Rectangular Microstrip Patch Antenna: Design and Analysis using III-Nitride Substrates

by

A K M Moniruzzaman

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Engineering in Department of Electrical and Electronic Engineering

Khulna University of Engineering & Technology

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Declaration

This is to certify that the thesis work entitled" *Rectangular Microstrip Patch Antenna : Design and Analysis using III-Nitride Substrates*" has been carried out by *A K M Moniruzzaman* in the Department of *Electrical and Electronics Engineering*, Khulna University of Engineering & Technology, Khulna, Bangladesh. The above thesis work or any part of this work has not been submitted anywhere for the award of any degree or diploma.

Signature of supervisor

……………………………………

Signature of Candidate

……………………………………

Approval

This is to certify that the thesis work submitted by *A K M Moniruzzaman* entitled "*Rectangular Microstrip Patch Antenna: Design and Analysis using III-Nitride Substrates*" has been approved by the board of examiners for the partial fulfillment of the requirements for the degree of *Master of Science in Electrical & Electronic Engineering* in the Department of *Electrical & Electronic Engineering*, Khulna University of Engineering & Technology, Khulna, Bangladesh in November 2013.

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Author

Abstract

In this paper, I have theoretically designed different microstrip patch antenna using commercially available substrates and III-Nitride substrates. The rectangular microstrip patch antenna has conspicuous for microwave device or cellular device in many wireless applications. Due to their advantages of light weight, low volume, low profile planar configuration, low fabrication cost on large scale production with a special process, capable of dual and triple frequency operations, mechanically robust when mounted on rigid surfaces rectangular patch antenna has great potential to use in mobile handset. In this work, commercial substrates are used as Taconic, Rogers & FR-4 and III-Nitride substrates are used as InN, AlN & GaN. And those substrates based rectangular microstrip patch antenna have been theoretically designed and analyzed. The antenna performances are evaluated using Ansoft High Frequency Structure Simulator (HFSS). These include the theoretical analysis and calculation of input impedance (Zi), voltage standing wave ratio (VSWR), return loss (RL), directivity, gain and efficiency. III-Nitride substrates are also compared with commercially available substrates and found better in all aspects for wireless applications.

The dielectric constant (ε) (frequency dependent parameter) for different substrates has a great influence on antenna performance and those values are used as $\varepsilon_{Taconic}$=2.2, ε_{Rogers}=2.2, ε_{FR-4}=4.4, ε_{InN}=8.4, ε_{AlN}=8.8 and ε_{GaN}=5.3 respectively. Physical parameters of each substrate like mass density, thermal conductivity, dielectric loss tangent and relative permeability are also catered irrespective of availability during simulation for making it little realistic. During calculation & simulation, substrate height (h) & operating frequency (f_0) are selected as 0.8 mm & 1.9 GHz. The value of Zi, VSWR (peak) and RL (peak) for III-Nitride substrates are found within the limit of standard values like Zi is around 50Ω, VSWR (peak) $\leq$ 2.5 and peak value of R_L < -10dB. Overall antenna radiation efficiency, total directivity and gain are found better. During analysis of commercially available substrates, it is found that all those values are not compatible for mobile device applications with f_0 = 1.9 GHz & h = 0.8mm.

The above studies, design parameters and analysis indicate that the proposed III-Nitride based rectangular microstrip patch antenna especially GaN substrate may be a promising candidate for mobile device applications.

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Nomenclature

Z_{in}	Input Impedance, $R_{in+} jX_{in}$
R_{in}	Antenna resistance at the terminals
X_{in}	Antenna reactance at the terminals
VSWR	Voltage Standing Wave Ratio
Γ	Reflection coefficient
V_r	Amplitude of the reflected wave
V_i	Amplitude of the incident wave
RL	Return Loss
BW	Bandwidth, $\frac{f_h}{f_L}$
$BW_{broadband}(\%)$	Bandwidth, $\left[\frac{f_H - f_L}{f_C}\right]100$
f_H	Upper frequency
f_L	Lower frequency
f_c	Center frequency
h	Height of substrate
W	Width, $\frac{c}{2f_0\sqrt{\frac{\varepsilon_r+1}{2}}}$
C	Constant speed of light in vacuum
ε_r	Dielectric constant of substrate
f_0	Operating frequency
ε_{eff}	Effective dielectric constant, $\frac{\varepsilon_r+1}{2}+\frac{\varepsilon_r-1}{2}\left(1+12\frac{h}{W}\right)^{-\frac{1}{2}}$ if, $\frac{W}{h}>$
L_{eff}	Effective length, $\frac{c}{Lf_0\sqrt{\varepsilon_{eff}}}$
L	Patch length, L_{eff} - $2\nabla L$

CHAPTER I

Introduction

1.1 Introduction

Communication has expanded much rapidly in the past couple of decades. With the rapid growth of wireless communications, the increasing popularity of cellular system is prompting the development of efficient antennas. Antenna is the critical device/equipment that is used to efficiently transmit wireless signal to the free space and/or receive wireless signal. The impact of mobile communications on antenna design, resulting in unbelievably compact and densely packaged handset antennas used entirely within the mobile phone case itself. Cellular phones are some of the most intricate devices people use on a daily basis. Modern digital cell phones can process millions of calculations per second in order to compress and decompress the voice stream.

In the last few years, the wireless communications industry has grown by orders of magnitude fueled by digital and RF circuit fabrication improvements, new large-scale circuit integration and other miniaturization technologies which make portable radio equipment smaller, cheaper and more reliable. Fig. 1.1 shows the kind of cellular handsets weight over a period of years, the handsets are becoming smaller and lighter. In high-performance aircraft, spacecraft, satellite and missile applications, where size, weight, cost, performance, ease of installation and aerodynamic profile are constraints and low-profile antennas are required.

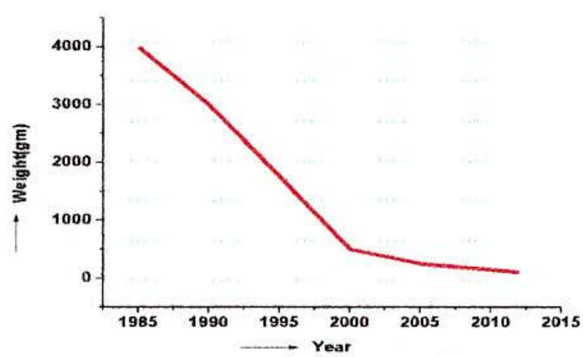


Fig.1.1 Cellular Handsets used in last few years

To meet these requirements, patch antenna is one of the most rapidly popular topics in the antenna field of last three decades [1] and the developments occurred time to time during the last two decades [2]. However, microstrip patch antennas are well suited for wireless application systems due to their advantages. Therefore, detail understanding of patch antennas are immense important for wireless applications.

1.2 Research Background of Microstrip Patch Antenna

Compared with other conventional antennas, patch antenna is relatively immature. Research works on microstrip antennas are of immense importance. Patch antennas received considerable attention starting in the 1970s, although the idea of a patch antenna can be traced to 1953 and a patent in 1955 [1]. The standard microstrip patch antenna has a very narrow bandwidth. To overcome the bandwidth disadvantages and to improve the performance of microstrip antennas, many techniques have been employed [2]. Research works on significant improvements of wideband patch antenna enhanced the performance, attempts for the stacked patch antenna, reactive capacitive loading and thicker substrates suggested in the recent years [3]-[5]. Another popular method for bandwidth enhancement is coaxial probe feed where feeding is employed with a slotted patch on an electrically thick substrate (0.08–0.1) of low dielectric constant. The achievable bandwidth can be 30% (SWR $\leq$ 2) with a gain around 6–8 dBi within the operating bandwidth [6]. Surface wave radiation from microstrip antennas is known to be source of many inconveniences, such as radiation efficiency reduction and radiation pattern perturbations due to the surface wave diffraction on the dielectric truncations [7].

In 2005, Wang and Chahine *et al* described a new technique to enhance the bandwidth of microstrip patch antennas [8],[9]. Chi-Lun *et al* proposed a simple twin-feed structure to reduce the narrow-bandwidth problem with increasing the gain [10] in 2006. Liang *et al* investigated the periodic metallic loading effects on a proximity coupled microstrip patch antenna for purpose of increasing bandwidth [11]. In 2008, Shanmuganantham *et al* designed and developed a compact broadband probe-fed microstrip patch antenna for bandwidth improvement and antenna size reduction in a single design [12]. However, the practical applications are still immature. In order to achieve further progress in the applicability of patch antenna, detailed device simulation is necessary.

