30, 53, 52, radio altimeter, U-NII-2A and U-NII-2C frequencies. Finally, chapter 5 summarizes the overall conclusions of the thesis along with the future scope of work.

Chapter 2

Types of Antennas and its Parameters

2.1 Introduction

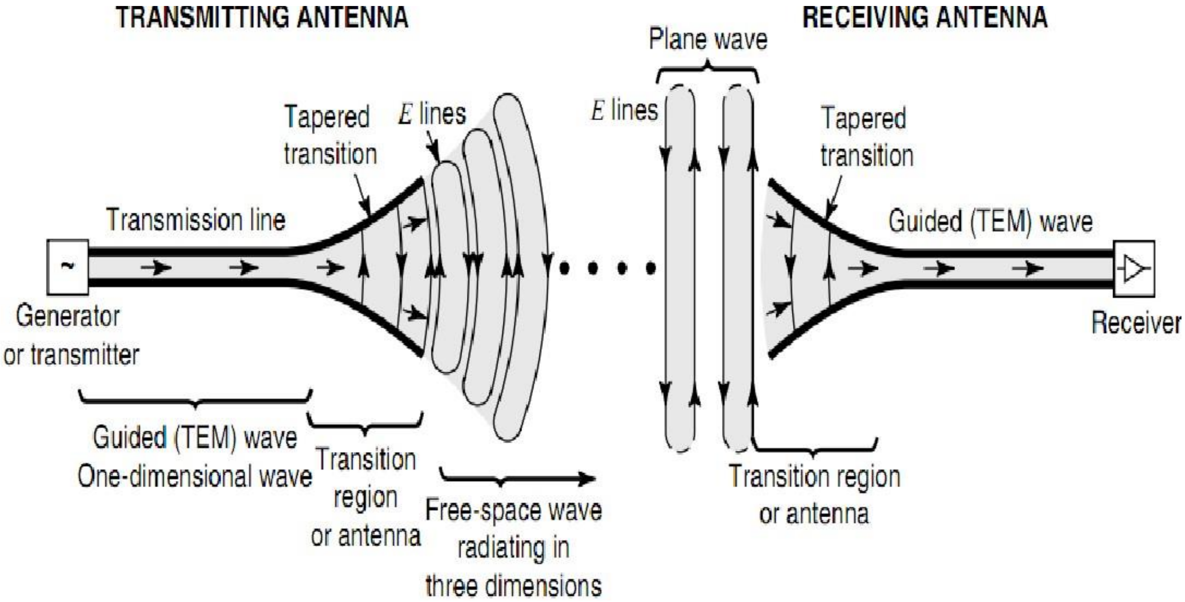
A person, who needs to convey a thought, an idea or a doubt, can do so by voice communication. Here, communication takes place through sound waves. However, if two people want to communicate who are at longer distances, then we have to convert these sound waves into electromagnetic waves. The device, which converts the required information signal into electromagnetic waves, is known as an Antenna.

2.2Definition Of Antenna

1. An antenna is defined by Webster's Dictionary as "a usually metallic device (as a rod or wire) for radiating or receiving radio waves."
2. The IEEE Standard Definitions of Terms for Antennas (IEEE Std 145–1983) defines the antenna or aerial as "a means for radiating or receiving radio waves."
3. An antenna is a transition device, or transducer, between a guided wave and a freespace wave, or vice-versa. The antenna is a device which interfaces a circuit and space.
4. An antenna can be defined as the source or radiator of electromagnetic waves.
5. An antenna can be used to sense the electromagnetic waves. Hence it can be defined as a sensor of electromagnetic waves.
6. An antenna act as a coupling device between a generator or transmitter and free space. Hence antenna is an impedance matching device between free space and transmission line.

In other words, the antenna is the transitional structure between free-space and a guiding device, as shown in Figure 2.1. The guiding device or transmission line may take the form of a coaxial line or a hollow pipe (waveguide), and it is used to transport electromagnetic energy from the transmitting source to the antenna, or from the antenna to the receiver. In the former case, we have a transmitting antenna and, in the latter, a receiving antenna.

The two-wire transmission line in Figure. 2.1 is connected to a radiofrequency generator (or transmitter). Along the uniform part of the line, energy is guided as a plane Transverse Electromagnetic Mode (TEM) wave with little loss. The spacing between wires is assumed to be a small fraction of a wavelength. Further on, the transmission line opensout in a tapered transition. As the separation approaches the order of a wavelength or more, the wave tends to be radiated so that the opened-out line acts like an antenna which launches a free-space wave. For wireless communication systems, the antenna is one of the most criticalcomponents.



(a) TRANSMITTING ANTENNA **(b) RECEIVING ANTENNA**

Figure 2.1 Radio (or wireless) communication link with (a) transmitting antenna and (b) receiving antenna

2.3 Classification of Antennas

2.3.1 Classification Based on Frequency Range

The Institute of Electrical and Electronics Engineers (IEEE) has been maintaining the standard letter designations for radar-frequency bands since 1976, which were revised recently in 2002. The letter designations are assigned to frequency bands that are spaced at intervals of about an octave within the frequency range from 3 MHz to 300 GHz. The frequency bands as per IEEE 521-2001 standard are shown in Table 2.1

Designation	**Frequency**	**Wavelength**
HF	3 – 30MHz	100m – 10m
VHF	30 – 300MHz	10m – 1m
UHF	300 – 1000MHz	100cm – 30cm
L Band	1 – 2GHz	30cm – 15cm
S Band	2 – 4GHz	15cm – 7.5cm
C Band	4 – 8GHz	7.5cm – 3.75cm
X Band	8 – 12GHz	3.75cm – 2.50cm
Ku Band	12 – 18GHz	2.50cm – 1.67cm
K Band	18 – 27GHz	1.67cm – 1.11cm
Ka Band	27 – 40 GHz	1.11cm – 0.75cm
V Band	40 – 75GHz	7.5mm – 4.00mm
W Band	75 – 110GHz	0.27cm – 0.4cm

Table 2.1 Frequency bands (IEEE 521-2002)

2.3.2 Isotropic, Directional and Omnidirectional Patterns

2.3.2.1 Isotropic

An isotropic radiator is defined as “a hypothetical lossless antenna having equal radiation in all directions.” Although it is ideal and not physically realizable, it is often taken as a reference for expressing the directive properties of actual antennas.

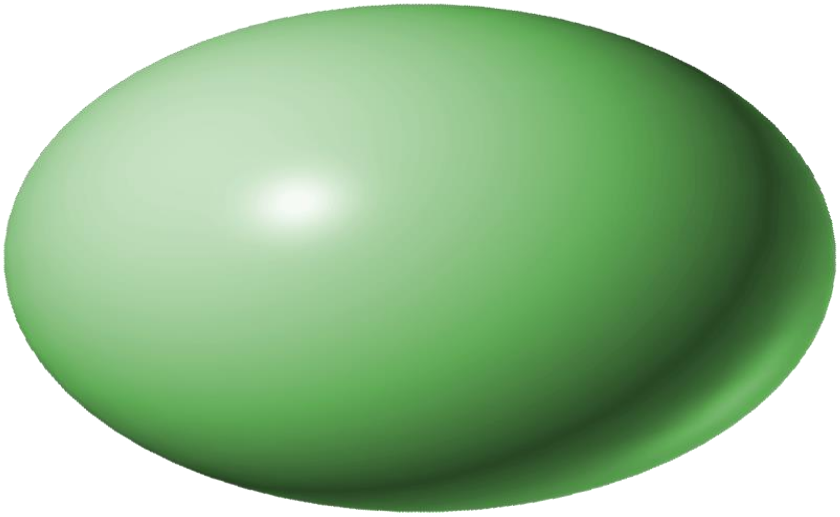


Figure 2.2 Isotropic Radiation

2.3.2.2 Directional

A directional antenna is one “having the property of radiating or receiving electromagnetic waves more effectively in some directions than in others. This term is usually applied to an antenna whose maximum directivity is significantly greater than that of a half-wave dipole.

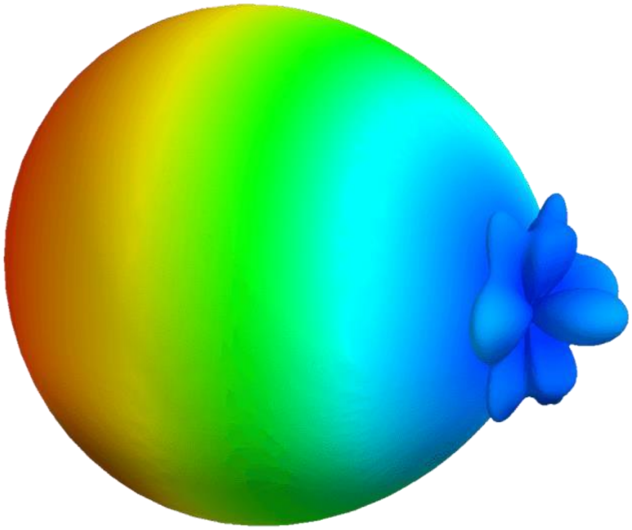


Figure 2.3 Directional Radiation

2.3.2.3 Omnidirectional

An omnidirectional antenna is defined as one “having an essentially nondirectional pattern in a given plane (in this case in azimuth) and a directional pattern in any orthogonal plane (in this case in elevation).” An omnidirectional pattern is then a special type of a directional pattern.

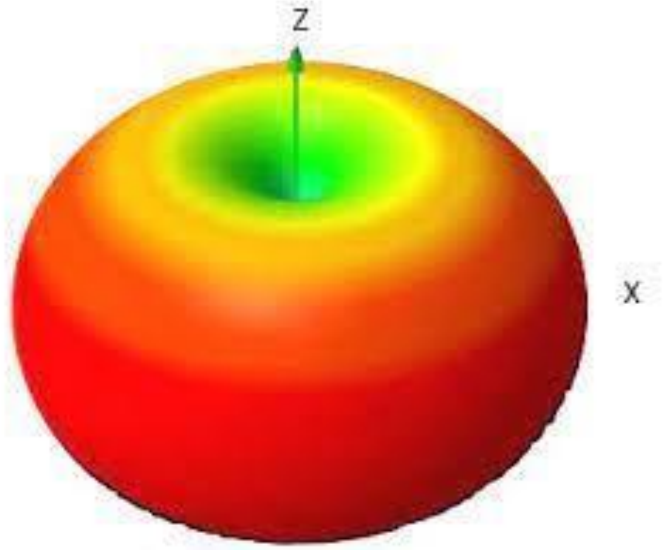


Figure 2.4 Omnidirectional Antenna

2.3.3 Resonant and Non-Resonant Antennas

2.3.3.1 Resonant Antenna

The resonant antennas are the antennas with a length in exact multiples of $\lambda/2$ such antennas are open at both ends and more of the ends is terminated in any resistance. They operate at fixed frequency. In these antennas, reflected waves and standing waves exist. The voltage and current along the length are not in phase. The radiation pattern of such antennas is multidirectional. Such antennas are known as periodic antennas.

2.3.3.2 Non-Resonant Antenna

The non-resonant antennas are travelling wave antennas with a length other than in multiples of $\lambda/2$. Such antennas are excited at one end while other end is terminated into characteristic impedance. These antennas operate over wideband of frequencies. There are no reflected waves and hence no standing waves. The radiation pattern is unidirectional. These antennas are also called directional antennas. Non-resonant antennas are known as aperiodic antennas.

2.4 TYPES OF ANTENNAS

Some of the common types of antennas are mentioned below:

1. Wire Antenna
    - Short Dipole Antenna
    - Half -Wave Dipole Antenna
    - Loop Antenna
    - Monopole Antenna
2. Folded Dipole Antenna
3. Yagi-uda Antenna
4. Helical Antenna
5. Horn Antenna
6. Log-Periodic Antenna
7. Rectangular Microstrip Patch Antenna

2.4.1 Wire Antenna

Wire antennas are also known as linear/curved antennas. One of the most commonly used antennas is wire antenna. They can be found in vehicles (automobiles), ships, aircraft, buildings, etc. Wire antennas come in different shapes and sizes like straight wire (dipole), loop and helix.

2.4.1.1 Short Dipole Antenna

The short dipole ($\lambda/50 < l \leq \lambda/10$) is a center fed antenna having a length that is very short in wavelengths. The current amplitude on such an antenna decreases uniformly from a maximum at the center to zero at the ends i.e. the triangular variation as shown in below Figure 2.5.

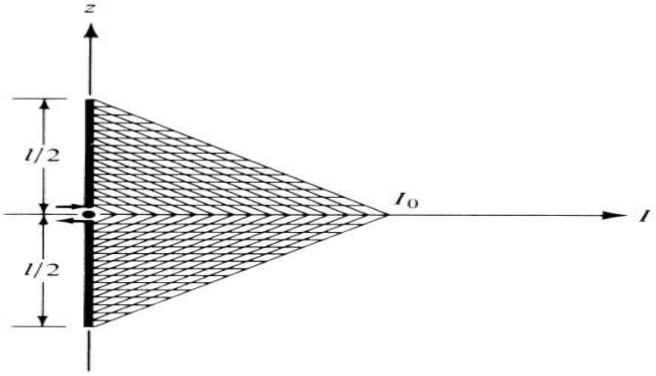


Figure 2.5 Current distribution on short dipole

Due to tapering of current the effective length is just half of the length of that of uniform case that is,

$$dl = \frac{I_{av}}{I_0} L \tag{2.1}$$

$$L = length\ of\ short\ dipole$$

$$I_{av} = Averagevalueoftraingularcurrentdistribution$$

$$I_0 = Maximumvalueoftraingularcurrentdistribution$$

$$dl = length\ of\ infinitesmal\ dipole$$

We know that

$$I_{av} = \frac{I_0}{2} \tag{2.2}$$

Substituting in Eq (2.2) We have

$$dl = \frac{L}{2} \tag{2.3}$$

Substituting *dl in* eq (2.1) we have

$$R_{rad}(shortdipole) = 20\,\pi^2 \left(\frac{L}{\lambda}\right)^2 \approx 200 \left(\frac{L}{\lambda}\right)^2 \Omega \tag{2.4}$$

Infinitesimal Dipole

A dipole whose length is far less than wavelength is infinitesimal dipole. This antenna is actually impractical. The length of the dipole, $\Delta \boldsymbol{l}$<<λ. Where, λ is the wavelength.

$$\Delta \boldsymbol{l} = \frac{\boldsymbol{\lambda}}{\mathbf{50}}$$

Hence, this is the infinitely small dipole, as the name implies.

2.4.1.2 Half-Wave Dipole Antenna

Adipole antenna (also known as a doublet **or** dipole aerial) is defined as a type of RF (Radio Frequency) antenna, consisting of two conductive elements such as rods or wires. The dipole is any one of the varieties of antenna that produce a radiation pattern approximating that of an elementary electric dipole. Dipole antennas are the simplest and most widely used type of antenna. The range of frequency in which half-wave dipole operates is around 3KHz to 300GHz. This is mostly used in radio receivers. A dipole means two poles hence the dipole antenna consists of two identical conductive elements such as rods or metal wires. The length of the metal wires is approximately half of the maximum wavelength (i.e.,) in free space at the frequency of operation. This wire or rod is split at the centre, and the two sections are separated by an insulator, these sections are known as an antenna section. These two antenna sections are connected to a feederorcoaxial cableat the end closest to the centre of the antenna**.** The basic dipole antenna with the centre feed point is shown in the Figure below.

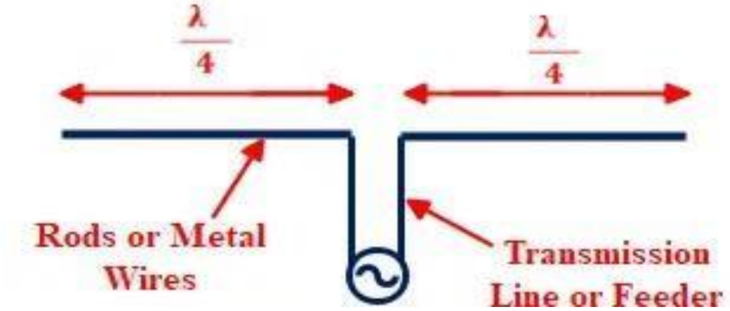


Figure 2.6 Half Wave Dipole Antenna with Centre Feed Point

The radio-frequency (RF) voltage sourceis applied to the centre between the two sections of the dipole antenna. This voltageand a currentflowing through the two conductive elements produce a radio signal or an electromagnetic wave to be radiated outwards from the antenna. The current is maximum and voltage is minimum at the centre of the dipole antenna. Conversely, the current is minimum and voltage is maximum at the ends of the dipole antenna.

2.4.1.3 Loop Antenna

A type ofantennawhich is formed by bending of a coil or uniform wire in the form of loop is known as a loop antenna. Basically, in loop antenna, the RF current-carrying coil is bent to various shapes like circle, square, rectangle, ellipse, etc as shown in Figure. Thus, we can say it as a current-carrying coil bent in the form of loops of different shapes is known as a loop antenna. These antennas are known to be simple, inexpensive and versatile antenna and thus has a wide range of applications.

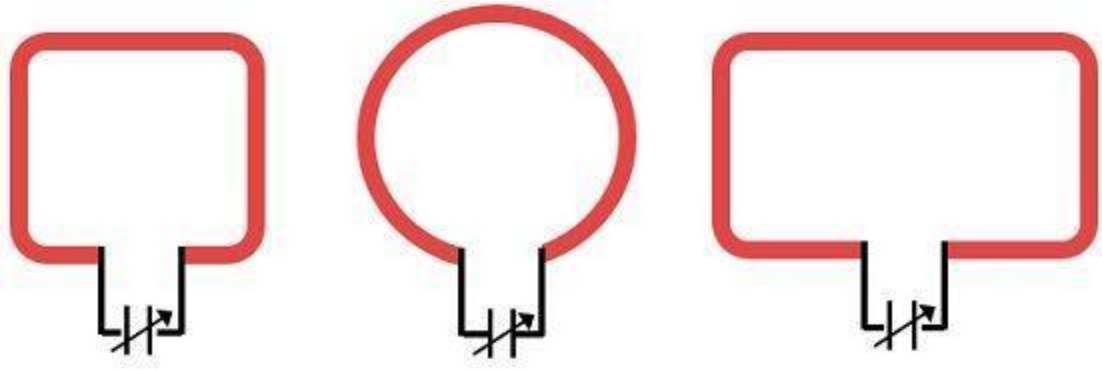


Figure 2.7 Loop antennas of different shapes

It is to be noted here that despite its availability in different shapes, circular type of loop antennas is widely used. The reason behind this is that circular loop antennas offer simplicity in construction as well as analysis. Generally, loop antennas are referred as a radiating coil with any cross-section having single or multiple turns. When a loop antenna contains two or more turns then it is called a frame. The operating frequency permitted by loop antenna ranges between 300 MHZ to 3 GHz.

Classification of Loop Antenna

Generally, loop antennas are classified as follows:

Electrically small loop antenna: The type of loop antenna having a length of wire or circumference of loop less than one-tenth of wavelength is known as a small loop antenna. Thus, here $C < \lambda / 10$.These types of antennas offer small radiation resistance having value even smaller than their loss resistances. So, it offers, poor radiating ability, thus is not considered as good radiators. Due to this reason these are not used in transmitting applications. Therefore, find uses at the receiving sections, where having a good signal to noise ratio is more important than the efficiency of the antenna. Irrespective of the shape of the loop, the field pattern of all the small loops is the same as that of infinitesimal dipole having maximum along the plane and null perpendicular to the plane of the loop.

Electrically large loop antenna: When the circumference of the loop is approximately equivalent to free space wavelength then it is referred as an electrically large loop antenna. This means C ~ λ. In the case of large loop antennas, the field pattern is such that the null is in the direction of the antenna axis. The increase in the perimeter or the number of turns in the loop electrically enhance the radiation resistance of the loop. This is so because, with the increase in the length, the circumference approximately reaches wavelength and in that case, the field pattern will vary and the maximum will shift from plane to the axis of the loop. Sometimes the placement of high permeability ferrite rod within the circumference of the loop also increases the radiation resistance.

2.4.1.4 Monopole Antenna

A monopole antenna is one half of a dipole antenna, almost always mounted above some sort of ground plane. The case of a monopole antenna of length L mounted above an infinite ground plane is shown in Figure2.8(a).

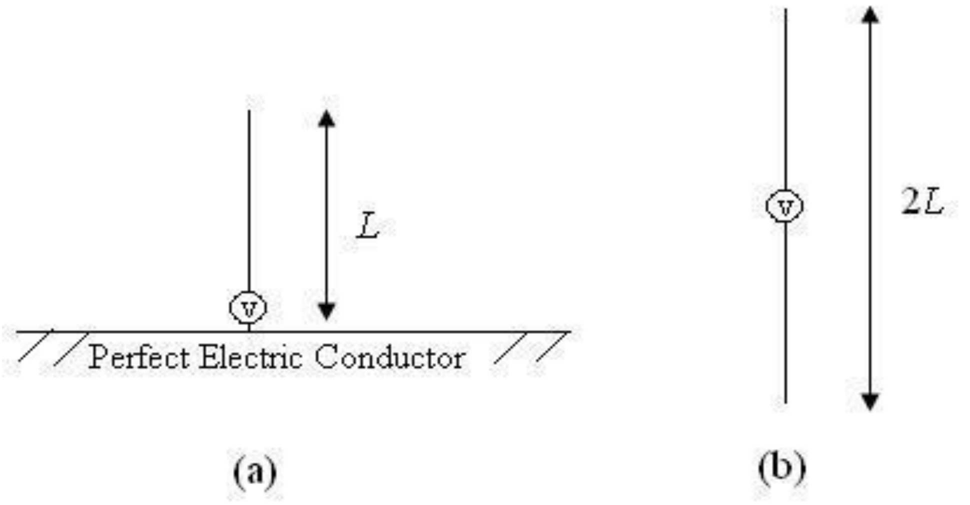


Figure 2.8 a) Monopole above a PEC and b) the equivalent source in free space

Using image theory, the fields above the ground plane can be found by using the equivalent source (antenna) in free space as shown in Figure:2.8(b). This is simply a dipole antenna of twice the length. The fields above the ground plane in Figure:2.8(a) are identical to the fields in Figure:2.8(b),which are known and presented in the dipole antenna section. The monopole antenna fields below the ground plane in Figure:2.8(a) are zero.

The radiation pattern of monopole antennas above a ground plane can be obtained from the dipole radiation pattern. The only change that needs to be noted is that the impedance of a monopole antenna is one half of that of a full dipole antenna. For a quarter-wave monopole ($\boldsymbol{L} = \mathbf{0.25} * \boldsymbol{\lambda}$),the impedance is half of that of a half-wave dipole, Zin = 36.5 + j21.25 Ohms. The directivity of a monopole antenna is directly related to that of a dipole antenna. If the directivity of a dipole of length 2L has a directivity of D1 [decibels], then the directivity of a monopole antenna of length L will have a directivity of D1+3 [decibels]. That is, the directivity (in linear units) of a monopole antenna is twice the directivity of a dipole antenna of twice the length. The reason for this is simply because no radiation occurs below the ground plane; hence, the antenna is effectively twice as directive. Monopole antennas are half the size of their dipole counterparts, and hence are attractive when a smaller antenna is needed. Antennas on older cell phones were typically monopole antennas, with an infinite ground plane approximated by the shell (casing) of the phone.

2.4.2 Folded Dipole Antenna

A very important variation of conventional half wave dipole is the folded dipole as shown in Fig:2.9.In this antenna two half wave dipole one continuous and other split at the centre have been folded and joined together in parallel at the ends. The split dipole is fed at the centre by a balanced transmission line. The two dipoles therefore have same voltages at their ends. The radiation pattern of a folded dipole and conventional half wave dipole is same but the input impedance of the folded dipole is higher. Generally, we have

$$Z_{foldeddipole} = \frac{V}{I_1} = n^2 Z_{11} \quad (2.5)$$

Where n is number of half wave dipoles

$$Z_{11} = 73\,\Omega\, foradipole$$

It differs from the conventional dipole mainly in two respects directivity and broadness in bandwidth

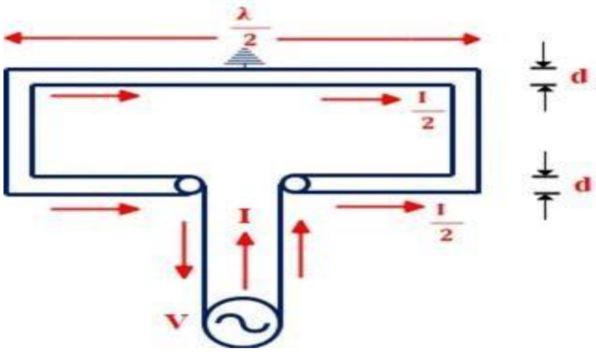


Figure 2.9 Folded Dipole Antenna

The folded dipole antenna is ideal for use as a feeder element in Yagi antenna, Parabolic antenna, turnstile antenna, log periodic antenna, phased and reflector arrays, etc. It is also used in radio receivers and is commonly used in TV receiver antennas.

2.4.3 Yagi-uda antenna

Yagi-uda or simply yagi antennas are the most high gain antennas and are known after the names of professor S.Uda and H. Yagi. It consists of a driven element, a reflector and one or more directors i.e., yagi-uda antenna is an array of a driven element and one or more parasitic elements Driven element*:* It is active element where the power from the Tx is fed or which feeds received power to Rx. Parasitic elements*:* They are the passive elements which are not connected directly to the transmission line but electrically coupled. The driven element is a resonant half-wave dipole usually of metallic rod at the frequency of operation. The parasitic elements of continuous metallic rods are arranged parallel to the driven element and at the same line of sight asshown in below Figure 2.10.

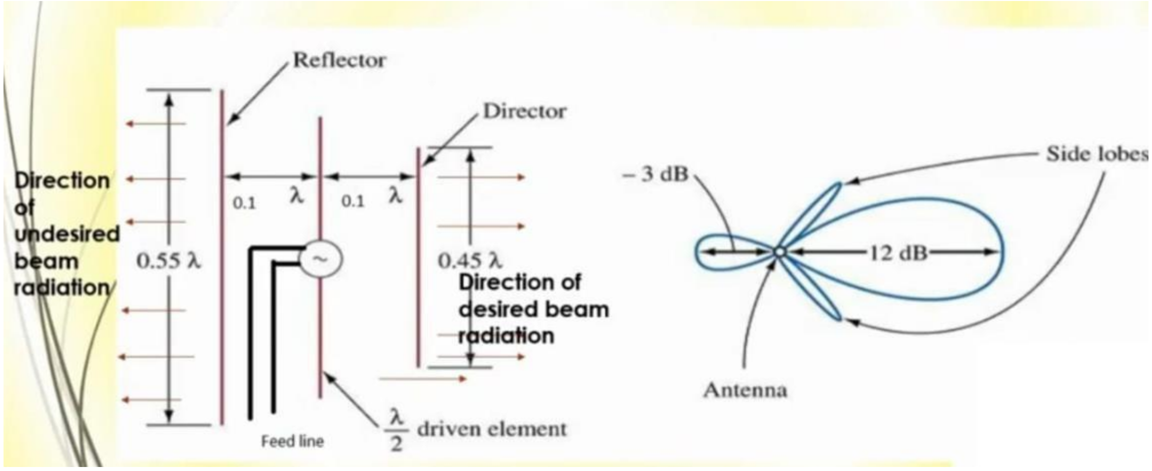


Figure 2.10 Yagi-uda antenna

The Parasitic elements receive their excitation from the voltages induced in them by the current flow in the driven element. The parasitic element in front of driven element is known as director and its number may be more than one whereas the element in back of it is known as reflector. A parasitic element of length shorter than λ acts as director and it is capacitive in nature and adds the fields of driven element in the direction away from the driven element. If more than one director is employed then each director will excite the next. Additional gain is achieved by using additional directors in the beam direction. On the other hand, a parasitic element of length equal to or greater than λ acts as reflector and it is inductive in nature and add up the fields of driven element in the direction from reflector toward driven element. The driven element radiates from front to rear i.e., from reflector to directors. By changing the lengths of parasitic elements and spacing between the elements the radiated energy is added up in the front and tend to cancel in the backward direction. If the distance between the driven and parasitic element is decreased then it will load the driven element irrespective of its length. Thus, the input impedance at the input terminals of driven element reduces. That is why a folded dipole is used as driven element so that reduction in input impedance is compensated. In general, the frequency range of the yagi antenna is 3MHz to 300 GHz. In practice for 3-element array of yagi antenna the following formulae gives lengths of different elements

$$Reflector\ length = \frac{500}{f(MHz)}\ feet = \frac{152}{f(MHz)}\ meter$$

$$Driven\ Element\ length = \frac{475}{f(MHz)}\ feet = \frac{143}{f(MHz)}\ meter$$

$$Director\ length = \frac{455}{f(MHz)}\ feet = \frac{137}{f(MHz)}\ meter$$

A few of the applications of the Yagi antenna are: Yagi UDA antennas are employed in TV signal reception as this antenna holds good receiving capability. Used in defense applications.

2.4.4 Helical Antenna

Helical antenna is another basic type of radiator and perhaps it is the simplest antenna to provide circularly polarized waves. Helical antenna is broadband VHF and UHF antenna. It consists of a thick copper wire wound in the form of a helix and used as an antenna in conjunction with a flat metal plate called a ground plate as shown in Figure. 2.11.Generally, the helix is fed by a coaxial cable and one end of the helix is connected to the centre conductor of the cable and outer conductor is connected to the ground plane. The dimensions of the helix are shown below

C = Circumference of helix = πD
α = Pitch angle
D = Diameter of helix
d = Diameter of conductor
S = Spacing between two turns
N = Number of turns

A = Axial length = NS

L = length of one turn

l = spacing of helix from ground plane

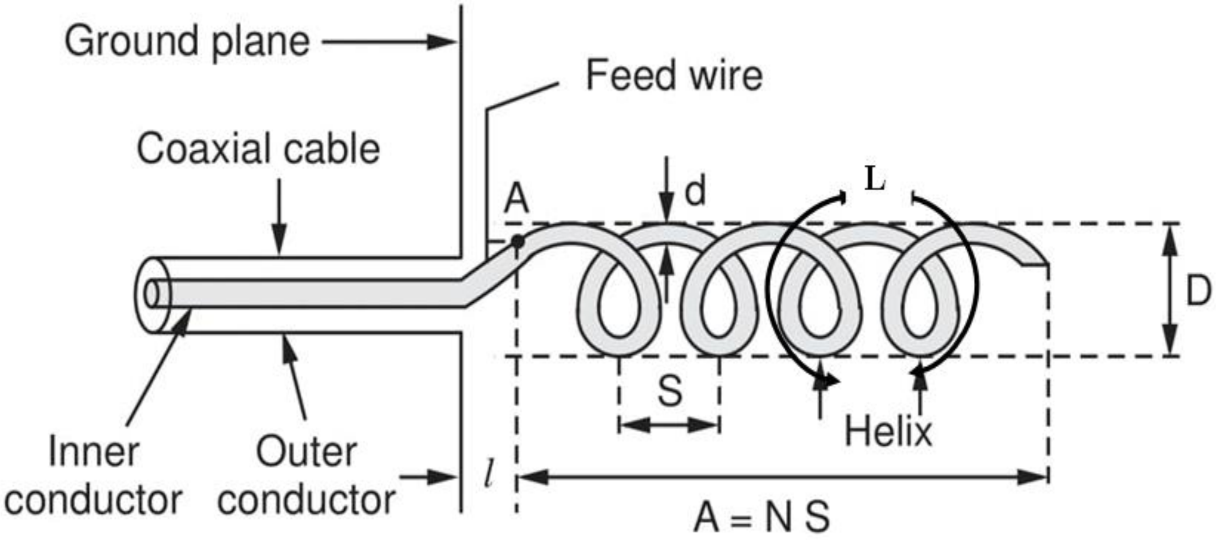


Figure 2.11 Structure of helical antenna

If one turn of helix is unrolled on a plane surface then the circumference (C), spacing between turns (S) and turn length and pitch angle (α) can be related to each other through the triangle terminology as shown in the Figure. 2.12.

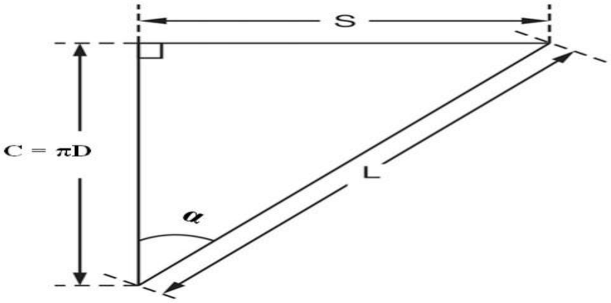


Figure 2.12 Triangle terminology for one turn of helix unrolled

Then we can write

$$L = \sqrt{S^2 + C^2} = \sqrt{S^2} + (\pi D)^2 \qquad (2.6)$$

The pitch angle is the angle between a line tangent to the helix wire and the plane normal to the helix axis. It is given by

$$\text{Tan } \alpha = \frac{S}{C} = \frac{S}{\pi D} \qquad (2.7)$$

$$\alpha = tan^{-1}(\frac{S}{\pi D}) \qquad (2.8)$$

The properties of helical antenna can be described in terms of these geometric parameters and different radiation characteristics are obtained by changing these parameters in relation to wavelength. A helical antenna may radiate in many modes but prominent modes of radiations are two i.e., normal or perpendicular mode of radiation and axial or end fire mode of radiation.

Normal mode of radiation

In the normal mode of radiation, the radiation field is maximum in broad way i.e., in the direction normal to the helix axis and is circularly polarized wave. This mode of radiation is obtained if the dimensions of the helix is small compared with wavelength. However, the bandwidth of such a small helix is very narrow and the radiation efficiency is low. The radiation pattern of helix in this mode is a combination of the equivalent radiation from a short dipole positioned on the same helix axis and a small loop which is also coaxial with the helix axis. It is because $\alpha = 0^o$ corresponds to loop and $\alpha = 90^o$ the helix becomes a linear dipole as shown in Figure. 2.13

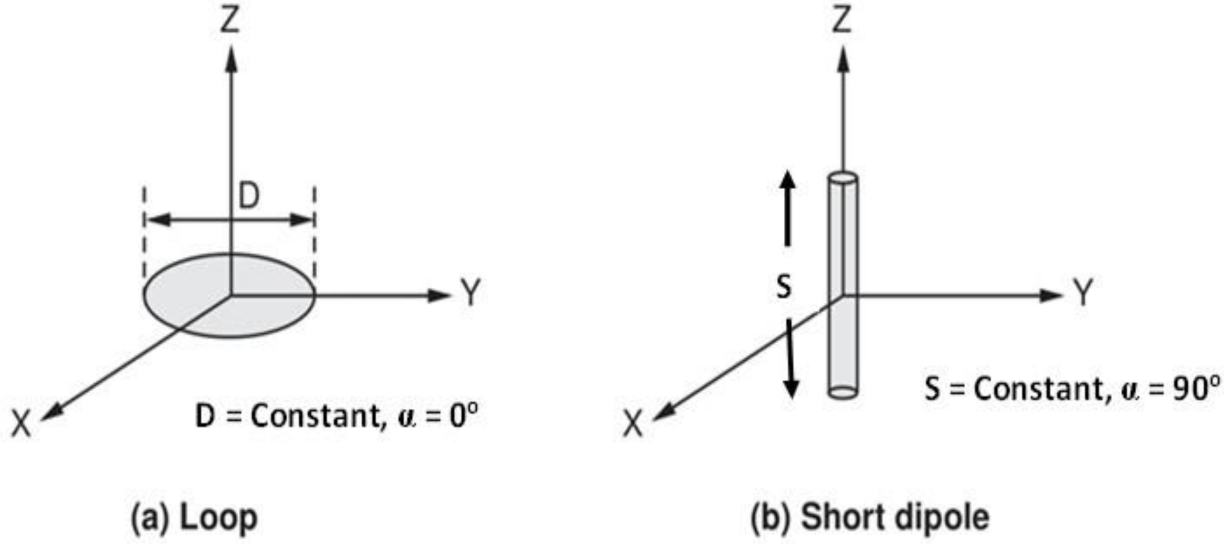


Figure 2.13 Limiting conditions of helix

Thus, loop and linear dipole are the limiting cases of the helix**.** Thus, in a helix of fixed diameter, if S → 0 helix collapses to a loop and if S = constant and D → 0, the helix straightens into a short dipole**.** The radiation patterns of these two equivalent radiators are same, however the polarizations are at right angles and hence the resultant field is either circularly polarized or elliptically polarized and it depends on pitch angle α**.** If α is small loop type of radiation predominates and when α becomes very large the dipole type of radiation predominates**.** A helix antenna may be considered of having a number of small loops and short dipoles connected in series in which loop diameter is same as helix diameter and helix spacing S is same as dipole length**.**

Axial or Beam mode of radiation

In axial mode of radiation, the radiation field is maximum in the end fire direction i.e., along the helix axis as shown in Figure. 2.14 with the axial mode of radiation, the polarization is circular or nearly circular. This mode occurs when the helix circumference

(D) and spacing S are appreciable of the order of one wavelength. This mode is more interesting as it produces a broad and fairly directional beam in the axial direction with minor lobes at oblique angles. It is this feature of the helical antenna in axial mode of radiation that accounts probably for most of the practical applications. It is this feature of the helical antenna in axial mode of radiation that accounts probably for most of the practical applications

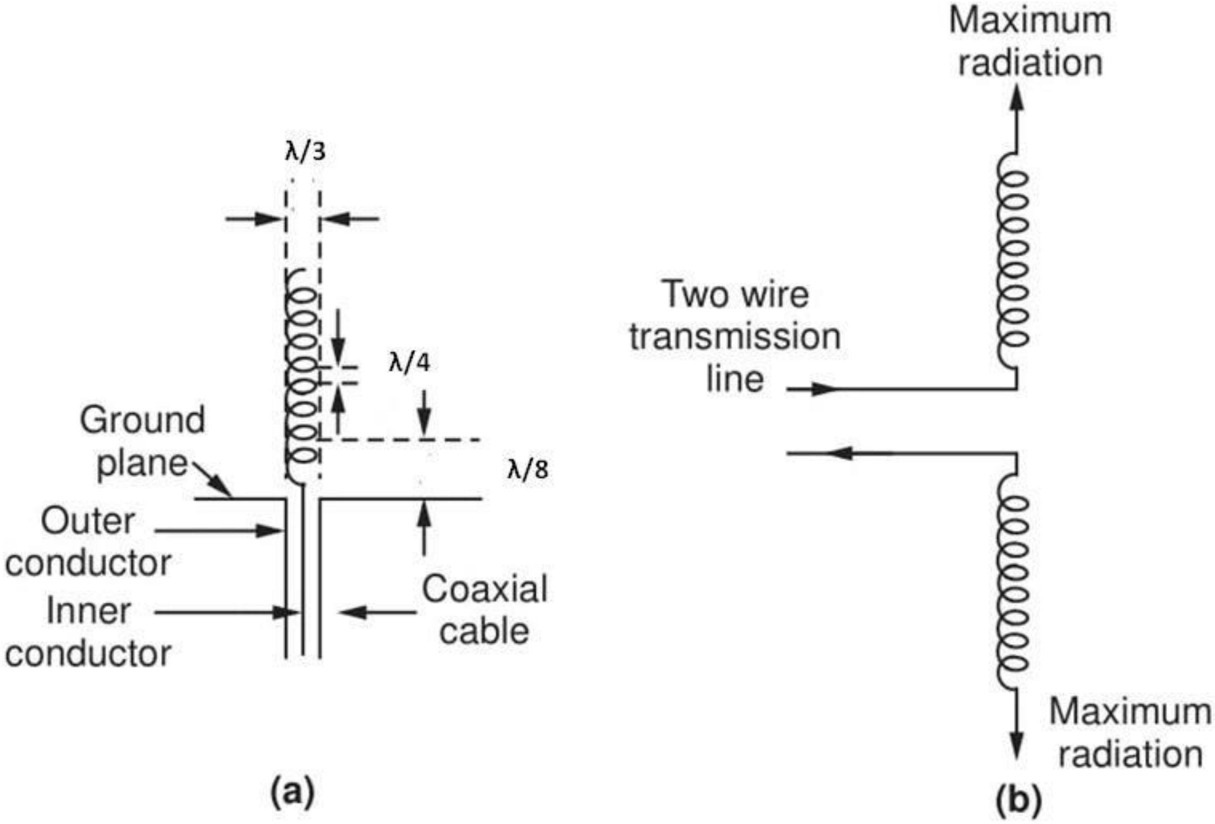


Figure 2.14 Helical antenna in axial mode

This mode is possible in the helical antenna if the circumference is selected of the order of one wavelength and spacing is selected approximately equal to λ/4. The pitch angle α varies from 12^o to 18^o and about 14^o is optimum pitch angle. The antenna gain and beam width depends upon the helix length (NS). In general, in axial mode the terminal impedance of helical antenna lies between 100 Ω to 200 Ω pure resistive.

2.4.5 Horn Antenna

The first horn antenna was designed with pioneering experiments through microwaves by a radio researcher namely Jagadish Chandra Bose in 1897. The current horn antenna was invented separately in 1938 by G. C. Southworth & Wilmer Barrow. After that frequent research was done to explain the design of horn-antenna, discover the radiation pattern & its applications in several fields. These antennas are very famous in the domains of waveguide transmission & microwave. So, these antennas are frequently called microwave antennas.