1.3 Why III-Nitride Based Microstrip Patch Antenna?

Microstrip patch antennas consist of a metallic patch, placed over a small fraction of wavelength above a ground plane separated by a dielectric substrate. Patch can be rectangular or circular or any shape[13]. They are widely used in the microwave frequency region because of their simplicity and compatibility with printed-circuit technology, making them easy to manufacture either as stand-alone element or as elements of arrays. Limited bandwidth is a major drawback, especially for mobile or satellite communications. So, an optimized substrate thickness and dielectric constant required to enhance the performance of microstrip antenna. As there is a limitation to increase substrate thickness and reduce dielectric constant, antenna should be designed to meet the requirements of these emerging trends in mobile communication.

The III-Nitride substrates such as Indium Nitride (InN), Aluminum Nitride (AlN) and Gallium Nitride (GaN) may be candidates to use as a substrate in patch antenna due to their attracting properties. AlN is a newer material in the technical ceramic family. It has been developed into a commercially viable product with controlled and reproducible properties within last 20 years. It has good dielectric properties, high thermal conductivity and low thermal expansion coefficient which are close to that of silicon. GaN is a semiconductor compound expected to make possible miniaturized, high power wireless transmitters. These transmitters will be combined with sensitive receivers into telephone sets capable of directly accessing communications satellite. The compound can also be used in light emitting diodes (LED) and other semiconductor devices. Owing to these unique properties, group III-Nitride semiconductors provide great promise for overcoming the fundamental limitations. An important property that makes group III-Nitride materials extremely attractive is a very large bandgap, i.e. the energy required to ionize atoms and create free electrons. A large bandgap is the key factor for high temperature operation, chemical inertness and high breakdown voltage. Recently, the research in the III-Nitride device applications has mainly focused on microwave electronics [14]. The advantages of GaN devices include high output power with small volume and high efficiency in power amplifiers at ultra high and microwave radio frequencies. Therefore, detail understanding and proper inclusion of these effects in the design and analysis of high performance III-Nitride based patch antenna substrates are of immense importance. However, there is a very little theoretical works on substrate improvement, most of the works carried out on conventional silicon, GaAs and other III-V compound materials [15],[16].

In this work, we have designed theoretically III-Nitride substrates namely InN, AlN & GaN based patch antenna for cellular device and evaluated their performances using HFSS (High Frequency Structure Simulator) . These include the theoretical analysis and calculation of input impedance, voltage standing wave ratio (VSWR), return loss, total directivity, gain and efficiency. The input impedance, VSWR, and return loss have been evaluated considering preset operating frequency. In Addition commercially available substrates like Taconic, Rogers & FR-4 are also analyzed and compared with III-nitride substrates.

1.4 Thesis Organization

To understand the fundamental of antenna, Chapter II starts with a description of antenna, several types of antenna and the electromagnetic wave radiation from an antenna. Further, discussion will be concentrated on antenna performance parameter and polarization of the antenna.

To insight the prospect of III-Nitride (InN, AlN and GaN) based patch, microstrip patch antenna with its advantages and the profit to use III-Nitride as a substrate in the patch is described first in Chapter III. For theoretical analysis of rectangular patch antenna its theoretical structure, several feeding techniques such as the microstrip line, coaxial probe, aperture coupling and proximity coupling are discussed with the comparison between different feed techniques. Finally, transmission line model which is a method analysis of the patch and some basic concept of conductance of patch conductor are narrated in this chapter.

For theoretical design and analysis of microstrip patch antenna Chapter IV starts with commercially available substrates (Taconic, Rogers and FR-4) and III-Nitride (InN, AlN and GaN) substrates based rectangular micro strip patch antenna. Finally, simulation models are made with the help of Ansoft HFSS and discussed their performance parameters.

To realize the performance of the proposed III-Nitride based patch antenna and conventional antenna with commercially available substrates, Chapter V starts with the simulation result of the performance parameter such as input impedance, VSWR, return loss, directivity and gain. The efficiency for different substrates is also discussed. Finally, we have shown a table with comparison between proposed antenna and other existing antenna which represents the performance of the proposed antenna.

Chapter VI provides the conclusions that can be drawn from the work described in this thesis and provides recommendations for future research.

CHAPTER II

Antenna Fundamentals

In this chapter, the basic concept of an antenna is provided and its working is explained. Next, some performance parameters of antennas are discussed. Finally, some common types of antennas are introduced.

2.1 Introduction

Antennas are metallic structures designed for radiating and receiving electromagnetic energy. An antenna acts as a transitional structure between the guiding device (e.g. waveguide, transmission line) and the free space. The official IEEE definition of an antenna as given by Stutzman [21] and Thiele follows the concept: "That part of a transmitting or receiving system that is designed to radiate or receive electromagnetic waves."

2.2 Types of Antenna

Antennas come in different shapes and sizes to suit different types of wireless applications. The characteristics of an antenna are determined by its shape, size and the type of material. Some of the commonly used antennas are half wave dipole, monopole antenna, helical antennas, and horn antennas etc [15].

2.3 How an Antenna Radiates

In order to know how an antenna radiates, let us first consider how radiation occurs. A conducting wire radiates mainly because of time-varying current or acceleration (or deceleration) of charge. If there is no motion of charges in a wire, no radiation takes place, since no flow of current occurs. Radiation will not occur even if charges are moving with uniform velocity along a straight wire. However, charges moving with uniform velocity along a curved or bent wire will produce radiation. If the charge is oscillating with time, then radiation occurs even along a straight wire as explained by Balanis. The radiation from an antenna can be explained with the help of Fig. 2.1 which shows a voltage source connected to a two conductor transmission line. When a sinusoidal voltage is applied across the transmission line, an electric field is created which is sinusoidal in nature and this result in the creation of electric lines of force which are tangential to the electric field. The magnitude of the electric field is indicated by the bunching of the electric lines of force. The free electrons on the conductors are forcibly displaced by the electric lines of force and the movement of these charges causes the flow of current which in turn leads to the creation of a magnetic field [15].

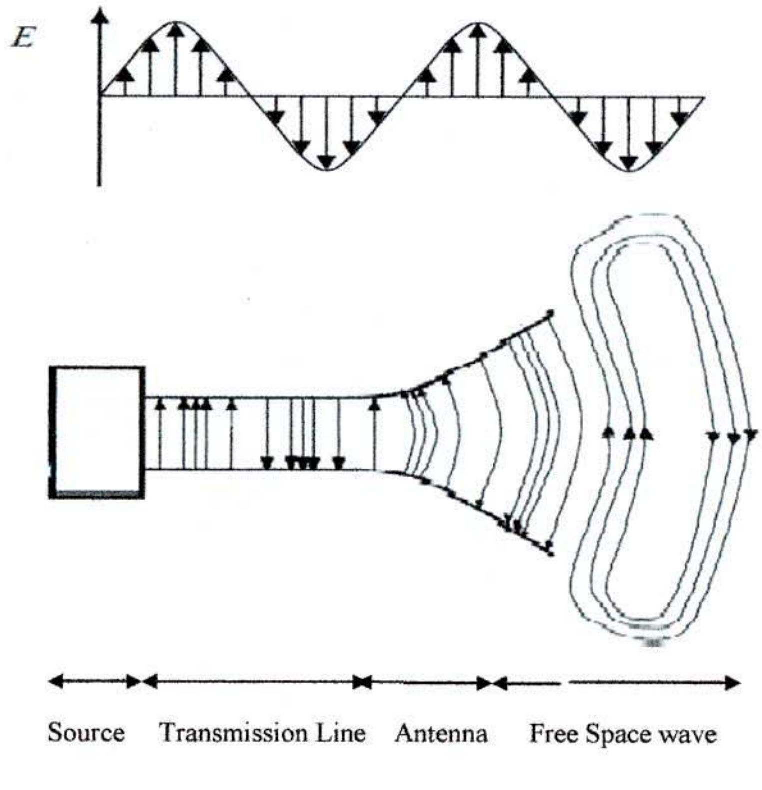


Fig. 2.1 Radiation from an Antenna

Due to the time varying electric and magnetic fields, electromagnetic waves are created and these travel between the conductors. As these waves approach open space, free space waves are formed by connecting the open ends of the electric lines. Since the sinusoidal source continuously creates the electric disturbance, electromagnetic waves are created continuously and these travel through the transmission line, through the antenna and are radiated into the free pace. Inside the transmission line and the antenna, the electromagnetic waves are sustained due to the charges, but as soon as they enter the free space, they form closed loops and are radiated. The field patterns, associated with an antenna, change with distance and are associated with two types of energy: - radiating energy and reactive energy. Hence, the space surrounding an antenna can be divided into three regions as shown in Fig. 2.2