A Horn antenna is a type of aperture antenna which is specially designed for microwave frequencies. The end of the antenna is widened or in the horn shape. Because of this structure, there is larger directivity so that the emitted signal can be easily transmitted to long distances. Horn antennas operate in microwave frequency, so the frequency range of these antennas is super high or ultra-high which ranges from 300 MHz – 30 GHz.

Figure 2.15 Horn Antenna

These antennas are used as feed horns for big antennas like parabolic antennas directive antennas, etc. The benefits of using these antennas are simple design &adjustment, low SWR (standing wave ratio), moderate directivity, and broad bandwidth.

Horn Antenna Design & Working

Horn antenna design can be done with a flared waveguide which is formed as a horn. These are used to transmit and receive RF microwave signals. Here, the flared portion can be in any shape like square, conical or rectangular. For proper working, this antenna should be in minimum size. If the wavelength is very large or the horn size is very small then the antenna will not work properly.

In this antenna, the fraction of incident energy can be radiated from the entry of the waveguide and the rest of the energy will be reflected back from the same entry because of the open entry, the poor impedance matching will exist in between the space &waveguide. Also, at the edges of the waveguide, diffraction affects the poor radiating capacity of the waveguide.

So,to overcome the drawbacks of the waveguide, its end is opened in an electromagnetic horn form. So that a smooth transition can be allowed in between the space & waveguide thus offering better directivity toward the radio wave. By changing the waveguide like a horn structure, the existing discontinuity in between the space & waveguide, 377 ohms impedance is eliminated. So, this provides the incident energy to be emitted in the forwarding direction by decreasing the diffraction on the edges. Therefore, the transmitting antenna’s directivity can be enhanced with superior gain.

Types of Horn Antenna

Horn antennas are classified into different types pyramidal, conical and exponential.

Pyramidal Horn Antenna

As the name suggests, this antenna is in a pyramid shape through a rectangular cross-section. This antenna can be formed by flaring both the waveguide walls. In this antenna, a rectangular waveguide is utilized & the flaring can be done within both the direction of magnetic and electric field vectors. These antennas are simply used to radiate linearly polarized radio waves & used with rectangular waveguides.

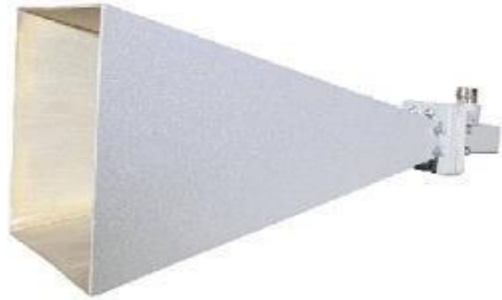


Figure 2.16 Pyramidal Horn Antenna

Sectoral Horn Antenna

It is a type of antenna where only one pair of faces are flared whereas the other pair is in parallel. It generates a fan-shaped thin beam in the flared side's plane, however broad in the narrow side's plane. Thesetypes of antennasare frequently used as feed horns, especially for wide search radar antennas.

Figure2.17 Sectoral Horn Antenna

So, in this antenna, flaring can be performed simply through one of the waveguide walls. Further, these are classified into two types E-plane and H-plane.

E-plane: Once one of the waveguide walls in an antenna is flared with the electric field vector direction is called an E-plane antenna. H-plane: Once the waveguide walls in an antenna are flared with the magnetic field vector direction then it is called an H-plane antenna.

Conical Horn Antenna

When an antenna horn is in a cone shape with a circular cross-section is known as a conical horn antenna. These antennas are simply used through cylindrical waveguides. A conical antenna formation is an effect of a circular waveguide flaring. A circular horn antenna can be either biconical or conical within nature.

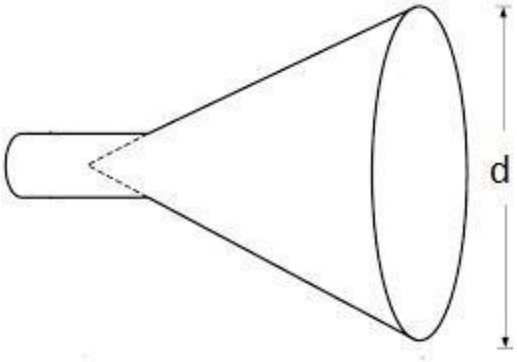


Figure 2.18 Conical Horn Antenna

Exponential Horn Antenna

These antennas are sometimes called scalar horn antennas. As compared to another horn antenna, this antenna is an alternative that has an exponentially tapered face that forms a curved plane from the antenna opening to the termination of the waveguide.

Figure 2.19 Exponential Horn Antenna

This antenna is known as an exponential horn antenna because the separating space among the sides increases exponentially like a function of length. These types of antennas provide a constant impedance to a huge frequency so there is less possibility of internal reflections. This type of design will reduce the number of internal reflections, permit a constant impedance & electrical performance over an extremely broad bandwidth.

2.4.6 Log-Periodic Antenna

The Yagi-Uda antenna is mostly used for domestic purpose. However, for commercial purpose and to tune over a range of frequencies, we need to have another antenna known as the Log periodic antenna. A Log-periodic antenna is that whose impedance is a logarithmically periodic function of frequency. The frequency range, in which the log-periodic antennas operate is around 30 MHz to 3GHz which belong to the VHF and UHF bands**.** The construction and operation of a log-periodic antenna is similar to that of a Yagi-Uda antenna. The main advantage of this antenna is that it exhibits constant characteristics over a desired frequency range of operation. It has the same radiation resistance and therefore the same SWR. The gain and front-to-back ratio are also the same. With the change in operation frequency, the active region shifts among the elements and hence all the elements will not be active only on a single frequency. This is its special characteristic. There are several type of log-periodic antennas such as the planar, trapezoidal, zig-zag, V-type, slot and the dipole. The mostly used one is log periodic dipole array, in short, LPDA.

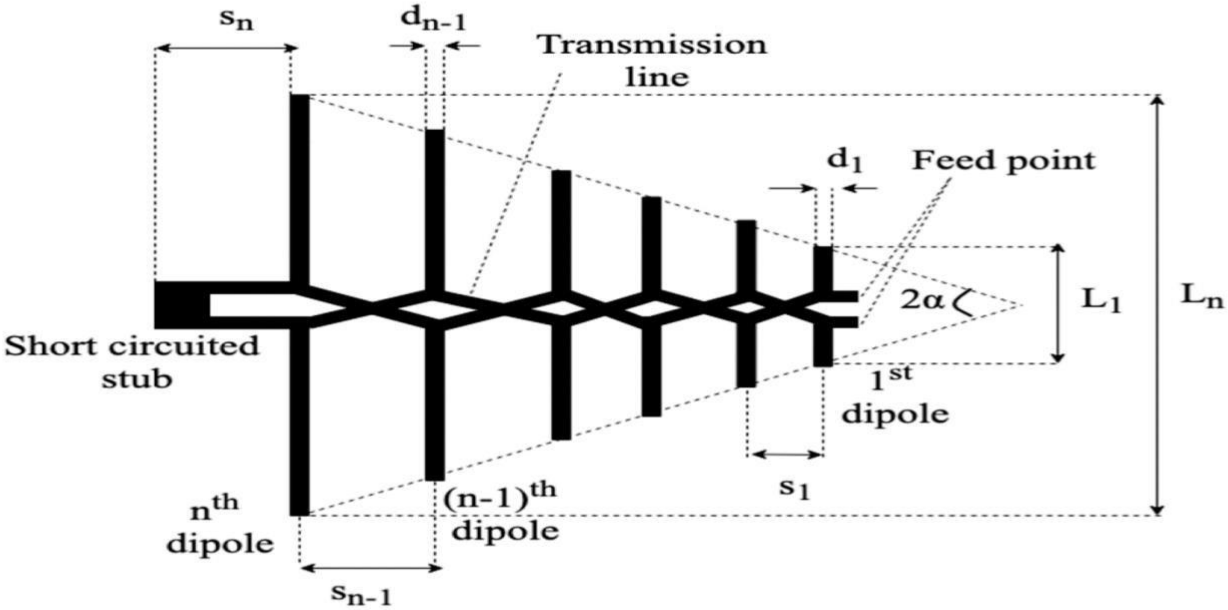


Figure 2.20 Log-Periodic Antenna

The log-periodic array is shown in Figure. The physical structure and electrical characteristics, when observed, are repetitive in nature. The array consists of dipoles of different lengths and spacing, which are fed from a two-wire transmission line. This line is transposed between each adjacent pair of dipoles. The dipole lengths and separations are related by the formula –

$$\frac{R_1}{R_2}=\frac{R_2}{R_3}=\frac{R_3}{R_4}=\tau=\frac{l_1}{l_2}=\frac{l_2}{l_3}=\frac{l_3}{l_4} \qquad (2.9)$$

Where, τ is the design ratio and τ < 1, R is the distance between the feed and the dipole and l is the length of the dipole. The directive gains obtained are low to moderate. The radiational patterns may be unidirectional or bi-directional.

2.4.7 Microstrip Patch Antenna

A Micro-strip patch antenna consists of a radiating patch on one side of a dielectric substrate which has a ground plane on the other side as shown in Figure. 2.21. These are mostly used at microwave frequencies.

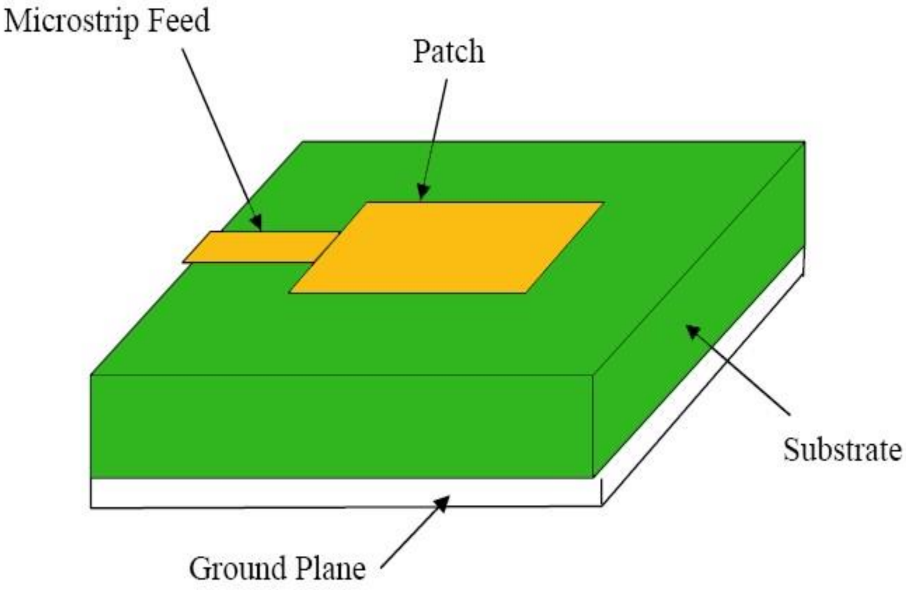


Figure 2.21 Microstrip Patch Antenna

<u>Different parameters of Rectangular microstrip patch antenna</u>

L = Length of the Micro-strip Patch Element, W = Width of the Micro-strip Patch Element, t= Thickness of Patch and h = Height of the Dielectric Substrate.

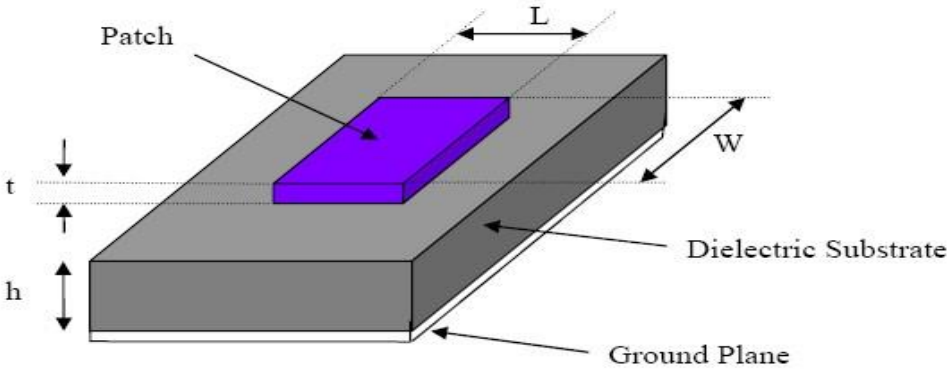


Figure 2.22 Microstrip patch

$t \ll \lambda_0$, where $\lambda 0$ is the free-space wavelength, $h \ll \lambda 0$, usually $0.003\lambda 0 \le h \le 0.05\lambda 0$ and $\lambda 0/3 < L < \lambda 0/2$

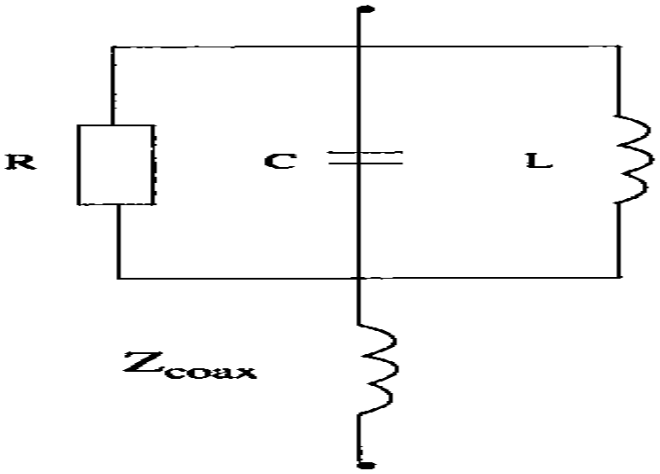


Figure 2.23 Equivalent circuit of Microstrip patch antenna

Equivalent resonant parallel RLC circuit

$$Q = \frac{R}{\sqrt{\frac{L}{C}}} \tag{2.10}$$

$$f_0 = \frac{1}{2\pi \sqrt{LC}} \tag{2.11}$$

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, but at the expense of larger element size. Thin substrates with higher dielectric constants are desirable for microwave circuitry, and lead to smaller element sizes , however because of their greater losses, they are less efficient and have relatively smaller bandwidths. Compromise has to be reached between good antenna performance and circuit design.

2.5 Main Parameters of An Antenna

There are several fundamental parameters that have major impact on the performance of an antenna such as

- Reflection Coefficient (S_{11})
- Impedance Bandwidth
- Radiation Pattern
- Polarisation
- Directivity
- Gain
- Radiation Efficiency
- Beam Width

2.5.1 Reflection Coefficient (S_{11})

In the context of antennas, the reflection coefficient is defined as the figure that quantifies how much of an electromagnetic wave is reflected by an impedance discontinuity in the transmission medium. The reflection coefficient is equal to the ratio of the amplitude of the reflected wave to the incident wave. If the power incident on the antenna-under-test (AUT) is P_{in} and the power reflected back to the source is P_{ref}, then reflection coefficient.

$$\boldsymbol{s_{11}} = \frac{\boldsymbol{p_{ref}}}{\boldsymbol{P_{in}}} \tag{2.12}$$

Where S_{11} is the reflection coefficient at the input of the AUT. In terms of the voltage - standing-wave ratio (VSWR), $\boldsymbol{s_{11}}$ is given by

$$|\boldsymbol{s_{11}}| = \textbf{VSWR-1/VSWR+1} \tag{2.13}$$

Theoretically for matched condition VSWR = 1 and $S_{11} = 0$ but practically VSWR = 2 and for VSWR = 2, $S_{11} = 1/3$. S_{11} in dB is given by

$$s_{11}(\mathrm{dB}) = 20log_{10}(s_{11}) \tag{2.14}$$

For $s_{11} = \frac{1}{3}$, $s_{11(\mathrm{dB})}$ = -9.64≈-10dB

So, for antenna to radiate properly at particular frequency with minimum reflections, reflection coefficient (S_{11}) should be less than -10 dB at that frequency.

2.5.2 Impedance Bandwidth (BW)

The bandwidth of an antenna is defined as “the range of frequencies within which the performance of the antenna, with respect to some characteristic, conforms to a specified standard. There are two types of bandwidths pattern bandwidth and impedance bandwidth. Associated with pattern bandwidth are gain, side lobe level, beamwidth, polarization, and beam direction while input impedance and radiation efficiency are related to impedance bandwidth.

Impedance bandwidth is another fundamental parameter of antenna. To define the impedance bandwidth of the antenna one normally measures its S_{11} magnitude as a function of frequency. The antenna impedance bandwidth is normally defined as the frequency range at which S_{11} magnitude is below -10 dB as shown in Figure. 2.22 The impedance bandwidth is often specified in terms of its fractional bandwidth.

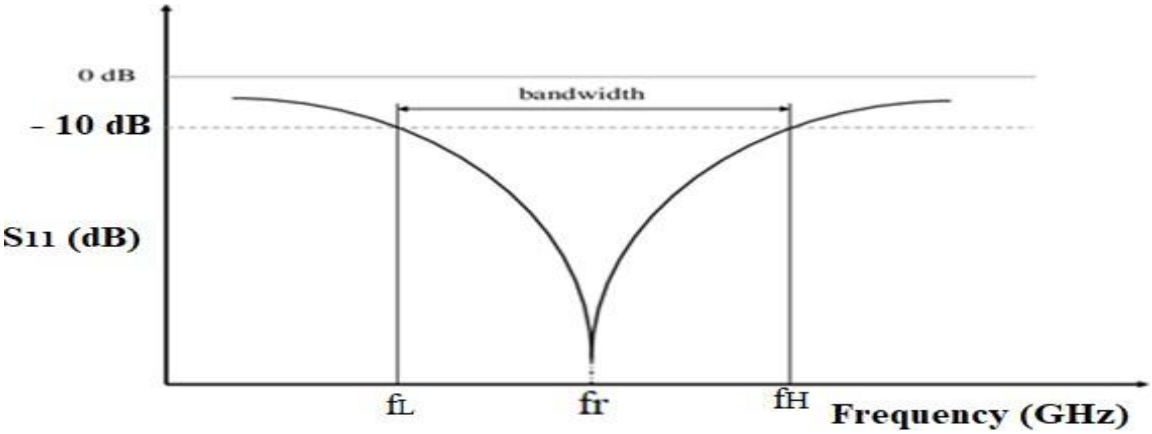


Figure 2.24 Reflection Coefficient Vs Frequency

The fractional or percentage bandwidth can be calculated as:

$$\%BW = \frac{2*(f_H - f_L)}{f_H + f_L} \quad (2.15)$$

Where $\frac{f_H + f_L}{2}$ is called center frequency f_c

Wideband antennas typically have a Fractional Bandwidth of 20% or more. Antennas with a FBW of greater than 50% are referred to as ultra-wideband antennas.

2.5.3 Radiation Pattern

An antenna radiation pattern, or antenna pattern, is defined as a graphical representation of the radiation properties of the antenna as a function of space coordinates. Since antennas are commonly used as parts of wireless telecommunication systems, the radiation pattern is determined in the far-field region where no change in pattern with distance occurs. That is, the antenna's pattern describes how the antenna radiates energy out into space (or how it recieves energy).

A plot of the normalized radiated or received power at a constant radius is called a **power pattern**.

A plot of the normalized electric or magnetic field along a constant radius is called **a field pattern**.

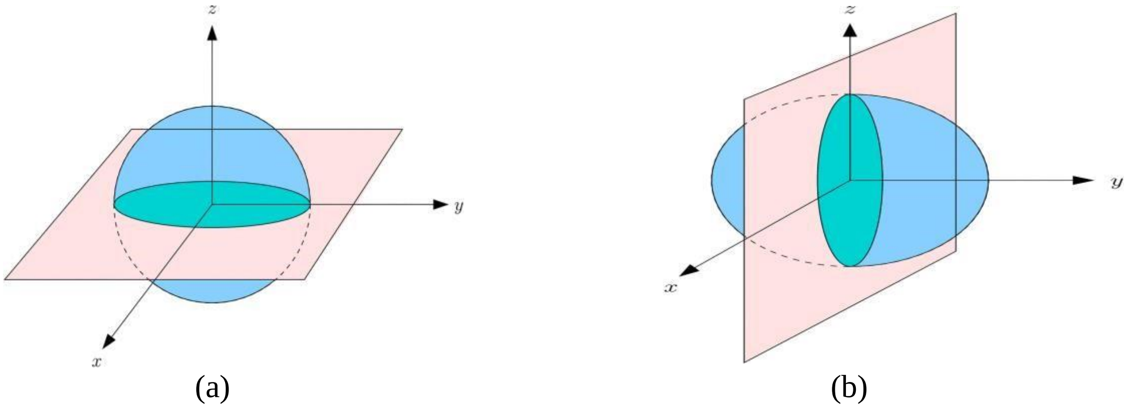
The power pattern and the field patterns are inter-related:

$$P(\theta, \phi) = (1/\eta)*|E(\theta, \phi)|2 = \eta*|H(\theta, \phi)|2 \quad (2.16)$$

P = power

E = electrical field component vector H = magnetic field component vector η = 377 ohm (free-space, plane wave impedance)

The radiation pattern is three-dimensional, but complete 3D pattern is difficult to visualize. It is common, however, to describe this 3D pattern with two planar patterns, called the principal plane patterns or 2D patterns. These principal plane patterns can be obtained by making two cuts through the 3D pattern as shown in Figure. It is these principal plane patterns that are commonly referred to as the antenna patterns.



(a) (b)

Figure 2.25 Two such cuts at right angles called principal plane patterns a) XY Cut and b) XZ Cut

The principal plane patterns are classified into azimuth plane pattern and elevation plane pattern. The term azimuth is commonly found in reference to "the horizon" or "the horizontal" whereas the term elevation commonly refers to "the vertical". In Figure , the x-y plane (θ = 90 deg) is the azimuth plane. The elevation plane is then a plane orthogonal to the x-y plane, say the y-z plane (φ = 90 deg).

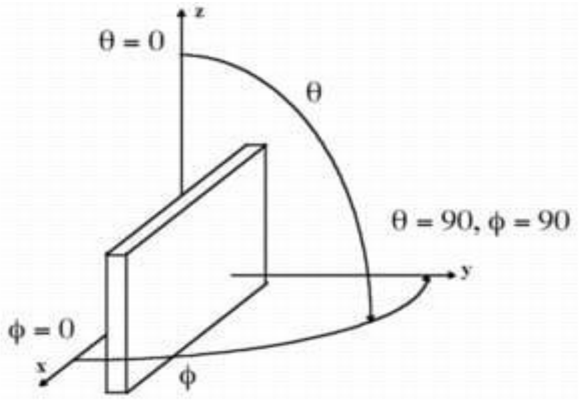


Figure 2.26 Antenna Measurement Coordinate System

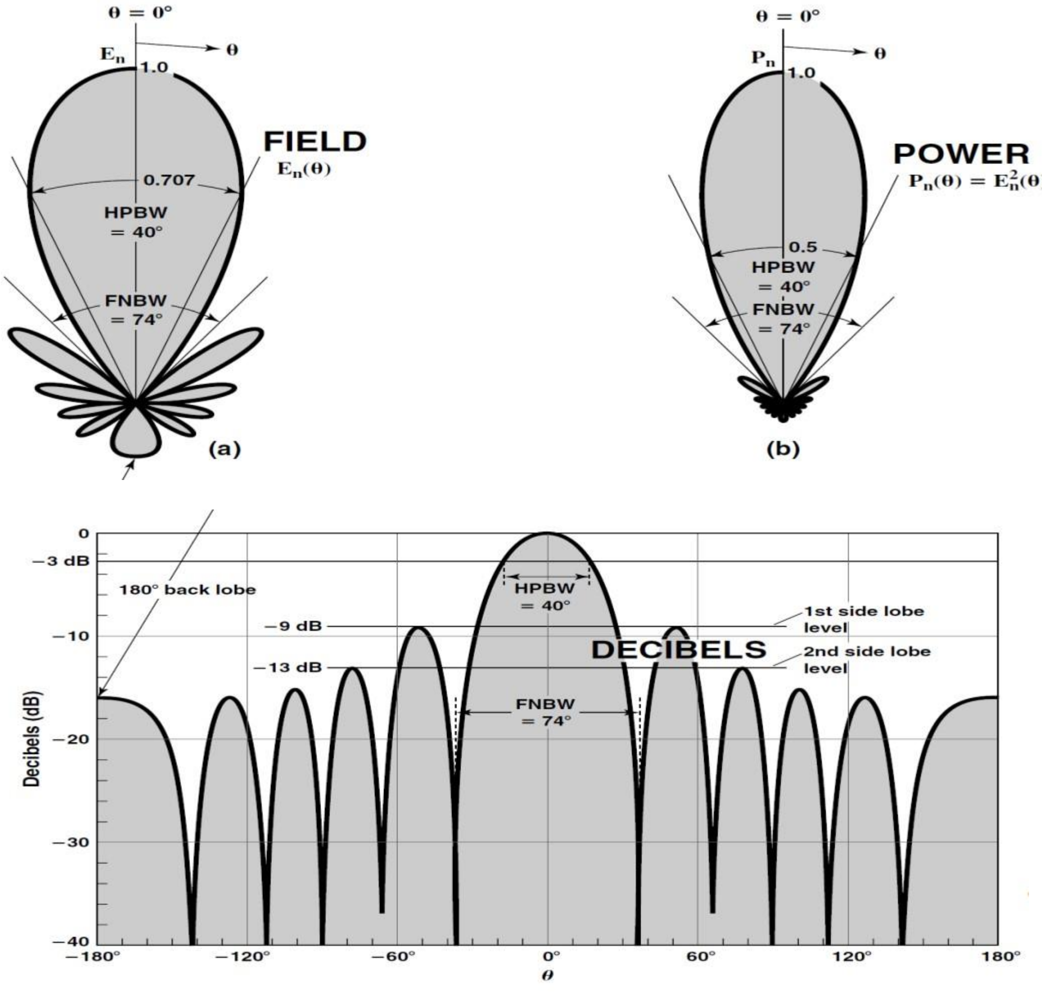


Figure 2.27 Two-dimensional field and power plots in polar coordinates. (a) Field pattern with normalized relative field $E_n(\theta) = 1$ at $\theta = 0^0$. (b) power plot (proportional to E^2) with relative power $P_n=1$ at $\theta = 0^0$. (c) Two-dimensional field pattern in rectangular coordinates on a logarithmic, or decibel, scale which gives the minor lobe levels in more detail.

2.5.4 Polarization of an antenna

The state of polarization of a wave is described by the geometrical shape which the tip of the electric field vector draws as a function of time at a given point in space.

Let us consider two waves with their electric fields oriented in x and y directions respectively.

$$E_x = E_1 = Re\left[E_{x0} e^{j\omega t - j\beta z} \right] = E_{x0} \cos(\omega t - \beta z)$$
$$E_y = E_2 = Re\left[E_{y0} e^{j\omega t + j\phi - j\beta z} \right] = E_{y0} \cos(\omega t - \beta z + \phi) \qquad (2.17)$$

Without losing generality let us take Z = 0 giving

$$\frac{E_x^2}{E_{x0}^2} - \frac{2E_x E_y \cos\phi}{E_{x0} E_{y0}} - \frac{E_y^2}{E_{y0}^2} = \sin^2\phi \qquad (2.18)$$

$$E_x = E_{x0} \cos \omega t$$
$$E_y = E_{y0} \cos(\omega t + \phi) \qquad (2.19)$$

This is the equation of an ellipse

Linear Polarization

The two components Ex and Ey may or may not have same amplitude but let us assume that the phase difference between them is zero. The equation of ellipse then reduces to

$$\left[\frac{E_x}{E_{x0}} - \frac{E_y}{E_{y0}} \right]^2 = 0$$
$$\Rightarrow E_y = \left(\frac{E_{y0}}{E_{x0}} \right) E_x \qquad (2.20)$$

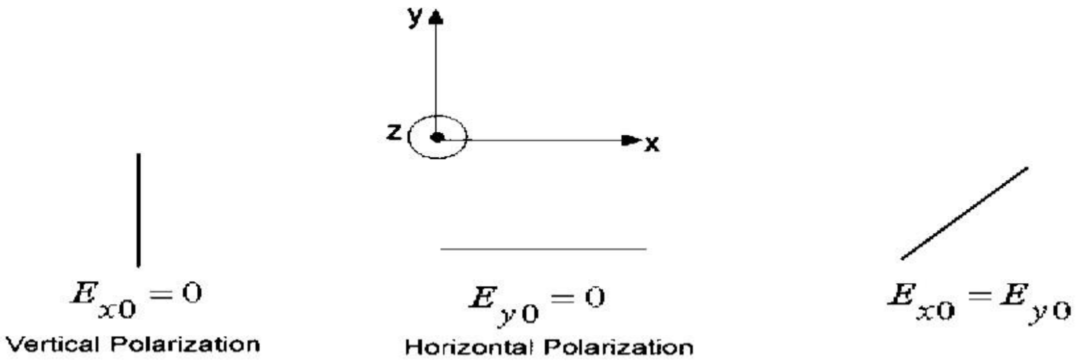


Figure 2.28 Linear Polarization a) Horizontal b) Vertical and c) Tilt

Circular Polarization

The two components Ex and Ey have same amplitude but the phase difference between them is ± π/2 i.e., **φ** = ± π/2 and E_{x0} = E_{y0} =E_0**.** First, we orient ourselves in the direction of wave (wave going away). Then if the vector rotates to our left hand (anti clockwise) it is called lefthanded/anti-clockwise circularly polarized wave and if the vector rotates to our right hand (clockwise) it is called the a right-handed/clockwise circularly polarized wave.

Elliptical Polarization

The two field components E_x and $E_y$neither have the same amplitude nor they have the phase difference of zero or ± π/2 (i.e**φ** ≠ ± π/2 and $E_{x0} \neq E_{y0}$)

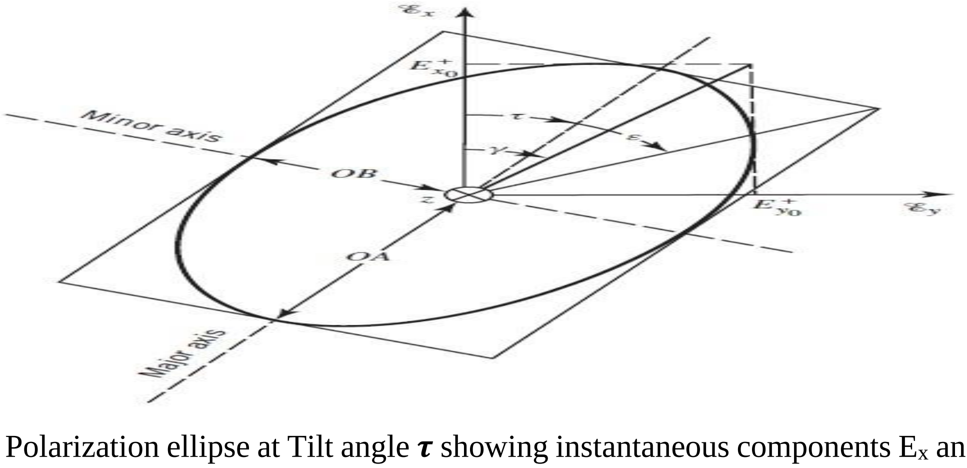


Figure 2.29 Polarization ellipse at Tilt angle ***τ*** showing instantaneous components E_x and

E_y From Figure, the ratio of the major to the minor axis, which is defined as the axial ratio

$$\mathrm{AR} = \pm\frac{\text{major axis}}{\text{minor axis}} = \pm\frac{OA}{OB}, \qquad 1 \le |\mathrm{AR}| \le \infty$$

If the axial ratio is near 0 dB, the antenna is said to be circular polarized. Practically for CP 0 dB ≤ AR ≤ 3 dB. If the axial ratio is greater than 1-2 dB, the polarization is often referred to as elliptical.

Co and Cross Polarization

Co-Polarization is defined as the polarization the antenna was meant to radiate. Co-polar means when the polarization of both the transmitting (test antenna) and receiving antenna (reference horn antenna) is the same and cross polarization means when the polarization of both the antennas are different. Cross polarization (sometimes written X-pol) is the polarization orthogonal to the polarization being discussed. For instance, if the fields from an antenna are meant to be horizontally polarized, the cross-polarization in this case is vertical polarization. If the polarization is Right Hand Circularly Polarized (RHCP), the cross-polarization is Left Hand Circularly Polarized (LHCP). A purely polarized antenna will have low cross polarized radiation. A measure of how purely polarized an antenna is the cross polarization level.

2.5.5 Directivity

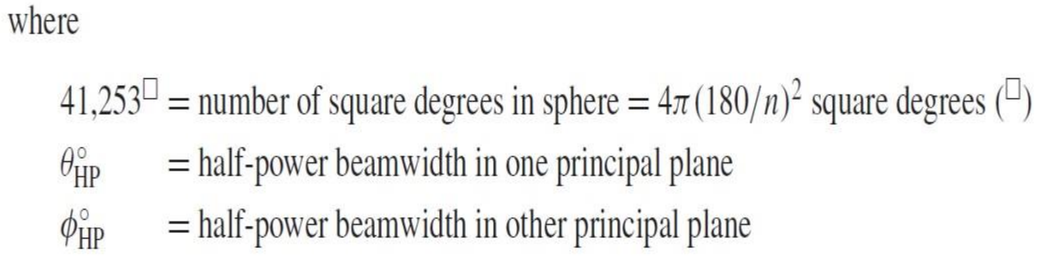
Directivity of an antenna can be defined as the ratio of its radiation intensity in a given direction (which usually is taken to be the direction of maximum radiation intensity) to the radiation intensity of an isotropic source with the same total radiation intensity.

$$\mathbf{D_{max} = D_0 = \frac{U_{max}}{U_0} = \frac{4\pi U_{max}}{P_{rad}}} \qquad (2.30)$$

Directivity of an antenna is equal to the solid angle of a sphere, which is 4π sr, divided by the antenna beam solid angle ΩA. We can say that by this relation the value of directivity is derived from the antenna pattern.

$$D = \frac{4\pi}{\Omega_A} \tag{2.31}$$

$$D = \frac{4\pi}{\Omega_A} \approx \frac{4\pi}{\theta_1\theta_2} = \frac{41{,}253}{\theta_1\theta_2} \tag{2.32}$$



where

$41{,}253^{□}$ = number of square degrees in sphere = $4\pi(180/n)^2$ square degrees (□)

θ°_{HP} = half-power beamwidth in one principal plane

ϕ°_{HP} = half-power beamwidth in other principal plane

It is obvious from this relation that the smaller the beam solid angle, the larger the directivity, or, stated in a different way, an antenna that concentrates its power in a narrow main lobe has a large directivity For antennas with pencil-beam patterns with peak at θ = 0^o, which means one narrow major lobe and negligible minor lobes, the beam solid angle can be approximated by the product of the half-power beamwidths in two perpendicular planes. For an isotropic source the directivity is unity since U, Umax, and U0 are all equal to each other. All actual antennas have directivities greater than 1 (D > 1).

D usually expressed in dB

$$D(dB) = 10\log_{10}[\,D(\text{dimensionless}] \tag{2.33}$$

2.5.6 Gain

The gain is commonly defined as the ratio of the maximum radiation intensity in a given direction to the maximum radiation intensity produced in the same direction from a reference antenna with the same power input.

$$G = \frac{U_{max}(\theta,\emptyset)}{U_i} = \frac{U_{max}(\theta,\emptyset)}{\frac{P_{in}}{4\pi}} \quad (2.34)$$

$$G=KD \quad (2.35)$$

Where, K = antenna radiation efficiency

2.5.7 Antenna radiation efficiency

Real antennas are not lossless, which means that if they accept an input power P_{in}, the radiated power P_{rad} generally will be less than P_{in}.

The antenna efficiency k is defined as the ratio of these two powers and it is less than one

$$K= \frac{P_{rad}}{P_{in}} = \frac{R_r}{R_r + R_{loss}} \quad (2.36)$$

where k = efficiency factor ($0 \le k \le 1$), dimensionless

where R_r is the radiation resistance of the antenna. R_{loss} is the loss resistance, which allows for any heat loss due to the finite conductivity of the materials used to construct the antenna or due to the dielectric structure of the antenna. Thus, the gain of an antenna over a lossless isotropic radiator equals its directivity if the antenna efficiency is K=1, and it is less than the directivity if k < 1.

2.5.8 Beam width

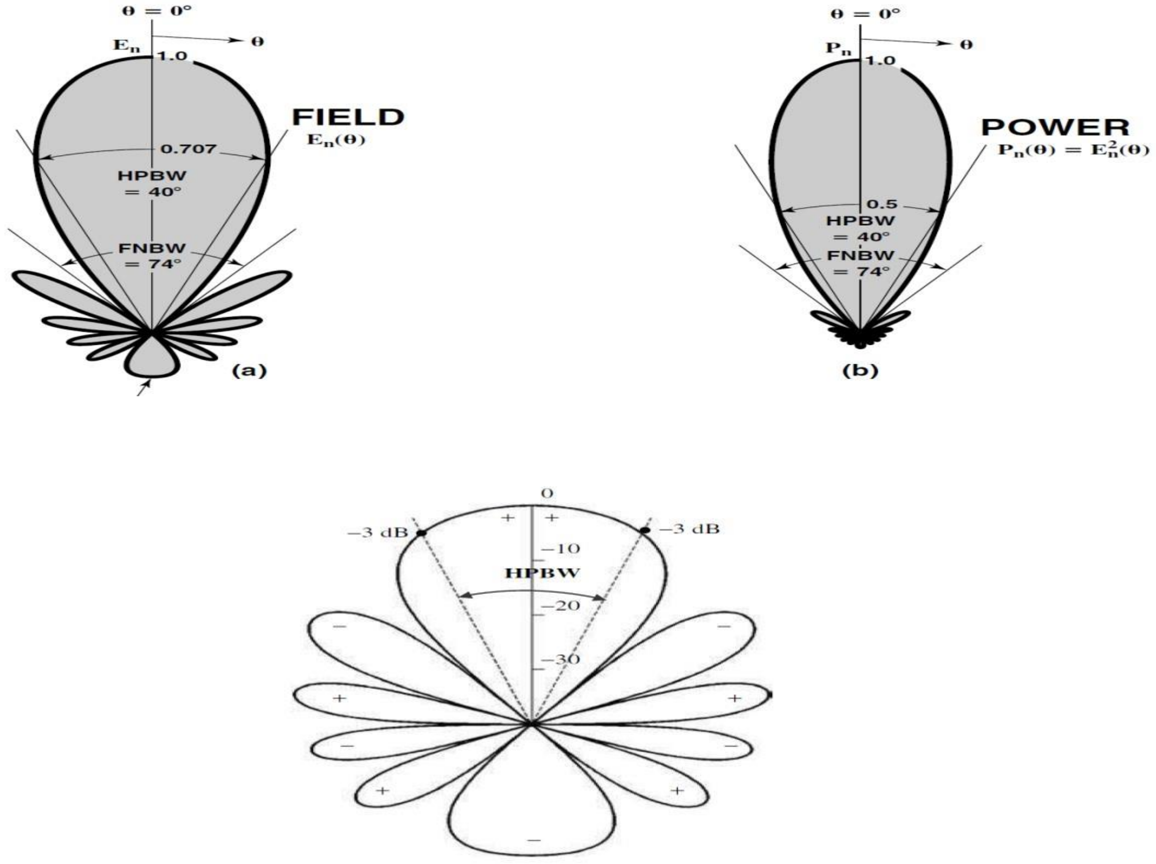
The beamwidth of a pattern is defined as the angular separation between two identical points on opposite side of the pattern maximum.

Half-Power Beamwidth (HPBW)

HPBW is defined as angular width in degrees, measured on radiation pattern between identical points

a) Where field pattern is at 0.707 value of its maximum, as shown in Figure:(a) Where power pattern (in a linear scale) is at its 0.5 value of its maximum, as shown in Figure:(b)

b) Where power pattern (in dB) is at −3 dB value of its maximum, as shown in Figure:(c) It is also called -3 dB beamwidth.



(c)

Figure 2.30 Two-dimensional field and power plots in polar coordinates. (a) Field pattern with normalized relative field $E_n(\theta) = 1$ at $\theta = 0^0$. (b) power plot (proportional to E^2) with relative power $P_n = 1$ at $\theta = 0^0$.(C)Two-dimensional normalized power pattern (in dB)

First-Null Beamwidth (FNBW)

FNBW is defined as the angular separation between the first nulls of the pattern.

2.6 Antenna Field Region

The space surrounding an antenna is usually subdivided into three regions: (a) reactive nearfield, (b) radiating near-field (Fresnel) and (c) far-field (Fraunhofer) regions as shown in Figure 2.29.

2.6.1 Reactive near-field region

It is defined as that portion of the near-field region immediately surrounding the antenna wherein the reactive field predominates.

For most antennas, the outer boundary of this $\sqrt{\frac{D}{\lambda}}$ region is commonly taken to exist at a distance $R< 0.62$ from the antenna surface, where λ is the wavelength and D is the largest dimension of the antenna.