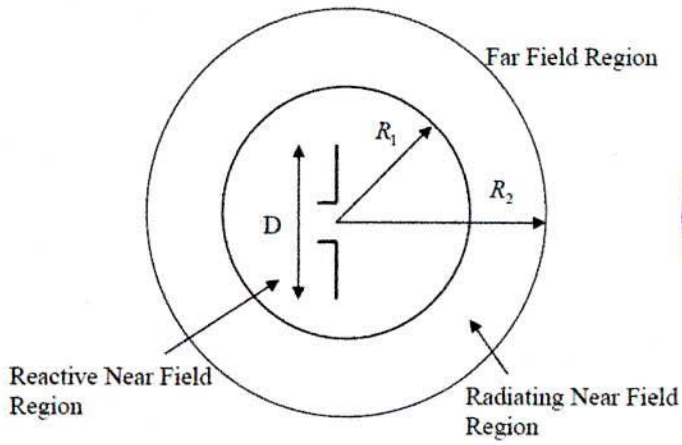


Fig. 2.2 Field region around an antenna

2.4 Antenna Performance Parameters

The performance of an antenna can be gauged from a number of parameters. Certain parameters are discussed below:

2.4.1 Input Impedance

The input impedance of an antenna is defined by as [15] "the impedance presented by an antenna at its terminals or the ratio of the voltage to the current at the pair of terminals or the ratio of the appropriate components of the electric to magnetic fields at a point". Hence the impedance of the antenna can be written as:

$$Z_{in} = R_{in} + jX_{in} \qquad (2.1)$$

Where

Z_{in} is the antenna impedance at the terminals
R_{in} is the antenna resistance at the terminals
X_{in} *is* the antenna reactance at the terminals

The imaginary part, X_{in} of the input impedance represents the power stored in the near field of the antenna. The resistive part, R_{in} of the input impedance consists of two components, the radiation resistance R_R and the loss resistance R_L. The power associated with the radiation resistance is the power actually radiated by the antenna, while the power dissipated in the loss resistance is lost as heat in the antenna itself due to dielectric or conducting losses.

Approximate expressions are stated which describe the variation of the resonant input resistance as a function of the inset-feed position, which can be used effectively to match the antenna element to the input transmission line. In general, the input impedance is complex and it includes both a resonant and a non resonant part which is usually reactive. Both the real and imaginary parts of the impedance vary as a function of frequency and a typical variation. Ideally both the resistance and reactance exhibit symmetry about the resonant frequency and the reactance at resonance is equal to the average of sum of its maximum value (which is positive) and its minimum value (which is negative). Typically the feed reactance is very small, compared to the resonant resistance, for very thin substrates. However, for thick elements the reactance may be significant and needs to be taken into account in impedance matching and in determining the resonant frequency of a loaded element. The variations of the feed reactance as a function of position can be intuitively explained by considering the cavity model for a rectangular patch with its four sides perfect magnetic conducting walls. As far as the impedance is concerned, the magnetic walls can be taken into account by introducing multiple images with current flow in the same direction as the actual feed. When the feed point is far away from one of the edges, the magnetic field associated with the images and that of the actual feed do not overlap strongly. Therefore the inductance associated with the magnetic energy density stored within a small testing volume near the feed will be primarily due to the current of the actual feed. However, when the feed is at one of the edges, the feed and one of the images, which accounts for the magnetic wall at that edge, coincide. Thus, the associated magnetic field stored energy of the equivalent circuit doubles while the respective stored magnetic energy density quadruples. However, because the volume in the testing region of the patch is only half from that when the feed was far removed from the edge, the net stored magnetic density is only double of that of the feed alone. Thus, the associated inductance and reactance, when the feed is at the edge, is twice that when the feed is far removed from the edge. When the feed is at a corner, there will be three images in the testing volume of the patch, in addition to the actual feed, to take into account the edges that form the corner. Using the same argument as above, the associated inductance and reactance for a feed at a corner is four times that when the feed is removed from an edge or a corner. Thus, the largest reactance (about a factor of four larger) is when the feed is at or near a corner while the smallest is when the feed is far removed from an edge or a corner. Although such an argument predicts the relative variations (trends) of the reactance as a function of position, they do predict very accurately the absolute values especially when the feed is at or very near an edge. In fact it overestimates the values for feeds right on the edge; the actual values predicted by the cavity model with perfect magnetic conducting walls are smaller. A formula [15] that has been suggested to approximate the feed reactance is

$$X_f \cong -\frac{\eta k h}{2\pi}\left[In\left(\frac{kd}{4}\right)+0.577\right] \quad (2.2)$$

Where, d is the diameter of the feed probe. More accurate predictions of the input impedance, based on full-wave models, have been made for circular patches where an attachment current mode is introduced to match the current distribution of the probe to that of the patch [15].

2.4.2 Voltage Standing Wave Ratio (VSWR)

In order for the antenna to operate efficiently, maximum transfer of power just take place between the transmitter and the antenna. Maximum power transfer can take place only when the impedance of the antenna (Z_{in}) is matched to that of the transmitter (Z_S). According to the maximum power transfer theorem, maximum power can be transferred only if the impedance of the transmitter is a complex conjugate of the impedance of the antenna under consideration and vice-versa. Thus, the condition for matching is:

$$Zin = Zs^* \quad (2.3)$$

Where

$Z_{in} = R_{in} + jXs$

Zs = Rs+ jXs

If the condition for matching is not satisfied, then some of the power maybe reflected back and this leads to the creation of standing waves, which can be characterized by a parameter called as the Voltage Standing Wave Ratio (VSWR). The VSWR is given as [15]:

$$VSWR = \frac{1+|\Gamma|}{1-|\Gamma|} \tag{2.4}$$

Where

$$\Gamma = \frac{V_r}{V_i} = \frac{Z_{in} - Z_s}{Z_{in} + Z_s} \tag{2.5}$$

Where

Γ is called the reflection coefficient

V_r is the amplitude of the reflected wave

V_i is the amplitude of the incident wave

The VSWR is basically a measure of the impedance mismatch between the transmitter and the antenna. The minimum VSWR which corresponds to a perfect match is unity. A practical antenna design should have an input impedance of either 50 Ω or 75 Ω since most radio equipment is built for this impedance [15].

2.4.3 Return Loss (*RL*)

The Return Loss (*RL*) is a parameter which indicates the amount of power that is lost to the load and does not return as a reflection. As explained in the preceding section, waves are reflected leading to the formation of standing waves, when the transmitter and antenna impedance do not match. Hence the *RL* is a parameter similar to the VSWR to indicate how well the matching between the transmitter and antenna has taken place. The *RL* is given for power co-efficient as [15]

$$R_L = -10\log_{10}|\Gamma| \text{ (dB)} \tag{2.6}$$

For perfect matching between the transmitter and the antenna, $\Gamma = 0$ and $RL = \infty$ which means no power would be reflected back, whereas a $\Gamma = 1$ has a $RL = 0$ dB, which implies that all incident power is reflected. For practical applications, a VSWR of 1 is more acceptable, since this corresponds to a RL of -29.54 dB.

2.4.4 Bandwidth

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 [15]. The bandwidth can be considered to be the range of frequencies, on either side of a center frequency usually the resonance frequency for a dipole, where the antenna characteristics such as input impedance, pattern, beamwidth, polarization, side lobe level, gain, beam direction, radiation efficiency are within an acceptable value of those at the center frequency. For broadband antennas, the bandwidth is usually expressed as the ratio of the upper-to-lower frequencies of acceptable operation. For narrowband antennas, the bandwidth is expressed as a percentage of the frequency difference (upper minus lower) over the center frequency of the bandwidth. Because the characteristics (input impedance, pattern, gain, and polarization, etc) of an antenna do not necessarily vary in the same manner or are even critically affected by the frequency, there is no unique characterization of the bandwidth. The specifications are set in each case to meet the needs of the particular application. Usually there is a distinction made between pattern and input impedance variations. Accordingly pattern bandwidth and impedance bandwidth are used to emphasize this distinction. 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. Therefore the bandwidth is usually formulated in terms of beamwidth, side lobe level, and pattern characteristics. For intermediate length antennas, the bandwidth may be limited by either pattern or impedance variations, depending upon the particular application. For these antennas, a 2:1 bandwidth indicates a good design. For others, large bandwidths are needed. It is possible to increase the acceptable frequency range of a narrowband antenna if proper adjustments can be made on the critical dimensions of the antenna and/or on the coupling networks as the frequency is changed. According to these definitions can be written in terms of equations as follows,