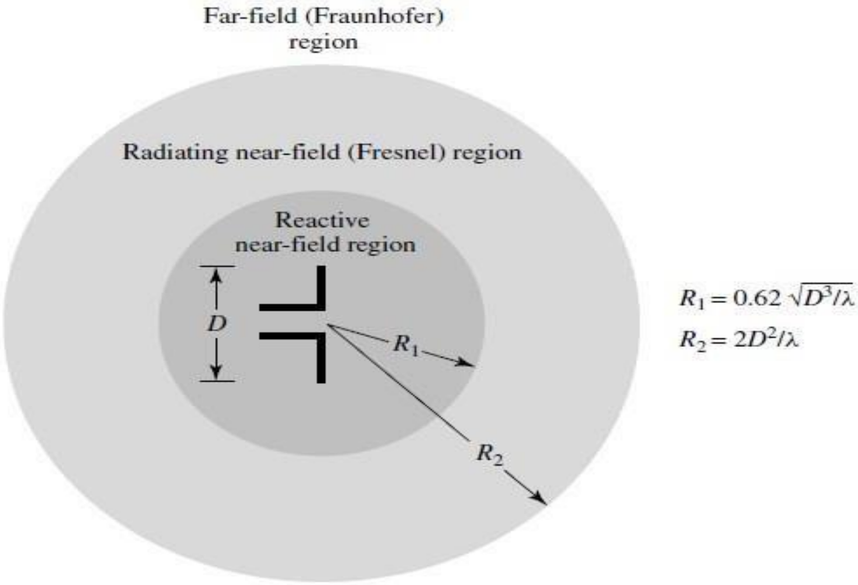


Figure 2.31 Field regions of an antenna

2.6.2 Radiating near-field (Fresnel) region

Itis defined as “that region of the field of an antenna between the reactive near-field region and the far-field region wherein radiation fields predominate and wherein the angular field distribution is dependent upon the distance from the antenna. For an antenna focused at infinity, the radiating near-field region is sometimes referred to as the Fresnel region on the basis of analogy to optical terminology.

If the antenna has a maximum overall dimension which is very small compared to the wavelength, this field region may not exist. The inner boundary is taken to be the distance $R \geq 0$.

$62\sqrt{\frac{D}{\lambda}{}^{3}}$ and the outer boundary the distance $R < 2D^2/\lambda$ where D is the largest dimension of the antenna. In this region the field pattern is, in general, a function of the radial distance and the radial field component may be appreciable.

2.6.3 Far-field (Fraunhofer) region

It is defined as “that region of the field of an antenna where the angular field distribution is essentially independent of the distance from the antenna. If the antenna has a maximum overall dimension D, the far-field region is commonly taken to exist at distances greater than $2D^2/\lambda$ from the antenna, λ being the wave length. To be valid, D must also be large compared to the wavelength ($D > \lambda$). For an antenna focused at infinity, the far-field region is sometimes referred to as the Fraunhofer region on the basis of analogy to optical terminology. In this region, the field components are essentially transverse and the angular distribution is independent of the radial distance where the measurements are made. The inner boundary is taken to be the radial distance $R = 2D^2/\lambda$ and the outer one at infinity.

Chapter 3

Investigation of Role of Reconfigurable Antennas in Wireless Communication

3.1 Introduction

The modern wireless cellular communication technologies necessitate multifunctional and smart antennas that are capable of addressing the changes in the system requirements and of adapting their properties accordingly. Additionally, due to the rapid changes in the concept of wireless-based service provided in different sectors, it is becoming challenging to offer more services without increasing the number of elements, system complexity and circuit size of the device. Furthermore, future communication trends will reshape the ways of connectivity and introduce new technologies to meet huge data requirements, high-speed connectivity, seamless communications and data services. Considering the demands of current and future wireless systems, it is of great interest to conceptualize and build antennas with flexible and controllable properties. Reconfigurable antennas appear to offer a solution that allows the integration of multiple radios into a single platform.To configure means to arrange or organize the parts of something to achieve a purpose. For instance, configuring a microstrip antenna consists of determining the patch shape, substrate parameters, type and location of the feed, etc., in order for the antenna to radiate at a desired frequency and polarization. If the desired operating characteristics of the antenna change, then the antenna must be reconfigured or rebuilt to meet the new specifications.

The IEEE Standard Definitions of Antenna Terms released in 2014 defines a ‘reconfigurable antenna’ as an antenna that is ‘capable of changing its performance characteristics (resonant frequency, radiation pattern, polarization, etc.) by mechanically or electrically changing its architecture’. The first patent on reconfigurable antennas appeared in 1983 by Schaubert. In 1999, the Defense Advanced Research Projects Agency (DARPA) launched a multiuniversity program between 12 well-known universities, research institutes, and companies in the United States under the name Reconfigurable Aperture Program (RECAP), to investigate reconfigurable antennas and their potential applications. The reconfiguration scheme usually interacts with the antenna fundamental operation mechanism and controls the surface current or electric field distribution of the antenna to produce reversible output characteristics from the antenna. Thus, the antenna configurations that do not have integrated reconfiguration mechanism but are controlled by external reconfiguration circuits and/or feeding/matching networks, are justifiably falling outside the ‘reconfigurable antenna’ family. For instance, the performances of a phased array antenna are basically controlled by external phase-shifters that are controlled from the outside, while the basic operation of the antenna remains same.

This chapter is organized as follows. Section 3.2 describes classification of reconfigurable antennas and their fundamental theory of operation. Section 3.3 describes the different reconfiguration techniques and comparison between them. Advantages of reconfigurable antennas are given in section 3.4. Finally, conclusions are provided in section 3.5.

3.2 Classification of Reconfigurable Antennas

When designing reconfigurable antennas, RF engineers must address three challenging questions. First one which reconfigurable property (e.g., frequency, radiation pattern, or polarization) needs to be modified. Second one how is the different radiating elements of the antenna structure reconfigured to achieve the required property. Third one which reconfiguration technique minimizes negative effects on the antenna radiation/impedance characteristics [5]. The design of reconfigurable antennas. is tedious and requires the consideration of multiple factors, such as achieving a good gain, stable radiation, and a good impedance match throughout all the antenna’s operation states. Reconfigurable antennas can be assembled into various groups based on the properties of each reconfiguration [6]. These groups are shown in Fig. 3.1 and are arranged as follows:

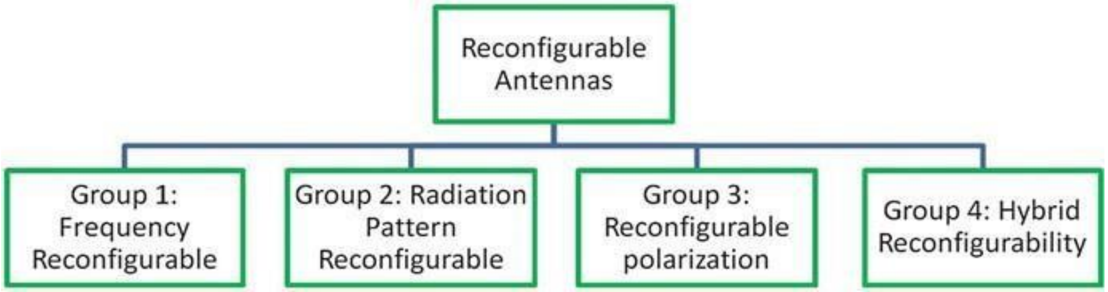


Figure 3.1 Categorization of reconfigurable antennas

3.2.1 Frequency reconfigurable antennas

Antennas under this group can change their frequency of operation based on the user's demand. They reconfigure their operation to function in multiple frequency bands. Such antennas are widely useful in wireless cellular communication applications that require a change in operating frequencies and to switch from one channel into another. Frequency-reconfigurable antennas (also called tunable antennas) can be classified into two categories: continuous and switched. Continuous frequency-tunable antennas allow for smooth transitions within or between operating bands without jumps as shown in Fig. 3.2. Switched tunable antennas, on the other hand, use some kind of switching mechanism to operate at distinct and/or separated frequency bands which are investigated in this thesis as shown in Fig. 3.3. Both kinds of antennas in general share a common theory of operation and reconfiguration, the main differences are in the extent of the effective length changes that enable operation over different frequency bands and the devices and/or means used to achieve these changes.

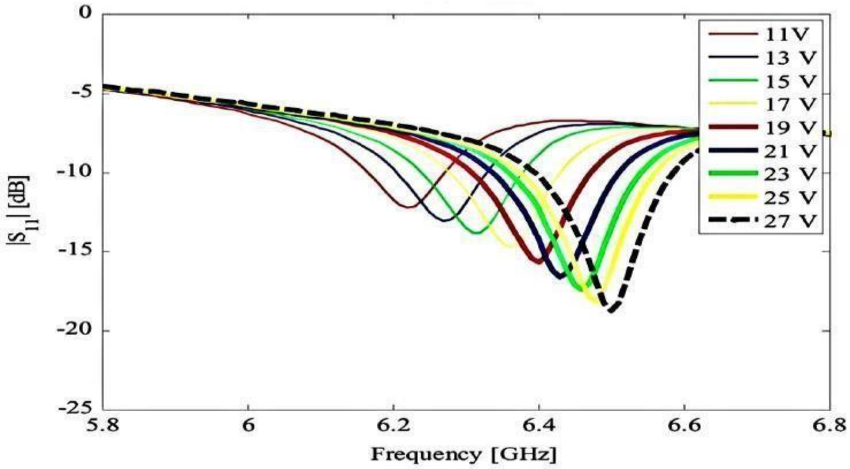


Figure 3.2 Reflection coefficient of continuous frequency tunable antennas

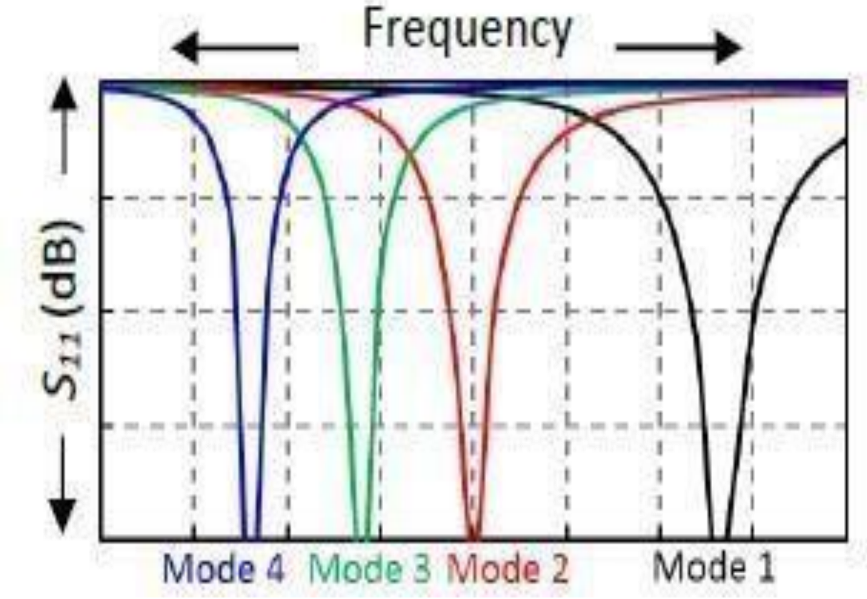


Figure 3.3 Reflection coefficient of switched frequency tunable antennas

The fundamental theory of operation is many common antennas such as linear antennas, loop antennas, slot antennas, and microstrip antennas, are usually operated in resonance. In these cases, the effective electrical length of the antenna largely determines the operating frequency, its associated bandwidth, and the current distribution on the antenna that dictates its radiation pattern. For instance, for a traditional linear dipole antenna, the first resonance occurs at a frequency where the antenna is approximately a half wavelength long, and the resulting current distribution results in an omnidirectional radiation pattern centered on and normal to the antenna axis. In this case, if one wants the antenna to operate at a higher frequency, the antenna can simply be shortened to the correct length corresponding to a half wavelength at the new frequency. The new radiation pattern will have largely the same characteristics as the first because the current distribution is the same relative to a wavelength. The same principle holds true for loops, slots, and microstrip antennas as well. A number of mechanisms mentioned in section 3.3, can be used to change the effective length of resonant antennas, although some of these are more effective than others in maintaining the radiating characteristics of the original configuration [7]. Cognitive radio is an example application for this antenna group as shown in Fig. 3.4.

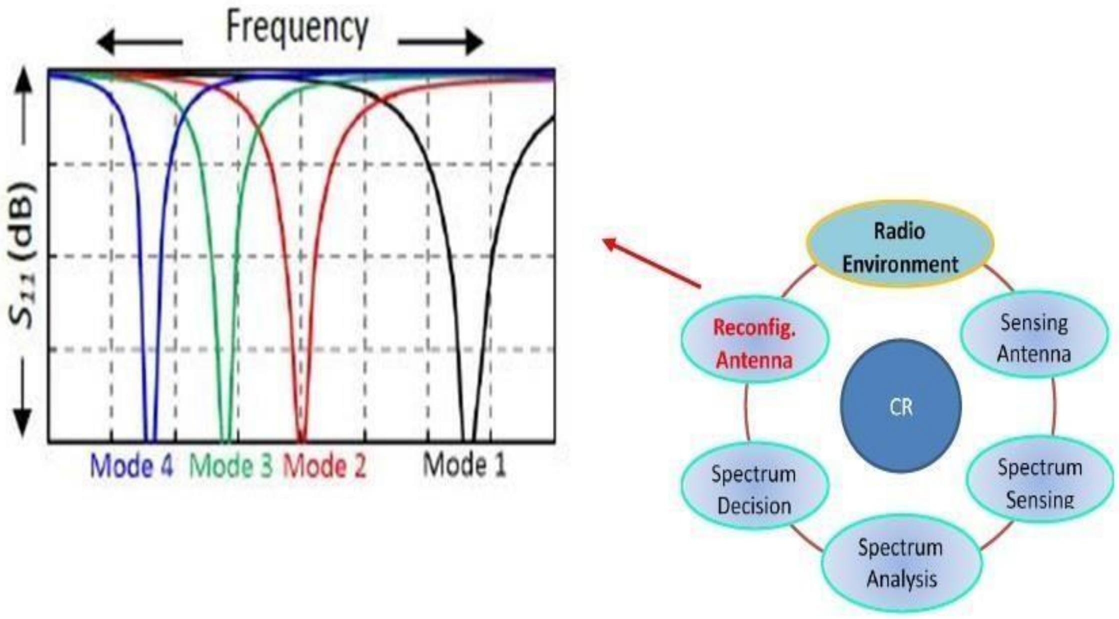
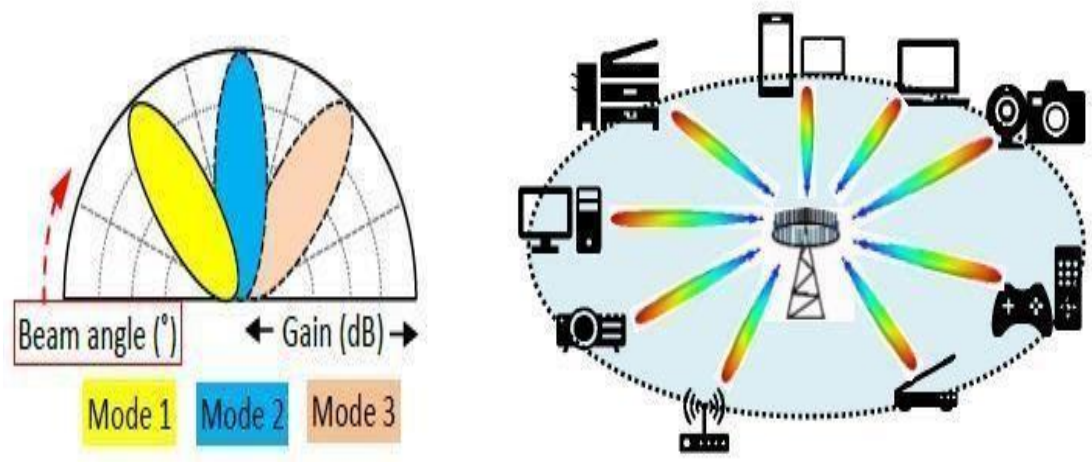


Figure3.4 Application of frequency reconfigurable antennas in cognitive radio platforms for better spectrum utilization

3.2.2 Radiation pattern reconfigurable antennas

Antennas under this group can change their radiation pattern while maintaining a fixed frequency of operation as shown in Fig. 3.5(a). These antennas reshape their radiation patterns to block a signal or to allow radiation in a certain predetermined direction. For this category, the antenna radiation pattern changes in terms of shape, direction, or gain. The fundamental theory of operation is the arrangement of currents, either electric or magnetic, on an antenna structure directly determines the spatial distribution of radiation from the structure. This relationship between the source currents and the resulting radiation makes pattern reconfigurability without significant changes in operating frequency difficult, but not impossible, to achieve. To develop antennas with specific reconfigurable radiation patterns, a designer must determine what kinds of source current distributions, including both magnitude and phase information, are necessary. Once a topology for the current distribution is determined, a baseline antenna design can be selected and then altered to achieve the desired source current distribution. This design process is very much akin to that of array synthesis. The remaining task is to either arrange the design so that the frequency characteristics are largely unchanged or to compensate for changes in impedance with tunable matching circuits at the antenna terminals.The most attractive features of pattern reconfigurable antennas are scanning the main beam. Beam-scanning (or beamsteering) antennas produce high gain radiation in the target direction, which is constructive in maintaining a strong and stable line-of-sight (LOS) communication link between portable and moving wireless devices. Fig. 3.5(b) shows an application scenario of beam-steering antennas to communicate with portable devices

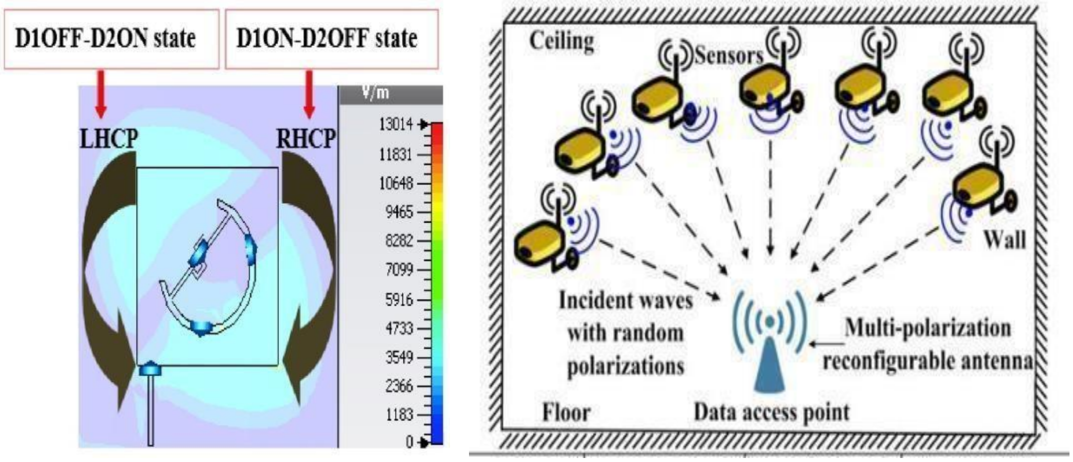


(a) (b)

Figure3.5 a) Representation of pattern reconfigurability provided by reconfigurable antenna. b) Application scenario of pattern reconfigurable antennas: beam-scanning

3.2.3 Antennas with reconfigurable polarization

Antennas under this group can change their polarization type while maintaining their fixed frequency and radiation pattern. The fundamental theory of operation is direction of current flow on the antenna translates directly into the polarization of the electric field in the far field of the antenna. To achieve polarization reconfigurability, the antenna structure, material properties, and/or feed configuration have to change in ways that alter the way current flows on the antenna. Polarization reconfigurations can take place between different kinds of linear polarization, between right- and left-handed circular polarizations, or between linear and circular polarizations as shown in Fig.3.6(a). The mechanisms to achieve these modifications (e.g., switches, structural changes) are largely the same as those described for frequency reconfigurability earlier, although their implementations are necessarily different. The main difficulty of this kind of reconfigurability is that this must be accomplished without significant changes in impedance or frequency characteristics. Polarization reconfigurable antenna is a very promising concept for reducing signal losses due to the polarization mismatch between transmitting and receiving devices.An example of a wireless sensor network system is portrayed in Fig. 3.6(b), where one receiving antenna is surrounded by several wireless sensors in an indoor environment. If the receiving antenna is single polarized and some random polarized signals are transmitted from a sensor incident on it, polarization mismatch will happen.



(a) (b)

Figure 3.6 a) Representation of polarization reconfigurability provided by reconfigurable antenna. b) Application scenario of polarization reconfigurable antennas: wireless sensor network.

3.2.4 Antennas with hybrid reconfiguration techniques

Antennas under this group can simultaneously change multiple characteristics in their operation. These antennas can, for example, change their operating frequency as well as their polarization scheme for each frequency of interest. They can also reshape their radiation pattern while changing their operating frequencies or polarizations.

3.3 Reconfiguration Techniques

The reconfiguration techniques are divided into four major categories: electrical, optical, mechanical, and material change as shown in Fig. 3.7. As for the selection of the reconfiguration technique, it is based on the reconfigurable antenna property. An antenna designer selects a technique that satisfies the imposed constraints and at the same time completes the antenna design task efficiently.

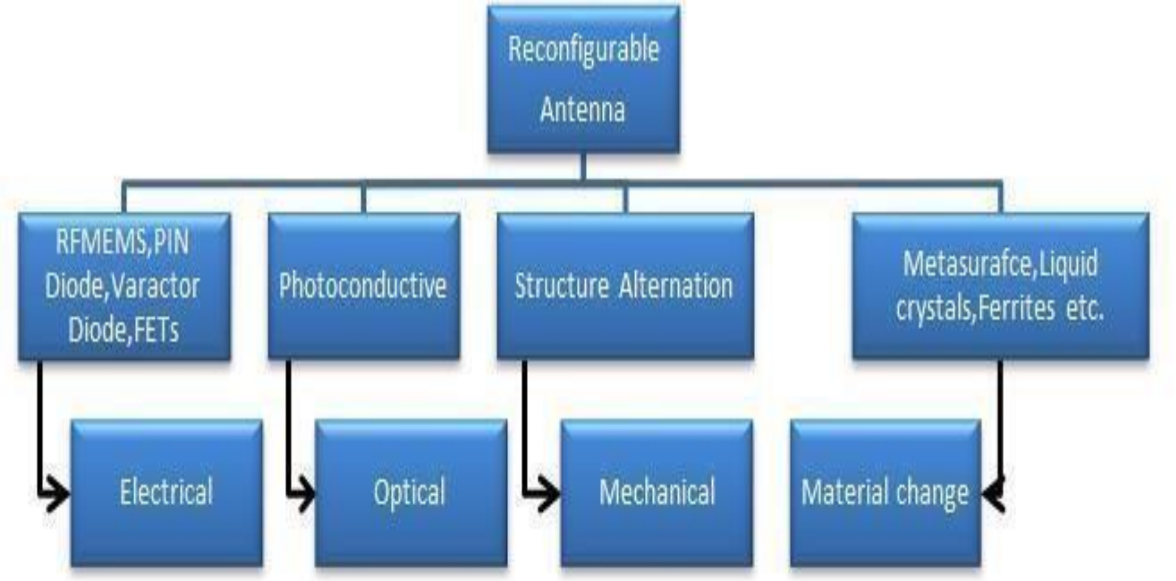


Figure 3.7 Antenna reconfiguration techniques

3.3.1 Electrically reconfigurable antennas

An electrically reconfigurable antenna relies on electronic switching components (RF-MEMs, PIN diodes, or varactors) to connect and disconnect antenna parts as well as to redistribute the antenna currents. RF switches may be mechanical or semiconductor. A switch is an open circuit when no actuation voltage is applied, and a low-impedance path for the RF signal when an actuation voltage is applied. Irrespective of the type of switch used, there are several important characteristics that must be evaluated for all RF switch applications and particularly reconfigurable antenna designs. The selection of switch type depends fundamentally on the switching speed required by the application and the switched signal power level.The on time for a switch is defined by the time from when the control pulse reaches 50% of its level to the time that the RF signal is at 90% of its peak. The off time for a switch is defined by the time from when the control pulse reaches 50% of its level to the time that the RF signal is at 10% of its peak. Switching time is the larger of the on and off switch times.

Impedance issues relating to switch characterization are also described by several related quantities. The overall impedance matching of the switch, insertion loss, and isolation are all related to switch impedance performance. Impedance mismatches in RF components result in undesirable reflections which degrade system performance. Insertion loss is directly related to impedance matching and provides a measure of the transmission efficiency. Insertion loss is given for the conduction or on-state of the switch and is normally specified by the S-parameter coefficient S_{21} in decibels. Efficient on-state switch transmission requires small insertion losses. Isolation is defined for the non-conduction or off-state and represents the coupling between the input and output points. A high level of isolation is necessary to block RF energy from propagating through the switch when it should be off.

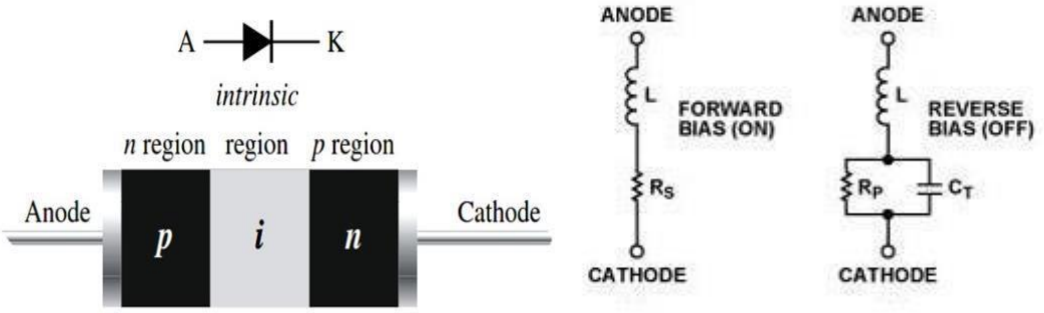
The power handling capability of a switch measures how well the switch will pass the RF signal level from switch input to output. An ideal switch would pass all signal levels through linearly with no distortion. However, real switches tend to have an upper limit to which signals will pass linearly. Above this level, input signals become compressed and are passed in a non-linear manner. This maximum signal level is typically used as a measure of switch performance.

3.3.1.1 MEMS Switches

MEMS switches are tiny mechanical switches made on a substrate (silicon, quartz, glass). Unlike the PIN-diode and FET switches, a MEMS switch is mechanical .RFMEMS based reconfigurable antennas rely on the mechanical movement of these switches to achieve reconfiguration. MEMS switches have low power consumption, low insertion loss, and high isolation, like mechanical switches, but are small, lightweight, and low cost, like semiconductor switches. On the other hand, MEMS switches have high losses at microwave and mm-wave frequencies, limited power handling capability (~100 mW), and the switching speed of RFMEMS is in the range of 1–200 µsec which may be considered low for some applications.

3.3.1.2 PIN diode

PIN (positive-intrinsic-negative) diodes have appeared to be a faster and a more compact alternative to RF-MEMS. The switching speed of a PIN diode is in the range of 1–100 nsec. Reconfigurable antennas using the PIN diodes have a more dynamic reconfiguration ability. A PIN diode is a diode with a wide, undoped intrinsic semiconductor region between a p-type semiconductor and an n-type semiconductor region as shown in Fig. 3.8(a). The p-type and n-type regions are typically heavily doped because they are used for ohmic contacts. The wide intrinsic region is in contrast to an ordinary p–n diode. The wide intrinsic region makes the PIN diode an inferior rectifier (one typical function of a diode), but it makes it suitable for attenuators, fast switches, photodetectors, and high-voltage power electronics applications.



(a) (b)

Figure 3.8 a) Layers of PIN diode and b) Equivalent circuit

3.3.1.2.1 Working operation and equivalent circuit of PIN diode

When the diode is forward biased, the injected carrier concentration is typically several orders of magnitude higher than the intrinsic carrier concentration. Due to this high-level injection, which in turn is due to the depletion process, the electric field extends deeply (almost the entire length) into the region. This electric field helps in speeding up of the transport of charge carriers from the P to the N region, which results in faster operation of the diode, making it a suitable device for high-frequency operation. PIN diode behaves as a current controlled resistor when forward biased. The equivalent circuit for the forward biased is shown in Fig. 3.8(b which consists of a series combination of the series resistance (Rs) and a small Inductance (L). The Rs inversely proportional to the stored charge $Q = I_f * \tau$ where I_f is the forward current and τ is the recombination time or carrier lifetime and inductance (L) depends on the geometrical properties of the package such as metal pin length and diameter. The resistance (Rs) of the I region under forward bias is given by equation (3.1);

$$Rs = \frac{W^2}{(\mu_n + \mu_p)Q} \tag{3.1}$$

W = I-region Width, μ_n, μ_p= electron and hole mobility

The equation (3.1) is valid for frequencies higher than the transit time of the I-region

1300

$f > \frac{1300}{W^2}$ (f in MHz and W in microns). At lower frequencies, the PIN diode rectifies the RF signal just as any PN-junction diode. According to equation (3.1) the high frequency resistance is inversely proportional to the DC bias current through the diode. A PIN diode, suitably biased therefore acts as a variable resistor. This high frequency resistance may vary over a wide range (from 0.1 Ω to 10 kΩ in some cases the useful range is smaller, though).

Now, as the reverse bias voltage is applied to the device. The depletion width starts increasing. As the reverse voltage is increased, the width of the depletion region increases as far as whole mobile carriers swept away from the intrinsic region. This particular voltage is known as swept out voltage. Usually, its value is -2V. At a lowenough frequency, the stored charge can be fully swept and the diode turns off. At higher frequencies, there is not enough time to sweep the charge from the drift region, so the diode never turns off. The time required to sweep the stored charge from a diode junction is its reverse recovery time, and it is relatively long in a PIN diode.

The reverse bias equivalent circuit consists of a parallel combination of capacitance (C_T) and resistance (Rp) as shown in Fig 3.8(b). The defining expression for C_T is given by equation (3.2);

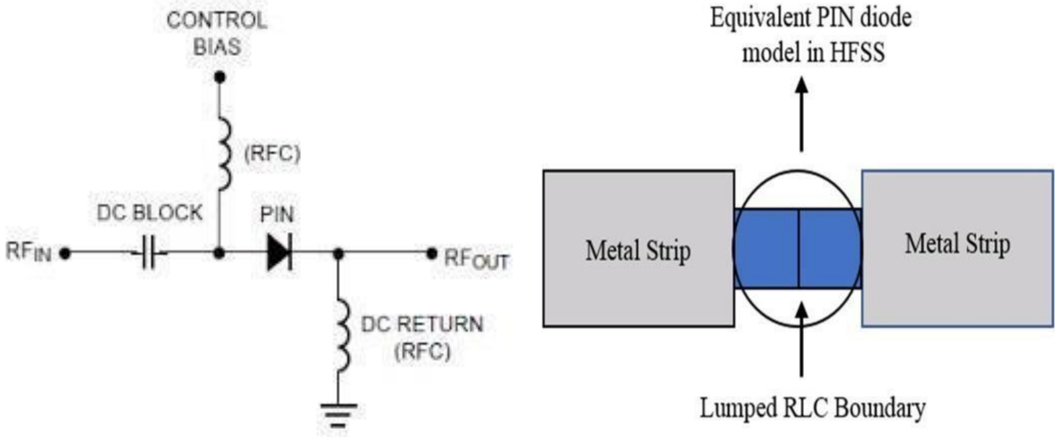
$$C_T = \frac{\varepsilon A}{W} \qquad (3.2)$$

Which is valid for frequencies above the dielectric relaxation frequency of the I-region, i.e, $f > \frac{1}{2\pi\rho\varepsilon}$Where ε = dielectric constant of silicon, A = diode junction area, ρ = resistivity of silicon. At frequencies much lower than f, the capacitance characteristic of the PIN diode resembles a varactor diode. Due to changes and variations in the capacitance PIN diode switches have low frequency limitations. Under zero- or reverse-bias (the "off" state), a PIN diode has a low capacitance. The low capacitance will not pass much of an RF signal. Under a forward bias of 1 mA (the "on" state), a typical PIN diode will have an RF resistance of about 1 ohm, making it a good conductor of RF. Consequently, the PIN diode makes a good RF switch.

3.3.1.2.2 Biasing circuit of PIN diode

To bias the PIN diode accurately, it is necessary to provide some degree of isolation between DC signal and the RF signal. Otherwise, RF current can flow into the power supply's output impedance, causing unfavourable effect to the efficient operation of the power control circuit. The DC bias supply is isolated from the RF circuits by inserting an RF inductor in series with the bias line and a RF by-pass capacitor, in series with the the RF input as shown in Fig. 3.9(a). In Ansoft HFSS simulation, PIN diodes are modeled using lumped RLC boundary as shown in Fig. 3.9(b).When the PIN diode is in the ON state, it acts as a resistance and if the PIN diode is in the OFF state, it acts as a capacitance.

In the simulation, different module can be created to check the results when switching the diode ON and OFF.



(a) (b)

Figure 3.9 a) Biasing circuit of PIN diode and b) HFSS model of PIN diode

3.3.1.3 Varactors

A varactor diode is a voltage-controlled device in contrast to a PIN diode which is a current controlled device.Varactor diode has a very thin depletion layer that acts like the insulating dielectric, and the P and N regions that act like the conducting plates. The capacitance is inversely proportional to the square root of the applied voltage, since the thickness of the depletion layer increases with the reverse biaswhere varying the biasing voltage can result in varying the capacitance of the corresponding varactor. Varactors have a high-to low capacitance ratio that is typically six over a voltage change of 0 V to 12 V.Varactors are useful for tuning the antenna’s frequency range.

Electronic switching components have been widely used to reconfigure antennas, especially after the appearance of RF-MEMS in 1998. One of the major advantages of such components is their good isolation and low-loss. While RF-MEMS represent an innovative switching mechanism, their response is slower than PIN diodes and varactors which have a response on the order of nanoseconds. All these switches and especially varactors add to the scalability of reconfigurable antennas. The ease of integration of such switching elements into the antenna structure has attracted antenna researchers to this type of reconfigurable antennas despite the numerous issues surrounding such reconfiguration techniques. These issues include the nonlinearity effects of switches, and the interference, losses, and negative effect of the biasing lines used to control the state of the switching components on the antenna radiation pattern. The incorporation of switches increases the complexity of the antenna structure due to the need for additional bypass capacitors and inductors which will increase the power consumption of the whole system.

3.3.2 Optically reconfigurable antennas

Optical reconfiguration techniques have been proposed based on photoconductive switches. An optical switch is formed when laser light is incident on a semiconductor material (silicon, gallium arsenide). This results in exciting electrons from the valence to the conduction band and thus creating a conductive connection. Integrating such a switch into an antenna structure and using it to reconfigure the antenna behaviour is called an optically reconfigurable antenna. These switches incorporated into an antenna structure become conductive once they are subjected to a laser beam. The laser beam originates from integrated laser diodes. Even though optical switches are less popular, they definitely present a reliable reconfiguration mechanism especially in comparison to RF-MEMS. The activation or deactivation of the photoconductive switch by shining light from the laser diode does not produce harmonics and intermodulation distortion due to their linear behaviour. Moreover, these switches are integrated into the antenna structure without any complicated biasing lines which eliminates unwanted interference, losses, and radiation pattern distortion. Despite all these advantages, optical switches exhibit lossy behaviour and require a complex activation mechanism. Table 3.1 shows a comparison of the characteristics for the different switching techniques used on electrically (RF-MEMS/PIN diodes) and optically reconfigurable antennas

Electrical Property	**RF MEMS**	**PIN Diode**	**Optical Switch (Si)**
Voltage [V]	20-100	3-5	1.8-1.9
Current [mA]	0	3-20	0-87
Power Consumptiom [mW]	0.05-0.1	5-100	0-50
Switching Speed	1-200 µsec	1-100 nsec	3-9 µsec
Isolation [1 – 10 GHz]	Very High	High	High
Loss (1 – 10 GHz) [dB]	0.05-0.2	0.3-1.2	0.5-1.5

Table 3.1 Electrical properties of Electrical and Optical switches

3.3.3 Mechanically reconfigurable antennas

Antennas can also be reconfigured by physically altering the antenna radiating structure. The tuning of the antenna is achieved by a structural modification of the antenna radiating parts. The importance of this technique is that it does not rely on any switching mechanisms, biasing lines, or optical fiber/laser diode integration. On the other hand, this technique depends on the limitation of the device to be physically reconfigured. However, their disadvantages include slow response, cost, size, power source requirements and the complex integration of the reconfiguring element into the antenna structure.

3.3.4 Smart materials based reconfigurable antennas

Antennas are also made reconfigurable through a change in the substrate characteristics by using materials such as liquid crystals or ferrites. The change in the material is achieved by a change in the relative electric permittivity or magnetic permeability. In fact, a liquid crystal is a nonlinear material whose dielectric constant can be changed under different voltage levels, by altering the orientation of the liquid crystal molecules. As for a ferrite material, a static applied electric/magnetic field can change the relative material permittivity/permeability. As for ferrite-based reconfigurable antennas, one major advantage is their small size that is due to the ferrites high relative permittivity's and permeabilities. The main disadvantage is their low efficiency that is a common inconvenience for liquid-crystal-based antennas as well, especially at microwave frequencies.

3.4 Advantages of Employing Reconfigurable Antennas

From the application perspective, it is quite understandable that reconfigurable antennas stand out as an excellent approach for wireless cellular communication. They are clearly advantageous over the fixed multiband antennas because of their dynamic capability, flexibility and contribution to enhancing system performances. Some gainful aspects of employing reconfigurable antennas are:

1) Integrated multi-functionality and adaptability: a) change of the antenna functionality as the system requires it; b) function as a single element or an array of multiple elements; c) compact and low-profile; d) suitable for narrow band and wideband reconfigurable operation.
2) Ability to support multiple wireless protocols: a) cost-effective and space economical; b) better selectivity; and d) improved isolation between different protocols.
3) Little front-end processing required: a) no need for front end filtering; b) good out of-band rejection.
4) Potential for software-defined radio (SDR) systems:
    a) capability to adapt and learn;
    b) automated via a microcontroller or a field programmable gate array (FPGA).

3.5 Conclusions

This chapter gives a thorough overview of reconfigurable antennas, their classification, reconfiguration techniques, and advantages of using these antennas.

Reconfigurable antennas were mainly classified into frequency reconfigurable, radiation pattern reconfigurable, polarization reconfigurable, and compound reconfigurable. Additionally, the different reconfiguration techniques which consists of RF MEMS, PIN diodes, varactors, optical switches etc. and about how the switches are selected depending upon electrical specification, fabrication complexity, switching time etc. are discussed. Since the technique used for reconfiguration in this thesis is PIN diode, the working operation, equivalent circuit and biasing circuit of PIN diode are thoroughly discussed. In addition, the advantages of reconfigurable antennas are discussed in the last part of this chapter.

Chapter 4

Design of A Compact Hexa-band Frequency Reconfigurable Antenna For Wireless Applications

4.1 Introduction

Quarter wave monopole antennas have been used extensively in portable wireless devices and mobile communication systems. Their omnidirectional radiation pattern, simple design, and low cost have led to its widespread use. However, the monopole antenna is potentially obtrusive. It is desirable that the antenna in a wireless device be as small as possible while still meeting the performance demands. Therefore, a need exists for electrically small, low-profile antenna designs with broad impedance bandwidth, omnidirectional radiation, and high radiation efficiency. One low-profile antenna design is the inverted L shaped antenna (ILA) which is used in the design of the proposed reconfigurable quad band antenna. In its simplest form, the inverted-L antenna is a $\lambda/4$ monopole that has been folded over so that some part of the radiating element is parallel to the ground plane. In the proposed antenna multiband operation is realized using two or more resonant structures closely located or even co-located with a single feed point.

This chapter presents the design and analysis of a compact hexa-band antenna employing the PIN diode to realize frequency reconfigurable characteristics is presented. The presented antenna is backed by a ground plane and printed on top of a 1.6 mm thicker FR4 substrate. The antenna size is very compact (24 mm × 19 mm × 1.6 mm), and can be readily incorporated with many other RF front-end circuits. The presented antenna consists of a rectangular microstrip patch antenna, F-shaped monopole, Z shaped monopole, two T shaped monopoles and inverted L-shaped monopole. The investigated antenna realizes hexa/Triple band characteristics by turning ON/OFF the PIN diode positioned between the F shaped monopole and metal strip. While in OFF state, the investigated antenna covers 6 unique frequencies 2.3 GHz (LTE Band 30), 2.5 GHz (LTE Band 53), 3.35 GHz (LTE Band 52), 4.4 GHz (Radio altimeter), 5.3 GHz (U-NII-2A) and 5.6 GHz (U-NII-2C) and in ON state, the antenna covers 3 unique frequencies 4.35 GHz (Radio altimeter), 5.25 GHz (U-NII-1 & U-NII-2A), and 5.65 GHz (U-NII-2C) for wireless applications. The investigated antenna exhibits very small frequency ratios between two consecutive bands of the value of 1.086/1.34/1.31/1.20/1.05, respectively. The equivalent model of the proposed hexaband antenna is developed by using an advanced design system (ADS) and compared with HFSS simulation in terms of the reflection coefficient indicating that an excellent agreement is achieved. The measurements demonstrate that the designed antenna has unidirectional radiation characteristics with 1 to 6 dB gain. The proposed design's simulated and measured results are compared, and they demonstrate good agreement**.**

This chapter is organized as follows: Section 4.2 presents the working principle, detailed design strategy, and evolution process of the investigated antenna. Section 4.3 presents the explanation about electrical model and biasing circuit of the PIN diode which is employed to achieve frequency reconfigurability. Section 4.4 depicts the fabricated prototype of the investigated antenna, as well as the results of the simulated and measured reflection coefficient, gain, and radiation patterns. Conclusions are provided in Section 4.5.