$$BW_{broadband} = \frac{f_h}{f_L} \tag{2.7}$$

$$BW_{broadband}(\%) = \left[\frac{f_H - f_L}{f_C}\right]100 \tag{2.8}$$

Where,

f_H = upper frequency

f_L = lower frequency

f_c = center frequency

2.4.5 Directivity and Gain

The directivity of an antenna has been defined as the ratio of the radiation intensity in a given direction from the antenna to the radiation intensity averaged over all directions. In other words, the directivity of a non isotropic source is equal to the ratio of its radiation intensity in a given direction, over that of an isotropic source. In mathematical form, using, it can be written as [15]

$$D = \frac{U}{U_i} = \frac{2\pi U}{P} \tag{2.9}$$

Where,

D = directivity of the antenna

U = radiation intensity of the antenna

U_i = radiation intensity of an isotropic source

P = total power radiated

Sometimes, the direction of the directivity is not specified. In this case, the direction of the maximum radiation intensity is implied and the maximum directivity is given as,

$$D_{max} = \frac{U_{max}}{U_i} = \frac{2\pi U_{max}}{P} \tag{2.10}$$

Where, D_{max} is the maximum directivity

U_{max} is the maximum radiation intensity

For an isotropic source, it is very obvious that the directivity is unity since U, U_{max}, and U_0 are all equal to each other. For antennas with orthogonal polarization components, we define the partial directivity of an antenna for a given polarization in a given direction as that part of the radiation intensity corresponding to a given polarization divided by the total radiation intensity averaged over all directions. With this definition for the partial directivity, then in a given direction the total directivity is the sum of the partial directivities for any two orthogonal polarizations. For a spherical co-ordinate system, the total maximum directivity D_0 for the orthogonal θ and φ components of an antenna can be written as,

$$D_0 = D_\theta + D_\varphi \tag{2.11}$$

While the partial directivities D_θ and D_φ are expressed as

$$D_\theta = \frac{4\pi U_\theta}{(P_{rad})_\theta + (P_{rad})_\theta} \tag{2.12}$$

$$D_\theta = \frac{4\pi U_\theta}{(P_{rad})_\theta + (P_{rad})_\theta} \tag{2.13}$$

Where

U_θ = radiation intensity in a given direction contained in θ field component

U_φ = radiation intensity in a given direction contained in φ field component

$(P_{rad})_\theta$ = radiated power in all directions contained in θ field component

$(P_{rad})_{\varphi}$ = radiated power in all directions contained in φ field component

Directivity is a dimensionless quantity, since it is the ratio of two radiation intensities. Generally directivity expressed in dBi. The directivity of an antenna can be easily estimated from the radiation pattern of the antenna. An antenna that has a narrow main lobe would have better directivity, then the one which has a broad main lobe, hence it is more directives.
Another useful measure describing the performance of an antenna is the gain. Antenna gain is a parameter which is closely related to the directivity of the antenna. Gain of an antenna (in a given direction) is defined as the ratio of the intensity, in a given direction, to the radiation intensity that would be obtained if the power accepted by the antenna were radiated isotropically [15].

$$\text{Gain} = 4\pi \frac{\text{radiation intensity}}{\text{total input (accepted) power}} = 4\pi \frac{U(\theta,\varphi)}{P_{in}} \quad \text{(dimensionless)} \qquad (2.14)$$

When the direction is not confirmed, the power gain is usually taken in the direction of maximum radiation. Than the directivity is how much an antenna concentrates energy in one direction in preference to radiation in other directions. Hence, if the antenna is 100% efficient, then the directivity would be equal to the antenna gain and the antenna would be an isotropic radiator. Since all antennas will radiate more in some direction that in others, therefore the gain is the amount of power that can be achieved in one direction at the expense of the power lost in the others. The gain is always related to the main lobe and is specified in the direction of maximum radiation unless indicated. According to the IEEE Standards, "gain does not include losses arising from impedance mismatches (reflection losses) and polarization mismatches. It is given as:

$$G(\theta,\varphi) = e_{cd} D(\theta,\varphi) \qquad (2.15)$$

2.4.6 Radiation Pattern

An antenna radiation pattern or antenna pattern is defined as a mathematical function or a graphical representation of the radiation properties of the antenna as a function of space coordinates [15]. Most of cases, the radiation pattern is determined in the far field region and is represented as a function of the directional coordinates. Radiation properties include power flux density, radiation intensity, field strength, directivity, phase or polarization. The radiation property of most concern is the two- or three-dimensional spatial distribution of radiated energy as a function of the observer's position along a path or surface of constant radius. A trace of the received electric (magnetic) field at a constant radius is called the amplitude field pattern. On the other hand, a graph of the spatial variation of the power density along a constant radius is called an amplitude power pattern. Often the field and power patterns are normalized with respect to their maximum value, yielding normalized field and power patterns. Also, the power pattern is usually plotted on a logarithmic scale or more commonly in decibels (dB). This scale is usually desirable because a logarithmic scale can accentuate in more details those parts of the pattern that have very low values, which later we will refer to as minor lobes.

For an antenna, the field pattern (in linear scale) typically represents a plot of the magnitude of the electric or magnetic field as a function of the angular space. Power pattern *(in* linear scale) typically represents a plot of the square of the magnitude of the electric or magnetic field as a function of the angular space. Power pattern (in dB) represents the magnitude of the electric or magnetic field, in decibels, as a function of the angular space. The radiation pattern of an antenna is a plot of the far-field radiation properties of an antenna as a function of the spatial co-ordinates which are specified by the elevation angle θ and the azimuth angle φ. More specifically it is a plot of the power radiated from an antenna per unit solid angle which is nothing but the radiation intensity. Consider the case of an isotropic antenna. An isotropic antenna is one which radiates equally in all directions.

If the total power radiated by the isotropic antenna is P, then the power is spread over a sphere of radius r, so that the power density S at this distance in any direction is given as:

$$S = \frac{P}{area} = \frac{P}{4\pi r^2} \qquad (2.16)$$

Then the radiation intensity for this isotropic antenna U_i can be written as:

$$U_i = r^2 S = \frac{P}{4\pi} \tag{2.17}$$

An isotropic antenna is not possible to realize in practice and is useful only for comparison purposes. A more practical type is the directional antenna which radiates more power in some directions and less power in other directions. A special case of the directional antenna is the omni directional antenna whose radiation pattern may be constant in one plane (e.g. E-plane) and varies in an orthogonal plane (e.g. H-plane). The total radiation field in the E plane of a rectangular microstrip antenna element operating in the TM_{11}, mode is given as

$$E_\theta(\theta)_{\varphi=0} = -jV_0 W k_0 \left(\frac{e^{-jk_0 R}}{4\pi r} \right) F_{E(\theta)} \tag{2.18}$$

Where,

$$F_{E(\theta)} = \sin\left(\frac{k_0 h}{2} \sin\theta \right) \left(\frac{k_0 h}{2} \sin\theta \right)^{-2} \cos\left(\frac{k_0 L}{2} \sin\theta \right) \tag{2.19}$$

For the H plane *(y-z* plane),

$$E_\varphi(\theta)_{\frac{\pi}{2}} = -jV_0 W k_0 \left(\frac{e^{-jk_0 R}}{4\pi r} \right) F_{H(\theta)} \tag{2.20}$$

Where,

$$F_{E(\theta)} = \sin\left(\frac{k_0 W}{2} \sin\theta \right) \left(\frac{k_0 W}{2} \sin\theta \right)^{-1} \cos\theta \tag{2.21}$$

Where, k_0 is the propagation constant in the free space, W and L is the width and length of the patch, V_0 is the voltage across the slot, θ and φ are the spherical co-ordinates.

The radiation pattern plot of a generic directional antenna is shown in Figure 2.3

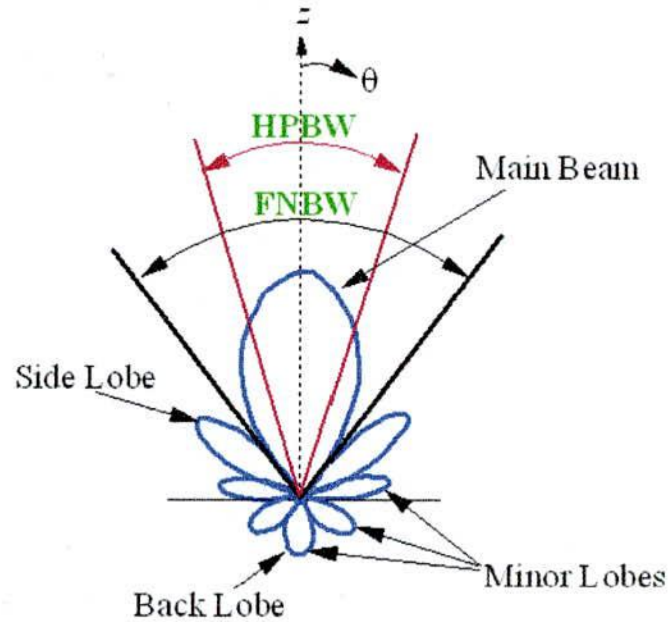


Fig. 2.3 Radiation pattern of a directional antenna

Fig. 2.3 shows the half power beam width (HPBW) can be defined as the angle subtended by the half power points of the main lobe. Main Lobe **is** the radiation lobe containing the direction of maximum radiation. Minor lobes are the lobes other then the main lobe are. These lobes represent the radiation in undesired directions. The level of minor lobes is usually expressed as a ratio of the power density in the lobe in question to that of the major lobe. This ratio is called as the side lobe level (expressed in decibels). Back lobe is the minor lobe diametrically opposite the main lobe. Side lobes are the minor lobes adjacent to the main lobe and are separated by various nulls. Side lobes are generally the largest among the minor lobes. In most wireless systems, minor lobes are undesired. Hence a good antenna design should minimize the minor lobes.

The Surface waves radiation from microstrip antennas is known to be the source of many inconveniences, such as strong mutual coupling in antenna arrays, deterioration of radiation patterns due to surface wave diffraction on the dielectric truncations and reduction of the antenna gain.

For the designer of microstrip antennas, the power carried by surface waves is an important parameter. This power has to be considered as a loss because it is trapped in the dielectric substrate. Moreover, unwanted radiation results when the surface wave encounters a discontinuity (e.g. the edge of the substrate). A parameter used to quantify this loss is the space wave efficiency which relates the power radiated in space waves to the total radiated power (including surface waves). It is defined as follows [21]

$$\eta = \frac{P_{sp}}{P_{sp} + P_{sp}} \qquad (2.22)$$

Where, P_{sp} is the power radiated in space waves and P_{su} is the power radiated in the surface wave.

2.4.7 Polarization

Polarization of a radiated wave is defined as "that property of an electromagnetic wave describing the time-varying direction and relative magnitude of the electric-field vector; specifically, the figure traced as a function of time by the extremity of the vector at a fixed location in space, and the sense in which it is traced, as observed along the direction of propagation." Polarization then is the curve traced by the end point of the arrow (vector) representing the instantaneous electric field. The field must be observed along the direction of propagation.

The polarization of a wave can be defined in terms of a wave *radiated (transmitted)* or *received* by an antenna in a given direction. The polarization of a wave *radiated* by an antenna in a specified direction at a point in the far field is defined as "the polarization of the (locally) plane wave which is used to represent the radiated wave at that point. At any point in the far field of an antenna the radiated wave can be represented by a plane wave whose electric-field strength is the same as that of the wave and whose direction of propagation is in the radial direction from the antenna. As the radial distance approaches infinity, the radius of curvature of the radiated wave's phase front also approaches infinity and thus in any specified direction the wave appears locally as a plane wave." This is a far-field characteristic of waves radiated by all practical antennas. The polarization of a wave *received* by an antenna is defined as the "polarization of a plane wave, incident from a given direction and having a given power flux density, which results in maximum available power at the antenna terminals."

Polarization of a radiated wave is defined as the property of an electromagnetic wave describing the time varying direction and relative magnitude of the electric field vector [15]. The polarization of an antenna refers to the polarization of the electric field vector of the radiated wave. In other words, the position and direction of the electric field with reference to the earth's surface or ground determines the wave polarization. The most common types of polarization include the linear (horizontal or vertical) and circular (right hand polarization or the left hand polarization).

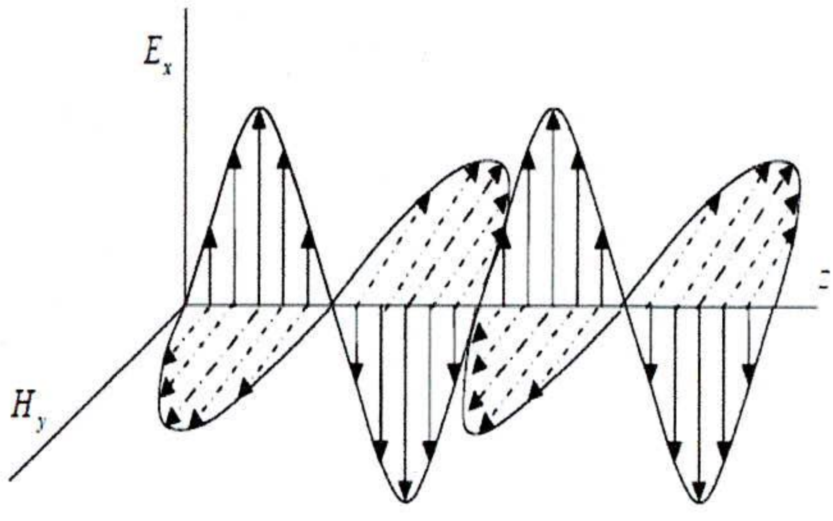


Fig. 2.4 A linearly polarized waves

If the path of the electric field vector is back and forth along a line, it is said to be linearly polarized. Fig. 2.4 shows a linearly polarized wave.

In a circularly polarized wave, the electric field vector remains constant in length but rotates around in a circular path. A left hand circular polarized wave is one in which the wave rotates counterclockwise whereas right hand circular polarized wave exhibits clockwise motion as shown in Fig. 2.5

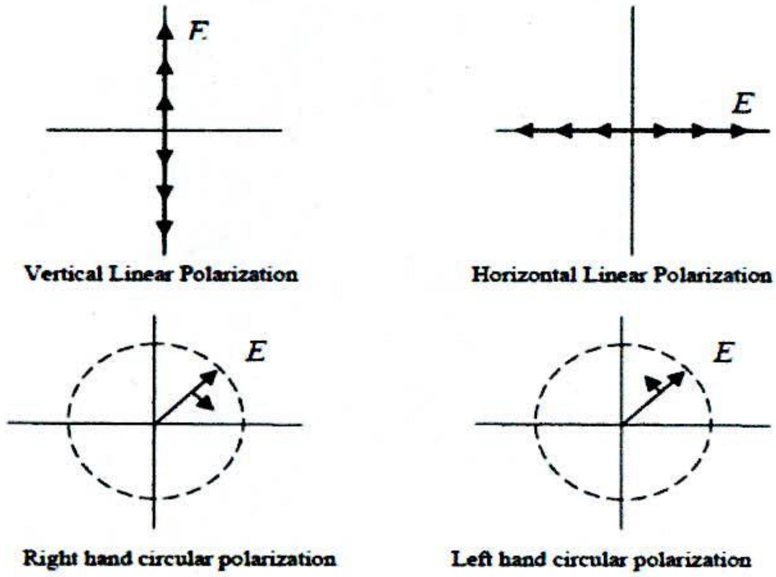


Fig. 2.5 various polarization schemes

CHAPTER III

Microstrip Patch Antenna

In this chapter, an introduction to the Microstrip Patch Antenna is followed by its advantages. Next, theoretical structure of proposed patch antenna and some feed modeling techniques are discussed. Finally, a detailed explanation of Microstrip patch antenna analysis is explained.

3.1 Introduction

The ever expanding need of communication bandwidth defines new communication protocols which in turn expect better technology to fill in the gap. Microstrip patch antenna has attracted lots of interest in the field of mobile communication due to its important characteristics along with easy to achieve multi frequency operation and relatively large area consumption.

To improve the performance of microstrip antennas, many techniques have been employed. The standard processing steps found in a boundary fit quite well the need to fabricate a standard patch antenna. The main challenge is the material to be used as substrate. Parameters like substrate thickness, dielectric permittivity, dielectric losses, metal conductivity and thickness, should be evaluated to understand its influence on overall antenna performance. Most of works is going the research in the matter of making light and low cost device. For these reasons III-Nitrite based substrates have been chosen. In this work, we present a wideband rectangular patch antenna on III-Nitride based substrate. Wide band gap III-Nitride semiconductor materials possess superior material properties as compared to silicon, GaAs and other III-V compound materials. High-power, high-temperature includes high electron mobility and saturation velocity, high breakdown voltages, and low thermal impedance which provide the maximum efficiency for microstrip patch antenna.