4.2 Antenna Design And Configuration Methodology

A. Antenna Geometry

Figure. 1(a)–(b) depicts the top, and side views of the investigated frequency reconfigurable hexaband antenna, respectively. An Inexpensive and commercially available material called FR4, with thickness, relative permittivity (ε_r), and tangent loss ($\tan \delta$), of 1.6 mm, 4.4, and

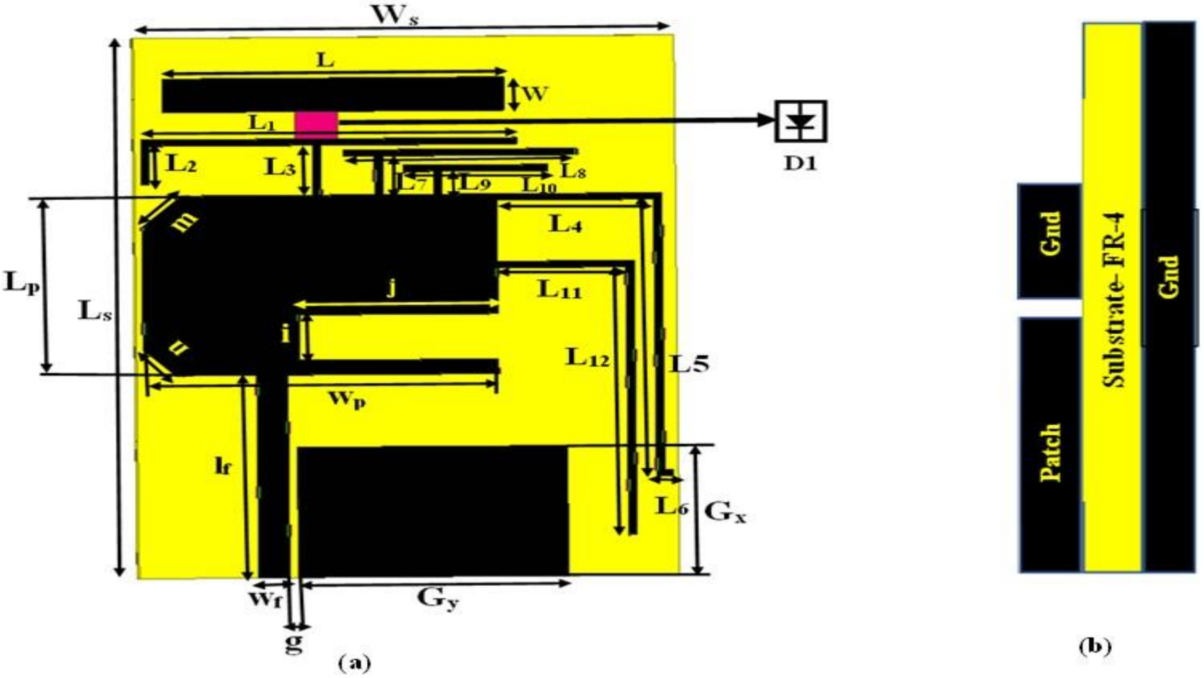


Figure 4.1 Schematic layout of the presented antenna a) Front view and b) Side view

0.024, respectively, is utilized for the substrate of the presented hexaband antenna.

The investigated hexaband antenna has compact size of 24 mm × 19 mm. The investigated antenna is fed via a 50 GACS feedline with a 1.1 mm signal strip and a 0.3 mm gap distance between the asymmetric ground plane and signal strip. The designed antenna is composed of a rectangular microstrip patch antenna connected to GACS feed line for better impedance matching corners of the patch are truncated on the left-hand side, and U-shaped slot is cut on the patch at the right-hand side. An F-shaped monopole, Z shaped monopole, two T shaped monopoles and inverted L-shaped monopole that are attached to a rectangular microstrip patch antenna. To achieve frequency reconfigurability an RF PIN diode switch is incorporated between the F- shaped monopole and metal strip of length L and width W. The investigated antenna is designed with the help of high frequency structure simulation software (HFSS).

Parameter	Value (mm)	Parameter	Value (mm)
$\mathbf{L_s}$	24	w_p	14
$\mathbf{W_s}$	19	i	2
$\mathbf{G_x}$	5.8	j	7
$\mathbf{G_y}$	9.5	m	1.97
$\mathbf{l_f}$	9	n	1.63
$\mathbf{w_f}$	1.1	L_1	13.05
g	0.3	L_2	2
$\mathbf{L_p}$	10	L_3	2.5
$\mathbf{L_4}$	5.5	L_7	1.7
$\mathbf{L_5}$	12.61	L_8	8.2
$\mathbf{L_6}$	0.3	L_9	1
$\mathbf{L_{10}}$	5.1	L_{11}	4.5
$\mathbf{L_{12}}$	12.2	L	12
W	1.5		

Table 4.1 Depicts the optimized dimensions

B. Design Evolution

The step wise development of the presented design is depicted in five consecutive stages as shown in Fig. 2. In the initial step (Antenna I) antenna consists of rectangular microstrip patch antenna connected to GACS feed linefor better impedance matching corners of the patch are truncated on the left-hand side, and U-shaped slot is cut on the patch at the right-hand side. The width and length of the basic rectangular patch antenna can be calculated by the following design equations [1].Antenna-I is developed to function at the primary fundamental frequency of $f_{U\text{-}NII\text{-}2C}$ = 5.68 GHz

The width of rectangular patch (W_p) of Antenna I is calculated as

$$W_p = \frac{c}{2f_{U-NII-2C}}\sqrt{\frac{2}{\varepsilon_r+1}} \tag{4.1}$$

where fr, ε_r and c are the resonant frequency, relative permittivity, and speed of light in free space, respectively.

The Length of rectangular patch (L_p) of Antenna I is taken as,

$$L_p = \frac{c}{2f_{U-NII-2C}\sqrt{\varepsilon_{reff}}} - 2\Delta L \tag{4.2}$$

where effective permittivity ε_{reff} is given by

$$\varepsilon_{reff} = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2\sqrt{1+\frac{12h}{W_p}}} \tag{4.3}$$

and

$$\Delta L = 0.412h\frac{(\varepsilon_{reff}+0.3)\left(\frac{W_p}{h}+0.264\right)}{(\varepsilon_{reff}-0.258)\left(\frac{W_p}{h}+0.8\right)} \tag{4.4}$$

where h is the thickness of substrate.

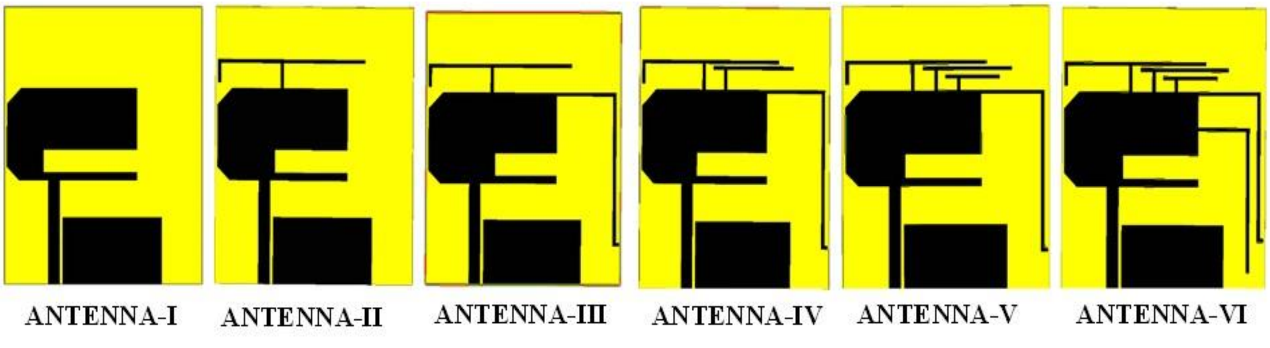


Figure 4.2 Evolution stages of the investigated design

In the second step (Antenna II), due to the addition of F-shaped monopole second mode resonating at 3.45 GHz is achieved to provide LTE band 52 services. Antenna II operates at the two frequencies 3.45 GHz and 5.68 GHz with a decent reflection coefficient of -21.27 dB and -20 dB, respectively as illustrated in Fig. 3.In the third step (Antenna III), an Z shaped monopole is attached to the patch antenna to achieve third resonance at 2.35 GHz to provide LTE band 30 services. Antenna III operates at the three frequencies 2.35 GHz, 3.53 GHz and 5.68 GHz with decent reflection coefficient of -20.3 dB, -22.85 dB and -14 dB, respectively as illustrated in Fig. 3.In the fourth step (Antenna IV), a T shaped monopole is added thus providing fourth resonance at 4.28 GHz to provide radio altimeter services.Antenna IV operates at four frequencies 2.35, 3.5, 4.28 and 5.68 GHz with a decent reflection coefficient of -13.3, -24.7, -18.1 and -31.6, respectively as illustrated in Fig. 3.In the fifth step (Antenna V), another T shaped monopole of shorter length is connected to patch to achieve fifth resonance at 5.2 GHz to provide U-NII-2A band services. Antenna V operates at five frequencies 2.32, 3.47, 4.23, 5.2 and 5.68 GHz with a good reflection coefficient of -17, -14, 22, -12.8 and -26.9 dB, respectively as illustrated in Fig. 3. In the final step (Antenna VI), an inverted L-shaped monopole is added to achieve sixth resonance at 5.2 GHz to provide LTE band 53 services.Antenna VI operates at five 2.35, 2.55, 3.45, 4.28, 5.22 and 5.68 GHz with very small frequency ratios of the values of 1.085, 1.352, 1.24, 1.219, and 1.088 between two consecutive resonant frequencies and a good reflection coefficient of -17.7, -16.3, -19.3, -22.6, -14.3 and -24.7 dB, respectively as illustrated in Fig. 3. Table 2 shows a simulated performance evaluation of the presented antenna under various evolution scenarios. The length of the monopoles (Antennas (II - VI)) are calculated as:

$$T_{2.35\,\mathrm{GHz}} = 18.11 \text{ mm } (L_4+L_5+L_6)$$

$$T_{2.55\,\mathrm{GHz}} = 16.7 \text{ mm } (L_{11}+L_{12})$$

$$T_{3.45\,\mathrm{GHz}} = 17.5 \text{ mm } (L_1+L_2+L_3)$$

$$T_{4.28\,\mathrm{GHz}} = 9.9 \text{ mm } (L_7+L_8)$$

$$T_{5.2\,\mathrm{GHz}} = 6.1 \text{ mm } (L_9+L_{10})$$

These lengths are approximately equal to one-quarter of the guided wavelength, i.e.

$$T_{f_r} = \frac{c}{2 f_r \sqrt{\varepsilon_{reff}}} \tag{4.5}$$

where, $c = 3 \times 10^{8}$ ms^{-1} is the velocity of light in vacuum, f_r is the resonance frequency, and ε_{reff} is the effective permittivity of the substrate, given by:

$$\varepsilon_{reff} = \frac{\varepsilon_r + 1}{2} \tag{4.6}$$

TABLE 4.2

SIMULATION-BASED PERFORMANCE ANALYSIS OF THE PRESENTED ANTENNA

Configuration	**Operating frequency (GHz)**	**S_{11} (dB)**	**Bandwidth (GHz)**	**Bandwidth (MHz)**	**Bandwidth (%)**	**Gain (dBi)**
Antenna-I	5.68	-25.9	5.6-5.76	160	2.8	1.7
Antenna-II	3.45	-21.27	3.35-3.54	190	5.5	1.2
	5.68	-20	5.6-5.76	160	2.8	2.5
Antenna-III	2.35	-20.3	2.33-2.38	50	2.1	1.47
	3.53	-22.85	3.45-3.63	180	5.1	2.6
	5.68	-14	5.56-5.75	190	3.4	4.8
Antenna-IV	2.35	-13.3	2.33-2.37	40	1.7	1.5
	3.5	-24.7	3.45-3.55	100	2.8	2.0
	4.28	-18.1	4.21-4.37	160	3.7	2.9
	5.68	-31.6	5.59-5.75	160	2.8	4.6
Antenna-V	2.32	-17	2.3-2.35	50	2.1	1.6
	3.47	-14	3.4-3.52	120	3.5	1.9
	4.23	-22	4.17-4.32	150	3.5	2.84
	5.2	-12.8	5.16-5.23	70	1.3	4.2
	5.68	-26.9	5.61-5.75	140	2.5	4.9
Antenna-VI	2.35	-17.7	2.34-2.36	20	0.9	1.6
	2.55	-16.3	2.53-2.59	60	2.3	1.9
	3.45	-19.3	3.37-3.52	150	4.3	2.84
	4.28	-22.6	4.22-4.36	140	3.3	4.2
	5.22	-14.3	5.18-5.25	70	1.3	4.9
	5.68	-24.7	5.62-5.75	130	2.3	5.8

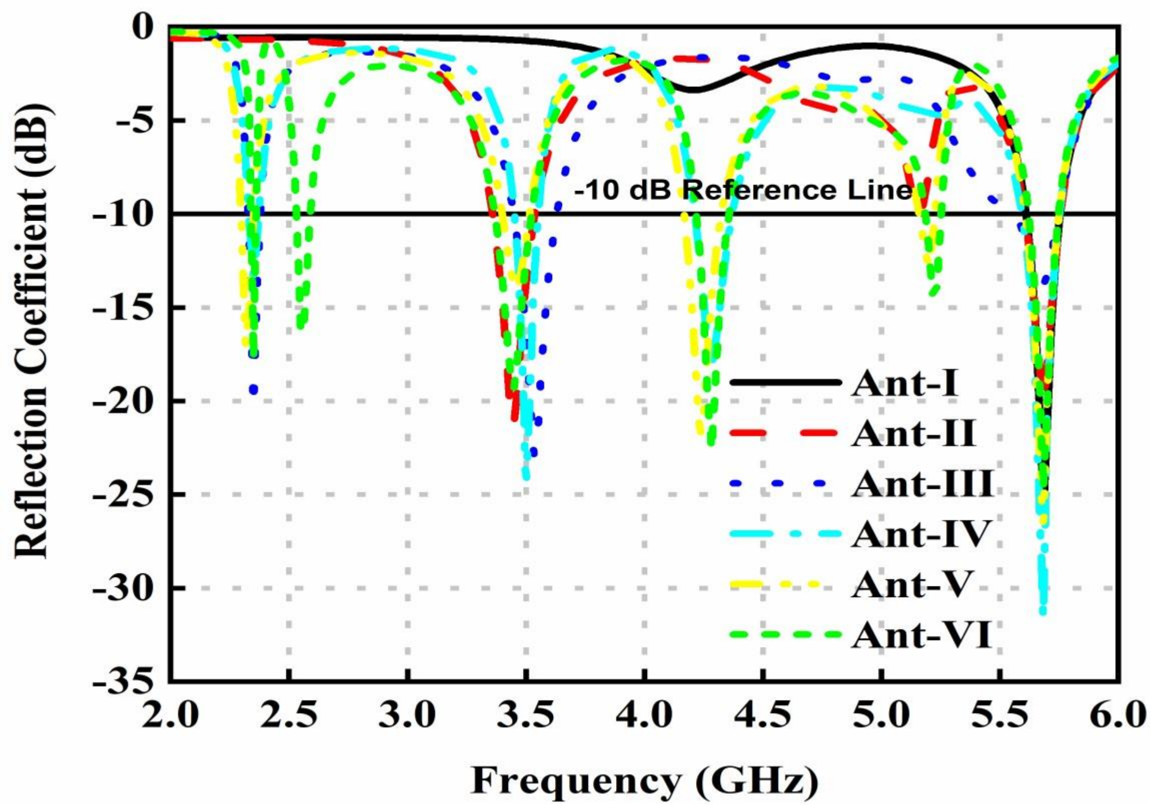
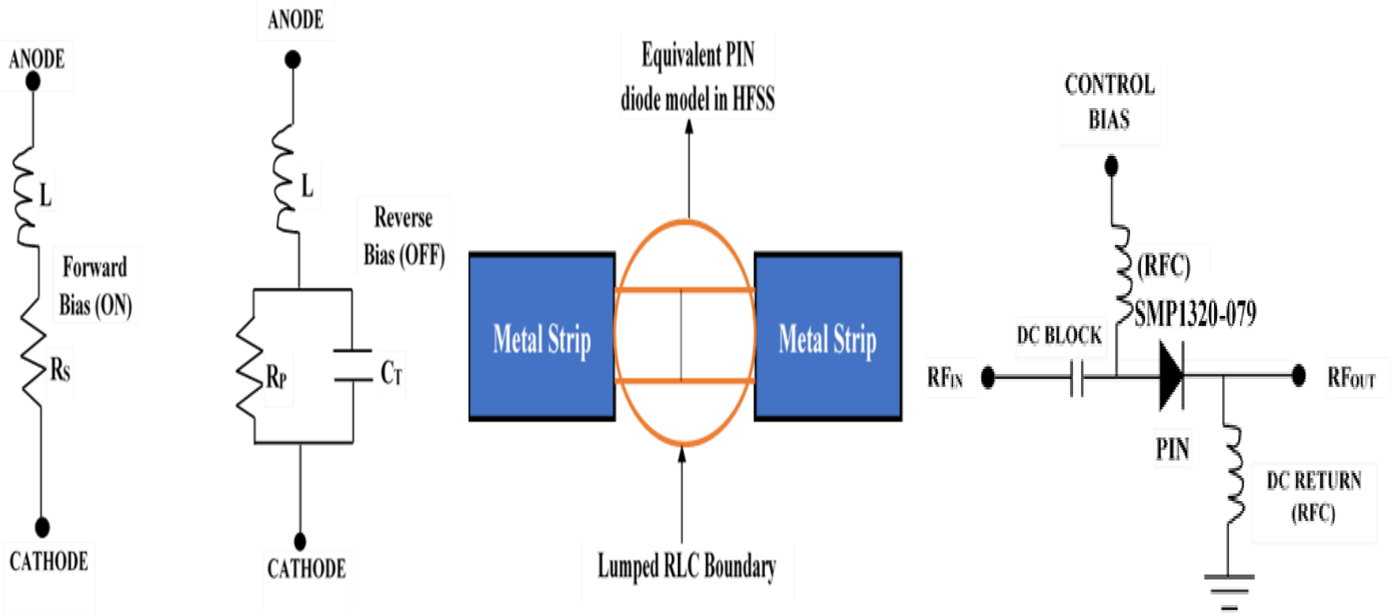


Figure 4.3 Simulated S11 at each step of evolution

4.3 Frequency reconfigurability

A. PIN diode model

Because of their small size, durability, fast switching speed, and low capacitance and resistance in the OFF and ON states, PIN diode is used to achieve reconfigurability in the investigated design. The equivalent circuit models for the PIN diode in ON and OFF states are depicted in Fig. 6(a). A package inductance L persists in both the ON and OFF states. In the ON state, the equivalent circuithas a low resistance RS, that adds to the insertion loss. The parallel combination of the total capacitance CT and reverse bias resistance Rp in the equivalent circuit for the OFF state adds to isolation. The PIN diode SMP 1320-079 LF from Skyworks Solutions Inc was employed to achieve frequency reconfigurability. From the datasheet of the SMP1320-079 the circuit parameters are L = 0.7 nH, RS = 0.9 Ω, CT = 0.3 pF, and Rp = 3 KΩ. In HFSS simulation, diode is modelled using the Resistance, Inductance, and Capacitance (RLC) boundary by introducing two rectangular sheets in the diode position as illustrated in Fig. 4(b).



(a) **(b)** **(c)**

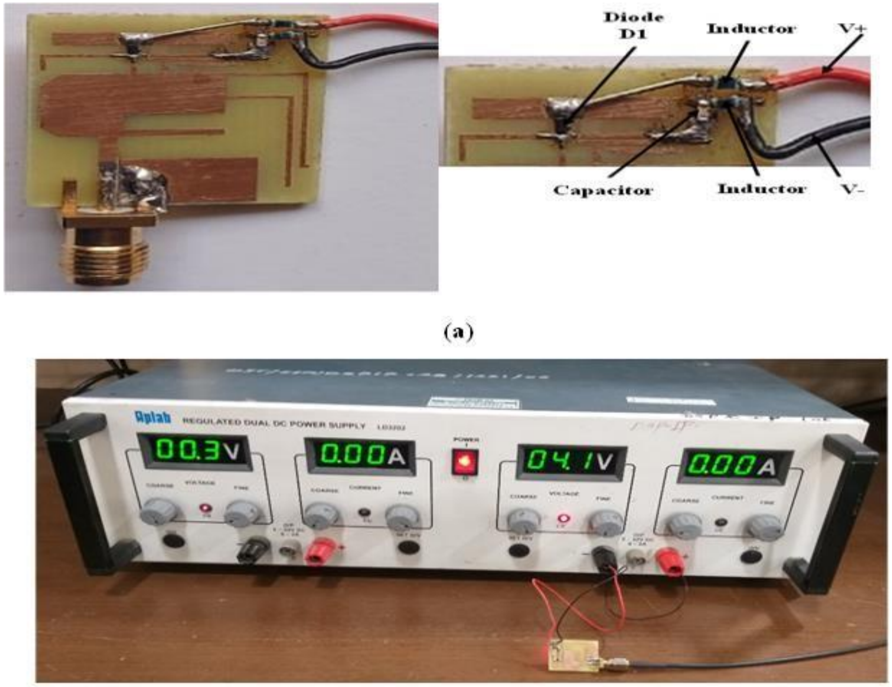
Figure 4.4 PIN diode electrical model a) Equivalent model using lumped elements b) Model in HFSSand c) Biasing circuit

B. Biasing circuit

To accurately bias the PIN diode, some isolation in between the RF signal and DC signal is required. Otherwise, the efficiency of the power control circuit is decreased by the flow of RF current into the output impedance of the power supply. The DC bias supply is isolated from the RF circuits by connecting an RF inductor of 33 nH from coilcraft in series with the bias line, and an RF by-pass capacitor of 10 pF from Murata in series with the RF input as shown in Fig 4(c). The circuit is also wired to 5V regulated supply as shown in Fig 4(c).