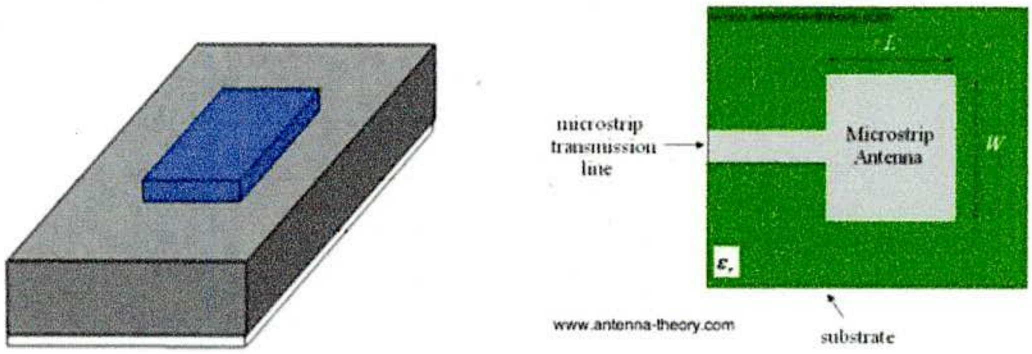


Figure 3.1 Microstrip Patch Antenna

A microstrip patch antenna as shown in figure 3.1 consists of a radiating patch on one side of a dielectric substrate which has a ground plane on the other side. The patch is generally made of conducting material, can take any possible shape. The radiating patch and the feed lines are usually photo etched on the dielectric substrate. In order to simplify analysis and performance prediction, the patch is generally square, rectangular, circular, triangular and elliptical or some other common shape. Microstrip patch antenna radiate primarily because of the fringing fields between the patch edge and the ground plane. For good antenna performance, a thick dielectric substrate having a low dielectric constant is desirable since this provides better efficiency, larger bandwidth and better radiation.

Personal communication handset demands the reduced height antennas that occupy less volume. Moreover, due to the emergence of new standards and the user's mobility requirements, mobile terminal should cover multiple standards. Microstrip patch antennas can be manufactured in large quantities, and easily integrated with microwave integrated circuits, capable of dual and triple frequency operations, mechanically robust when mounted on rigid surfaces. The microstrip antennas are relatively inexpensive at its manufacturing and design is not complex. In order to design a microstrip patch antenna for a cellular handset, a compromise must be reached between antenna dimensions and antenna performance.

3.2 Theoretical Structure

Microstrip antennas, as shown in Fig.3.2, consist of a very thin ($t \ll \lambda_0$, where λ_0 is the free-space wavelength) metallic strip (patch) placed a small fraction of a wavelength ($h \ll \lambda_0$, usually $0.003\lambda_0 \leq h \leq 0.05\lambda_0$) above a ground plane. The microstrip patch is designed so its pattern maximum is normal to the patch. This is accomplished by properly choosing the mode (field configuration) of excitation beneath the patch. End-fire radiation can also be accomplished by judicious mode selection. For a rectangular patch, the length L of the element is usually $\lambda_0/3 < L < \lambda_0/2$.The strip (patch) and the ground plane are separated by a dielectric sheet (referred to as the substrate). There are numerous substrates that can be used for the design of microstrip antennas, and their dielectric constants (ε_r) are usually in the range of $2.2 \leq \varepsilon_r \leq 12$. The ones that are most desirable for good antenna performance are thick substrates whose dielectric constant is in the lower end of the range because they provide better efficiency, larger bandwidth, loosely bound fields for radiation into space, but at the expense of larger element size. Thin substrates with higher dielectric constants are desirable for microwave circuitry because they require tightly bound fields to minimize undesired radiation and coupling, and lead to smaller element sizes.

Since microstrip antennas are often integrated with other microwave circuitry, a compromise has to be reached between good antenna performance and circuit design. Often microstrip antennas are also referred to as patch antennas. The radiating elements and the feed lines are usually photo etched on the dielectric substrate. The radiating patch may be square, rectangular, thin strip (dipole), circular, elliptical, triangular, or any other configuration. Square, rectangular, dipole (strip), and circular are the most common because of ease of analysis and fabrication, and their attractive radiation characteristics, especially low cross-polarization radiation. Linear and circular polarizations can be achieved with either single elements or arrays of microstrip antennas.

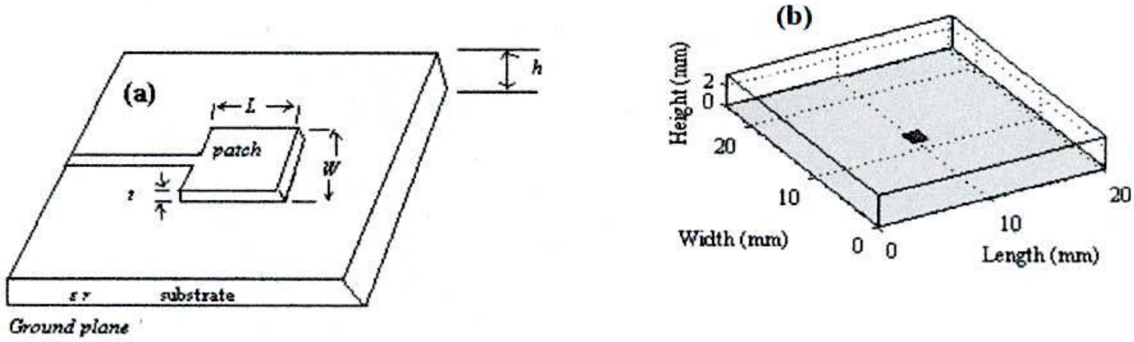


Figure 3.2 Proposed Schematic Rectangular Patch antenna and its Cross sectional view

The patch dimensions can be calculated using the following equations [15].
For the patch width,

$$W = \frac{c}{2f_0\sqrt{\frac{\varepsilon_r + 1}{2}}} \tag{3.1}$$

Where,

c = Constant speed of light in vacuum.

ε_r = Dielectric constant substrate.

f_0 = Operating frequency.

The effective dielectric constant,

$$\varepsilon_{eff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left(1 + 12\frac{h}{W}\right)^{-\frac{1}{2}} \quad \text{if, } \frac{W}{h} > 1 \tag{3.2}$$

The effective length is calculated using,

$$L_{eff} = \frac{c}{Lf_0\sqrt{\varepsilon_{eff}}} \tag{3.3}$$

The two increments in the length, which are generated by the fringing fields, make electrical length slightly larger than the physical length of the patch,

$$\Delta L = 0.412h\frac{(\varepsilon_{eff} + 0.3)\left(\frac{W}{h} + 0.264\right)}{(\varepsilon_{eff} - 0.258)\left(\frac{W}{h} + 0.8\right)} \tag{3.4}$$

The patch length is given by,

$$L = L_{eff} - 2\nabla L \tag{3.5}$$

The length and width of ground plane (and the substrate), L_g and W_g, are,

$$L_g = 6h + L \tag{3.6}$$

$$W_g = 6h + W \tag{3.7}$$

From the above equations, our proposed rectangular antenna has designed. For our proposed antenna the centre frequency, $f_0 = 1.9$ GHz, $\varepsilon_r = 5.3$, $\varepsilon_{eff} = 8.446$, h = 0.80 mm, W = 16.7 mm, L = 26.57mm and GaN (as III-nitride based substrate) has been considered for designing the proposed patch antenna.

3.3 Feeding Technique

Microstrip patch antennas can be fed by a variety of methods. These methods can be classified into two categories- contacting and non-contacting. In the contacting method, the RF power is fed directly to the radiating patch using a connecting element such as a microstrip line. In the non-contacting scheme, electromagnetic field coupling is done to transfer power between the microstrip line and the radiating patch [15]. The four most popular feed techniques used are the microstrip line, coaxial probe (both contacting schemes), aperture coupling and proximity coupling (both non-contacting schemes).

3.3.1 Proximity Coupling

This type of feed technique is also called as the electromagnetic coupling scheme. As shown in Fig.3.3, two dielectric substrates are used such that the feed line is between the two substrates and the radiating patch is on top of the upper substrate. The main advantage of this feed technique is that it eliminates spurious feed radiation and provides very high bandwidth (as high as 13%) [15], due to overall increase in the thickness of the microstrip patch antenna. This scheme also provides choices between two different dielectric media, one for the patch and one for the feed line to optimize the individual performances.

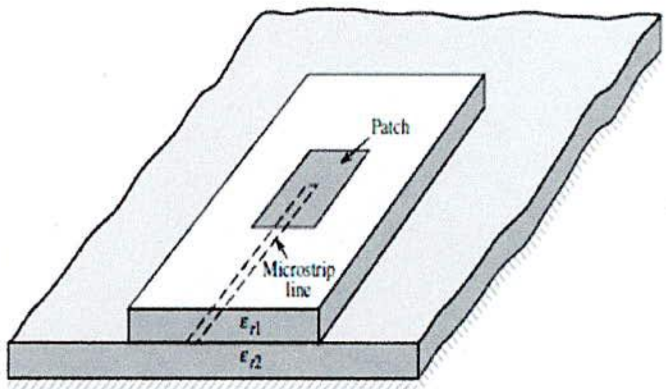


Figure 3.3 Proximity Coupling Feed

3.3.2 Aperture Coupling

In this type of feed technique, the radiating patch and the microstrip feed line is separated by the ground plane as shown in Fig.3.4. Coupling between the patch and the feed line is made through a slot or an aperture in the ground plane.