4.4 Results and Discussion

To justify the HFSS simulation results, the investigated antenna is fabricated, and an antenna model integrated with a biasing circuit is shown in Fig. 7. A calibrated Agilent/HP N9923A 6 GHz Handheld RF Vector Network Analyzer is employed to measure the reflection coefficient. Single PIN diode (D1) is used for possible two modes of operation of the presented antenna.



(a)

(b)

Figure 4.5a) Fabricated model of the proposed design integrated with biasing circuit and (b) Experimental setup

A. Mode 1

When the PIN diode (D1) is turned OFF, the proposed antenna operates in Mode 1. Fig. 8 demonstrates the measured and simulated S_{11} characteristics of the investigated antenna in this mode. As illustrated in Fig. 8, in this mode the proposed antenna exhibits hexa-band characteristics with measured $S_{11} < -10$ dB impedance bandwidth of about 2.3

GHz (2.25-2.32 GHz, 3%), 2.5 GHz (2.46-2.52 GHz, 2.4%), 3.35 GHz (3.23-3.45 GHz, 6.6%), 4.4 GHz (4.33-4.47 GHz, 3.2%), 5.3 GHz (5.24-5.36 GHz, 2.3%) and 5.6 GHz (5.53-5.67 GHz, 2.5%)

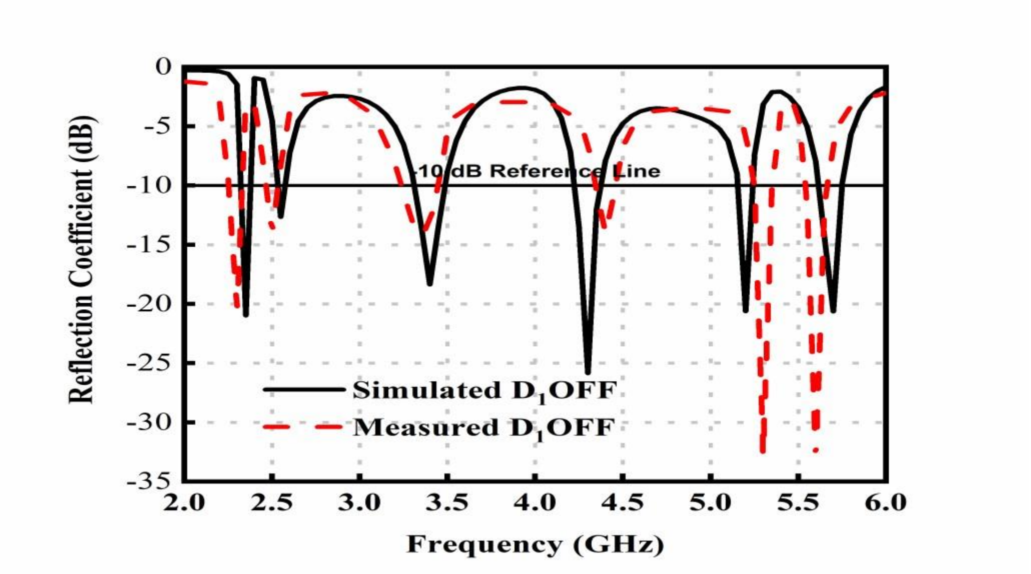


Figure 4.6 Compared S_{11} results of the proposed design for Mode 1

The simulated surface current densities (A/m) for the six resonating frequencies are plotted in Fig 9 to understand better the radiating features of the investigated antenna. Figure 9(a) demonstrates that the maximum current distribution is recognized along the Z shaped monopole at a lower resonant frequency, 2.3 GHz. Figure 9(b) illustrates that at 2.5 GHz, the maximum current distribution is focused along the inverted L-shaped monopole. At the operating frequency of 3.35 GHz, the maximum current distribution is centeredalong the Fshaped monopole, as depicted in Fig 9(c). At the operating frequency of 4.4 GHz, the surface current is extremely distributed along the T shaped monopole, depicted in Fig 9(d). At the operating frequency of 5.3 GHz, the surface current is extremely distributed along the smaller T shaped monopole, depicted in Fig 9(e). A further finding has been that the surface current distribution is most focused across the bottom part of patch and feed line at 5.6 GHz, as illustrated in Fig 9(f). The operational frequency bands of the investigated antenna in this mode as illustrated from the simulated and measured reflection coefficients can cover six commercial bands of LTE Band 30, LTE Band 53, LTE Band 52, radio altimeter, U-NII-2A, and U-NII-2C, respectively.

B. Mode 2

When the PIN diode (D1) is turned ON, the proposed antenna operates in Mode 2. Fig. 10 demonstrates the measured and simulated S_{11} characteristics of the proposed antenna in this mode. It can be seen from Fig. 10, in this mode the proposed antenna exhibits triple-band characteristics with measured $S_{11} < -10$ dB impedance bandwidth of about 4.35 GHz (4.274.43 GHz,3.7%), 5.25 GHz (5.17-5.33 GHz,3%), and 5.65 GHz (5.57-5.72 GHz,2.7%). The proposed antenna in the Mode 2 covers three commercial bands of radio altimeter, U-NII-1 & U-NII-2A and U-NII-2C, respectively.

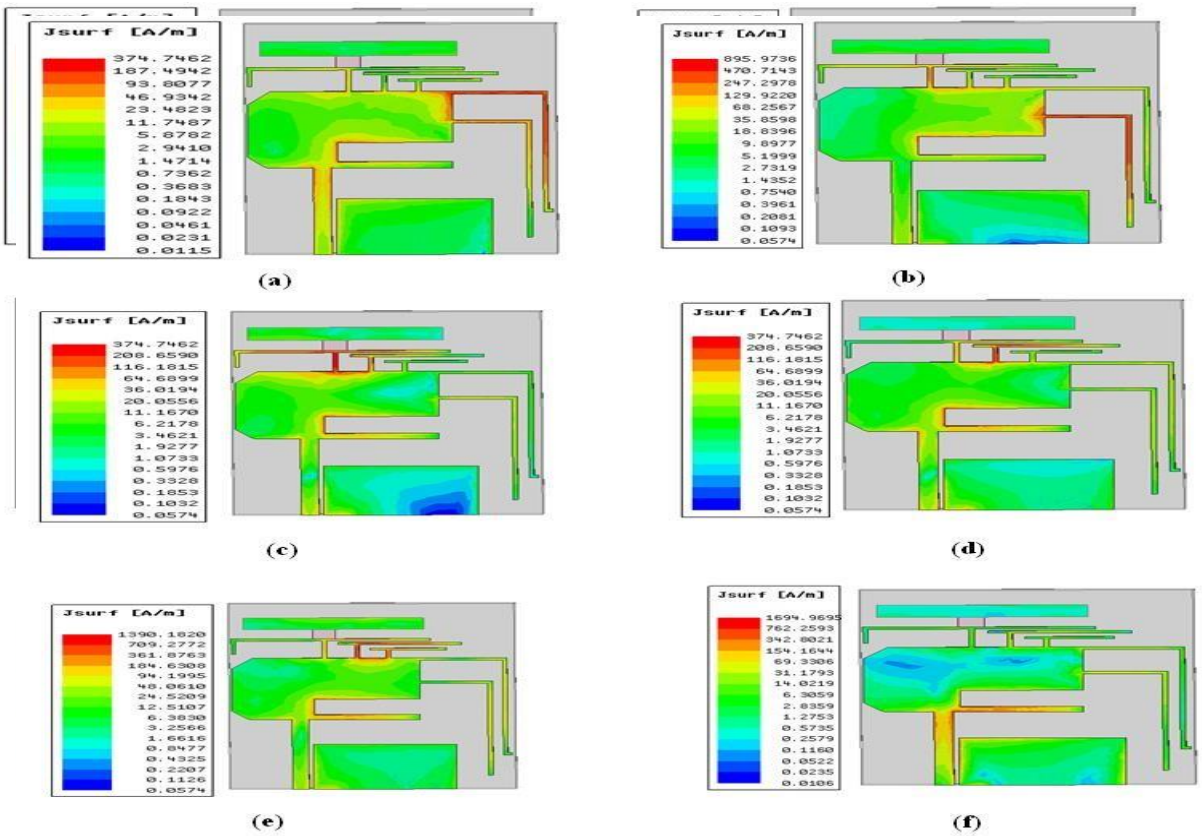


Figure 4.7 Simulated surface current distributions at (a) 2.3 GHz, (b) 2.5 GHz (c) 3.35 GHz, (d) 4.4 GHz, (e) 5.3 GHz and (f) 5.6 GHz.

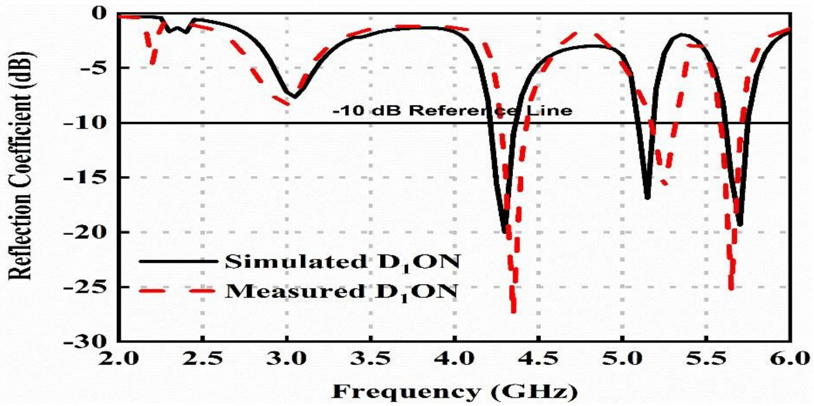
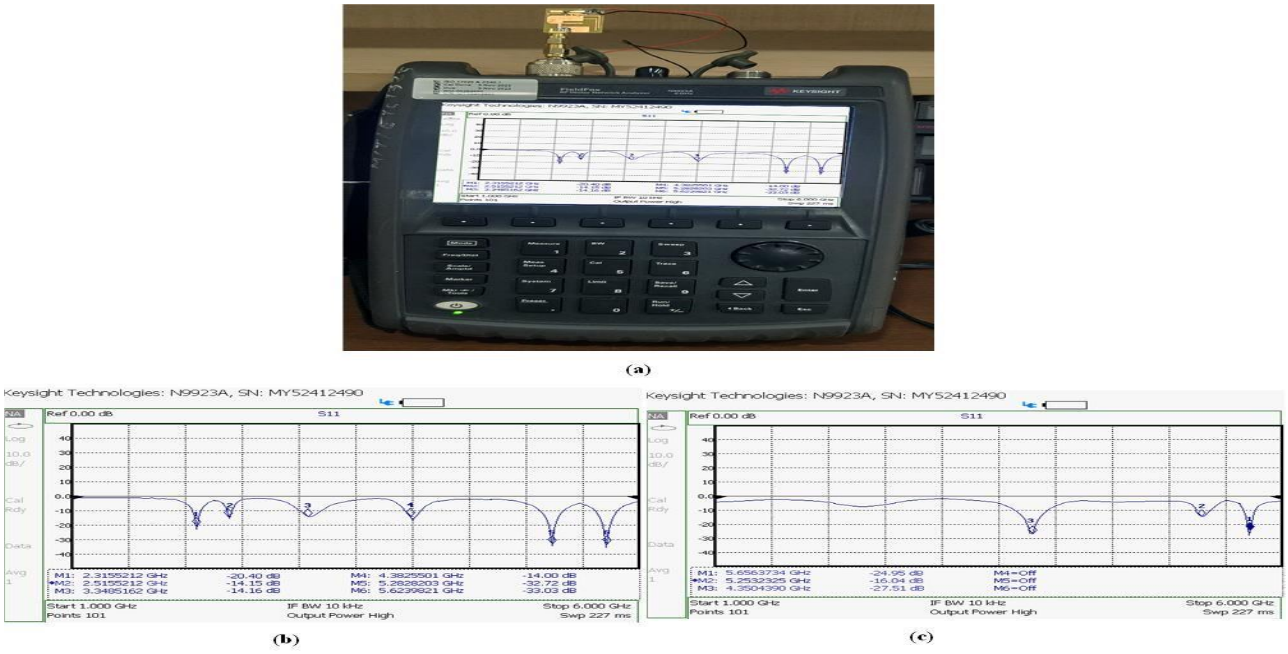


Figure 4.8 Compared S_{11} results of the proposed design for Mode 2

Fig. 4.9 (a) illustrates the set-up to measure S11 using vector network analyzer (VNA), Fig. 4.9 (b) presents the snapshot of VNA for Mode 1 and Fig. 4.9 (c) presents the snapshot of VNA for Mode 2. The proposed antenna's simulation and measurement values are compared in terms of reflection coefficients S11(dB), impedance bandwidth, gain, and the resulting values are illustrated in Table.


(a)

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Keysight Technologies: N9923A, SN: MY52412490
Ref 0.00 dB                         S11
 M1:  2.3155212 GHz    -20.40 dB     M4:  4.3825501 GHz    -14.00 dB
•M2:  2.5155212 GHz    -14.15 dB     M5:  5.2828203 GHz    -32.72 dB
 M3:  3.3485162 GHz    -14.16 dB     M6:  5.6239821 GHz    -33.03 dB
Start 1.000 GHz              IF BW 10 kHz              Stop 6.000 GHz
Points 101                   Output Power High          Swp 227 ms
```

(b)

```
Keysight Technologies: N9923A, SN: MY52412490
Ref 0.00 dB                         S11
 M1:  5.6563734 GHz    -24.95 dB     M4=Off
•M2:  5.2532325 GHz    -16.04 dB     M5=Off
 M3:  4.3504390 GHz    -27.51 dB     M6=Off
Start 1.000 GHz              IF BW 10 kHz              Stop 6.000 GHz
Points 101                   Output Power High          Swp 227 ms
```

(c)

Figure 4.9 (a) S_{11} measurement set-up using VNA (Model No: N9923A), (b) Snap shot of VNA screen for Mode 1 and (c) Snap shot of VNA screen for Mode 2

To further investigate the radiation characteristics of the proposed antenna, 2D E & H plane pattern are examined. In both simulation and measurement modes, the principal plane (E & H) patterns (co/cross-polarization states) are observed, demonstrating a good correlation among these two mode outcomes. The 2D radiation patterns for mode 1 operation are outlined at various wireless communication operating frequencies: 2.3 GHz, 3.35 GHz and 5.6 GHz, respectively as indicated in Figure 12. The investigated antenna has a unidirectional radiation pattern in the E- and H-planes at all operating frequencies.

TABLE 4.3
POSSIBLE MODES WITH THEIR CORRESPONDING $S_{11,}$ IMPEDANCE BANDWIDTH, and GAIN

Model	**Mode**	**Operational frequency band (GHz)**	**Reflection coefficient (dB)**	**Bandwidth (GHz)**	**Bandwidth (%)**	**Gain (dBi)**
Simulated	1	2.35	-30	2.32-2.38	2.5	1.85
		2.55	-12.6	2.53-2.57	1.6	2.28
		3.4	-18.4	3.31-3.49	5.3	3.46
		4.3	-25.8	4.22-4.37	3.5	2.93
		5.2	-20.6	5.15-5.24	1.7	5.55
		5.7	-20.6	5.62-5.75	2.3	6.26
	2	4.3	-20	4.21-4.36	3.5	2.85
		5.15	-16.8	5.09-5.18	1.8	5.46
		5.7	-19.3	5.61-5.73	2.1	5.98
Measured	1	2.3	-20.4	2.25-2.32	3	1
		2.5	-14	2.46-2.52	2.4	1.5
		3.35	-14.2	3.23-3.45	6.6	2.4
		4.4	-14	4.33-4.47	3.2	2.78
		5.3	-32.7	5.24-5.36	2.3	5.2
		5.6	-33	5.53-5.67	2.5	6.02
	2	4.35	-27.5	4.27-4.43	3.7	2.77
		5.25	-16	5.17-5.33	3	5.13
		5.65	-25.2	5.57-5.72	2.7	5.97

4.5 Conclusion

A compact GACS fed frequency reconfigurable hexa-band antenna was presented and investigated. Computer simulations and measurements have shown that the proposed antenna operates at six different frequencies 2.3/2.5/3.35/4.4/5.3/5.6 GHz by switching ON and OFF the PIN diode. The proposed antenna covers six commercial bands of LTE Band 30, LTE Band 53, LTE Band 52, radio altimeter, U-NII-2A, and U-NII-2C. In addition, the RLC equivalent model of the proposed hexa-band antenna designed with the ADS Agilent software yields resonance frequencies nearly identical to those generated by simulation (with HFSS) th CST) and measurement. The investigated antenna has simulated gains of 1.85, 2.28, 3.46, 2.93, 5.55 and 6.26 dBi and measured gains of 1, 1.5, 2.4, 2.78, 5.2 and 6.02 dBi at 2.3, 2.5, 3.35, 4.4, 5.3 and 5.6 GHz, respectively. The investigated design yields unidirectional radiation patterns with high reliability and minimal cross-polarization, as well as consistent radiation efficiency/gain and improved impedance matching across all operating wireless communication bands, making it a good choice for inbuilt antennas in multiband wireless portable devices.

Chapter 5

Conclusion and Future Scope

5.1 Conclusion

The continuous growth and commercial interest in wireless cellular communications, especially in personal and mobile communication systems significantly increase the demand for low cost, compact size, multiple bands, and high-performance antennas, which are the key components used in any communication system. Multiband antennas are very much desirable for current mobile wireless devices because they can cover multiple frequencies using a relatively simple structure, and they are usually less expensive to produce when compared to the other alternatives. However, they require complicated filters with stringent requirements to improve their out-of-band noiserejection performance. These filters, moreover, are generally bulky and expensive. In contrast, frequency reconfigurable antennas have great potential for reducing production costs and offer better out-of-band noise rejection without filters. This thesis presented a detailed study of frequency reconfigurable hexaband antenna designs to demonstrate the frequency reconfigurable concept employing the electrical reconfiguration technique using PIN diodes.

A compact GACS fed frequency reconfigurable hexa-band antenna was presented and investigated. Computer simulations and measurements have shown that the proposed antenna operates at six different frequencies 2.3/2.5/3.35/4.4/5.3/5.6 GHz by switching ON and OFF the PIN diode. The proposed antenna covers six commercial bands of LTE Band 30, LTE Band 53, LTE Band 52, radio altimeter, U-NII-2A, and U-NII-2C. The investigated antenna has simulated gains of 1.85, 2.28, 3.46, 2.93, 5.55 and 6.26 dBi and measured gains of 1, 1.5, 2.4, 2.78, 5.2 and 6.02 dBi at 2.3, 2.5, 3.35, 4.4, 5.3 and 5.6 GHz, respectively.The investigated design yields unidirectional radiation patterns with high reliability and minimal cross-polarization, as well as consistent radiation efficiency/gain and improved impedance matching across all operating wireless communication bands, making it a good choice for inbuilt antennas in multiband wireless portable devices. Hence, it is concluded that the proposed compact reconfigurable hexa-band antenna design is useful for the next generation wireless communication system applications.

5.2 Future scope of the work

The material used in the antennas presented in this thesis is FR4, which is considered as a lossy material. Therefore, these antennas can be investigated by using expensive lossless materials to further improve efficiency. The reconfigurable antenna designs using PIN diodes are reported in this thesis and the scope is there to extend the designs by using the RF micro electro mechanical systems (MEMS) switches which give the superior performance than the PIN diodes with respect to bandwidth, linearity, power consumption, insertion loss, and isolation. Further studies can be carried out by using smart materials for reconfigurability as it can decrease the size of the antenna. Attempts can be made to design a hybrid reconfigurable antenna with frequency, pattern and polarization reconfigurability. In some designs, the bandwidth of the operating frequencies is narrow, and therefore, they can be extended to enhance the bandwidth by using other techniques.

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