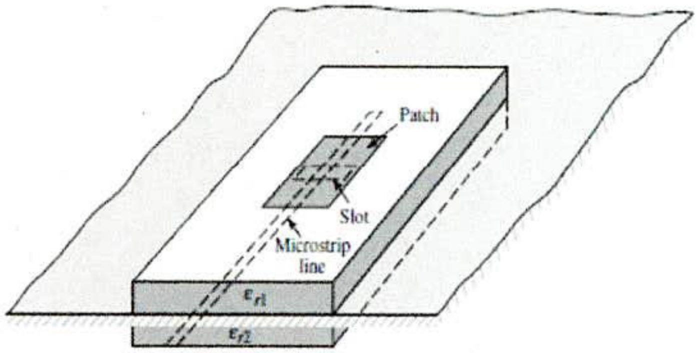


Figure 3.4 Aperture Coupled Feed

The coupling aperture is usually centered under the patch, leading to lower cross polarization due to symmetry of the configuration. The amount of coupling from the feed line to the patch is determined by the shape, size and location of the aperture. Since the ground plane separates the patch and the feed line, spurious radiation is minimized. Generally, a high dielectric material is used for the bottom substrate and a thick, low dielectric constant material is used for the top substrate to optimize radiation from the patch [15]. The major disadvantage of this feed technique is that it is difficult to fabricate due to multiple layers, which also increases the antenna thickness. This feeding scheme also provides narrow bandwidth. Matching can be achieved by controlling the length of the feed line and the width-to-line ratio of the patch. The major disadvantage of this feed scheme is that it is difficult to fabricate because of the two dielectric layers which need proper alignment. Also, there is an increase in the overall thickness of the antenna.

3.3.3 Coaxial Probe Feed

The Coaxial feed or probe feed is a very common technique used for feeding Microstrip patch antennas. As seen from Fig.3.5, the inner conductor of the coaxial connector extends through the dielectric and is soldered to the radiating patch, while the outer conductor is connected to the ground plane.

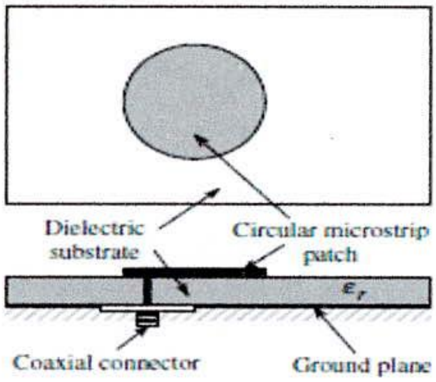


Figure 3.5 Coaxial Probe Feed

The main advantage of this type of feeding scheme is that the feed can be placed at any desired location inside the patch in order to match with its input impedance. This feed method is easy to fabricate and has low spurious radiation. However, its major disadvantage is that it provides narrow bandwidth and is difficult to model since a hole has to be drilled in the substrate and the connector protrudes outside the ground plane, thus not making it completely planar for thick substrates ($h > 0.02\lambda o$). Also, for thicker substrates, the increased probe length makes the input impedance more inductive, leading to matching problems [15]. It is seen above that for a thick dielectric substrate, which provides broad bandwidth, the microstrip line feed and the coaxial feed suffer from numerous disadvantages.

3.3.4 Microstrip Line Feed

In this type of feed technique, a conducting strip is connected directly to the edge of the microstrip patch as shown in Figure 3.6. The conducting strip is smaller in width as compared to the patch and this kind of feed arrangement has the advantage that the feed can be etched on the same substrate to provide a planar structure.

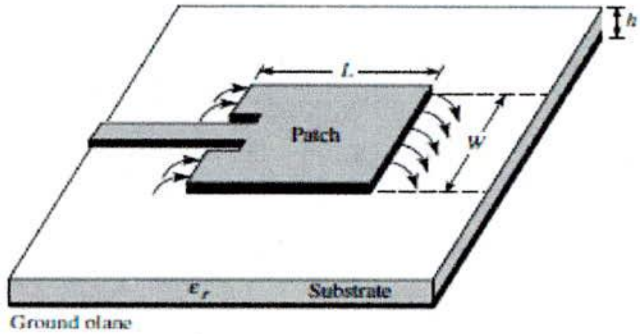


Figure 3.6 Microstrip Line Feed

The purpose of the inset cut in the patch is to match the impedance of the feed line to the patch without the need for any additional matching element. This is achieved by properly controlling the inset position. Hence this is an easy feeding scheme, since it provides ease of fabrication and simplicity in modeling as well as impedance matching.
However as the thickness of the dielectric substrate being used, increases, surface waves and spurious feed radiation also increases, which hampers the bandwidth of the antenna [15]. The feed radiation also leads to undesired cross polarized radiation.

Table 3.1: Comparing the different feed technique

Characteristics	Micro strip Line	Coaxial Feed	Aperture couple Feed	Proximity couple Feed
Spurious feed radiation	More	More	Less	Minimum
Reliability	Better	Poor due to soldering	Good	Good
Ease of fabrication	Easy	Soldering and drilling needed	Alignment	Alignment required
Impedance Matching	Easy	Easy	Easy	Easy
Bandwidth (with impedance matching)	2-5%	2-5%	2-5%	13%

3.4 Transmission Line Model

Transmission Line Model is one of the methods of analysis for microstrip patch antenna. This model represents the microstrip patch antenna by two slots of width W and height h, separated by a transmission line of length L. The microstrip is a non homogeneous line of two dielectrics, typically the substrate and air. Hence, as seen from Fig.3.6, most of the electric field lines reside in the substrate and parts of some lines in air. An effective dielectric constant (ε_{reff}) must be obtained in order to account for the fringing and the wave propagation in the line. The value of ε_{reff} is slightly less then ε_r because the fringing fields around the periphery of the patch are not confined in the dielectric substrate but are also spread in the air as shown in Figure 3.7.

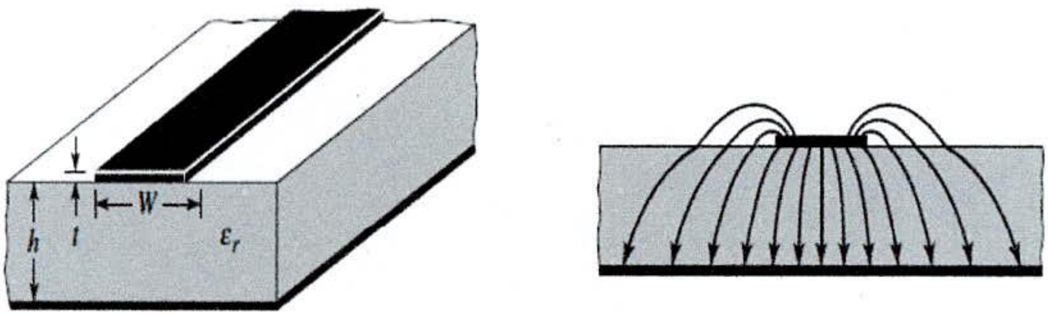


Figure 3.7 Microstrip Feed Line and Electric Field Lines

Consider Fig.3.7, which shows a rectangular microstrip patch antenna of length *L*, width *W* resting on a substrate of height *h*. The co-ordinate axis is selected such that the length is along the *x* direction, width is along the *y* direction and the height is along the *z* direction.

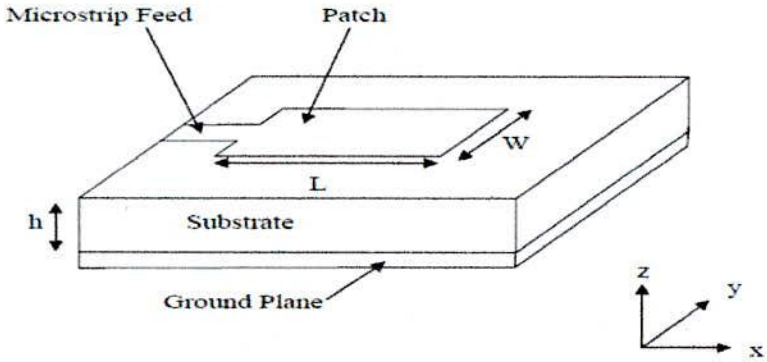


Figure 3.8 Microstrip Patch Antenna

It was indicated earlier that the transmission-line model is the easiest of all but it yields the least accurate results and it lacks the versatility. However, it does shed some physical insight. A rectangular microstrip antenna can be represented as an array of two radiating narrow apertures (slots), each of width W and height h, separated by a distance L. Basically the transmission-line model represents the microstrip antenna by two slots, separated by a low-impedance Z_c transmission line of length L which is shown in Fig.3.8 [15].

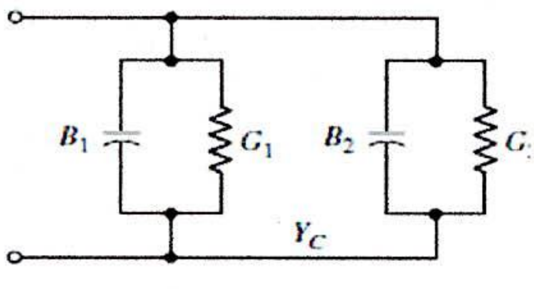
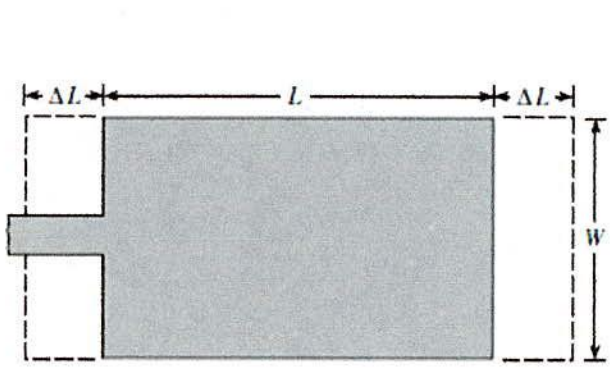


Figure 3.9 Equivalent circuit of Transmission Line- Model



(a)

(b)

Figure 3.10 Top and Side View of Antenna

3.4.1 Fringing Effects

Because the dimensions of the patch are finite along the length and width, the fields at the edges of the patch undergo fringing. This is illustrated along the length in Fig. 3.9(a) and Fig. 3.10(b) for the two radiating slots of the microstrip antenna. The same applies along the width. The amount of fringing is a function of the dimensions of the patch and the height of the substrate. For the principal *E*-plane (*xy*-plane) fringing is a function of the ratio of the length of the patch L to the height h of the substrate (L/h) and the dielectric constant ε_r of the substrate. Since for microstrip antennas $L/h \gg 1$, fringing is reduced; however, it must be taken into account because it influences the resonant frequency of the antenna. The same applies for the width. As most of the electric field lines reside in the substrate and parts of some lines exist in air. As $W/h \gg 1$ and $\varepsilon r \gg 1$, the electric field lines concentrate mostly in the substrate. Fringing in this case makes the microstrip line look wider electrically compared to its physical dimensions.

Since some of the waves travel in the substrate and some in air, an effective dielectric constant ε_{eff} is introduced to account for fringing and the wave propagation in the line. To introduce the effective dielectric constant, let us assume that the center conductor of the microstrip line with its original dimensions and height above the ground plane is embedded into one dielectric. The effective dielectric constant is defined as the dielectric constant of the uniform dielectric material so that the line has identical electrical characteristics, particularly propagation constant, as the actual line. For a line with air above the substrate, the effective dielectric constant has values in the range of $1 < \varepsilon_{eff} > \varepsilon_r$. For most applications where the dielectric constant of the substrate is much greater than unity ($\varepsilon_r >> 1$) the value of ε_{eff} will be closer to the value of the actual dielectric constant ε_r of the substrate. The effective dielectric constant is also a function of frequency. As the frequency of operation increases, most of the electric field lines concentrate in the substrate. Therefore the microstrip line behaves more like a homogeneous line of one dielectric (only the substrate), and the effective dielectric constant approaches the value of the dielectric constant of the substrate. For low frequencies the effective dielectric constant is essentially constant. At intermediate frequencies its values begin to monotonically increase and eventually approach the values of the dielectric constant of the substrate.

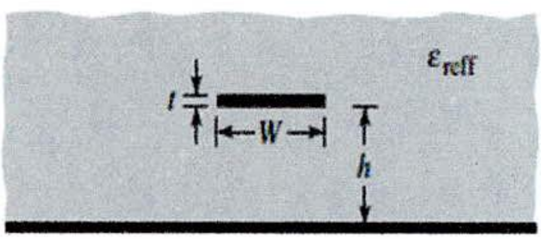


Figure 3.11 Effective dielectric constant

The initial values (at low frequencies) of the effective dielectric constant are referred to as the static values, and they are given by [21],

$$\varepsilon_{reff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left[1 + 12\frac{h}{W}\right]^{-1/2} \qquad \text{when, } W/h >> 1 \qquad (3.8)$$

Because of the fringing effects, electrically the patch of the microstrip antenna looks greater than its physical dimensions. For the principal *E*-plane (*xy*-plane), where the dimensions of the patch along its length have been extended on each end by a distance ΔL, which is a function of the effective dielectric constant ε_{eff} and the width-to-height ratio (W/h). A very popular and practical approximate relation for the normalized extension of the length is,

$$\frac{\Delta L}{h} = 0.412 \frac{(\varepsilon_{eff} + 0.3)\left(\frac{W}{h} + 0.264\right)}{(\varepsilon_{eff} - 0.258)\left(\frac{W}{h} + 0.8\right)} \tag{3.9}$$

Since the length of the patch has been extended by ΔL on each side, the effective length of the patch is now ($L = \lambda/2$ for dominant TM_{010} mode with no fringing),

$$L_{eff} = L + 2\Delta L \tag{3.10}$$

For the dominant TM_{010} mode, the resonant frequency of the microstrip antenna is a function of its length. Usually it is given by,

$$(f_r)_{010} = \frac{1}{2L\sqrt{\varepsilon_r}\sqrt{\mu_0 \varepsilon_0}} = \frac{v_0}{2L\sqrt{\varepsilon_r}} \tag{3.11}$$

Where, υ_0 is the speed of light in free space.

Since does not account for fringing, it must be modified to include edge effects and should be computed using,

$$(f_r)_{010} = \frac{1}{2L\sqrt{\varepsilon_r}\sqrt{\mu_0 \varepsilon_0}} = \frac{v_0}{2L\sqrt{\varepsilon_r}} = q \frac{1}{2L\sqrt{\varepsilon_r}\sqrt{\mu_0 \varepsilon_0}} = q \frac{v_0}{2L\sqrt{\varepsilon_r}} \tag{3.12}$$

Where,

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

The q factor is referred to as the fringe factor (length reduction factor). As the substrate height increases, fringing also increases and leads to larger separations between the radiating edges and lower resonant frequencies.

CHAPTER IV

III-Nitride Substrates Based Rectangular Microstrip Patch Antenna

In this chapter, commercial and III-Nitride substrate based rectangular Microstrip Patch Antennas (MPA) are theoretically designed with their analysis. Then simulation models are made by Ansoft HFSS and discussed their performance parameters.

4.1 Introduction

The input impedance (Z_i) and voltage standing wave ratio (VSWR) are the key parameter to analyze the antenna performance such as return loss (RL), bandwidth (BW), radiation pattern, directivity, gain, and efficiency. In this chapter, commercial substrates (Taconic, Rogers & FR-4) and III-Nitride (InN, AlN & GaN) based rectangular micro strip patch antennas (MPA) have been theoretically designed and evaluated their performances using Ansoft High Frequency Structure Simulator (HFSS).

4.2 Theoretical Design of MPA and Analysis

Theoretical design of MPA includes the calculation of different design parameters like effective dielectric constant (ε_{reff}), effective length (L_{eff}) & delta length (ΔL) to get the actual length (L) and width (W) of rectangular micro strip patch antenna (MPA). Subsequently the dimension (Lg & Wg) of ground plane is also calculated. Equations 3.1 to 3.7 are used from chapter 3 to get these values, where constant speed of light in vacuum (c) = 3 x 10^8 m/s, operating frequency (f_0) = 1.9 GHz and height (h) = 0.8 mm are same for all substrates. Only dielectric const (ε_r) and height value is used as the value of individual substrate. It is to be mentioned here that I have used the value of f_0=1.9 GHz & h=0.8 mm and rectangular shape MPAs are designed as those are normally used in RF or mobile applications. Analysis of each design is also carried out. During design of different MPAs, feeding technique has been used as micro strip line feed due to its easy feeding scheme. Since it provides ease of fabrication and simplicity in modeling as well as impedance matching. Transmission line model is used for the perfect matching of MPA. This model represents the micro strip patch antenna by two slots of width and height, separated by a transmission line. A quarter wave ($\lambda/4$) transformer is also used for perfect impedance matching. A commercial design assistant named as appCAD shown in figure 4.1 is made by Avago Technologies. This may be used to calculate different microstrip parameters which is also found from simulation or some prescribed formula [15].

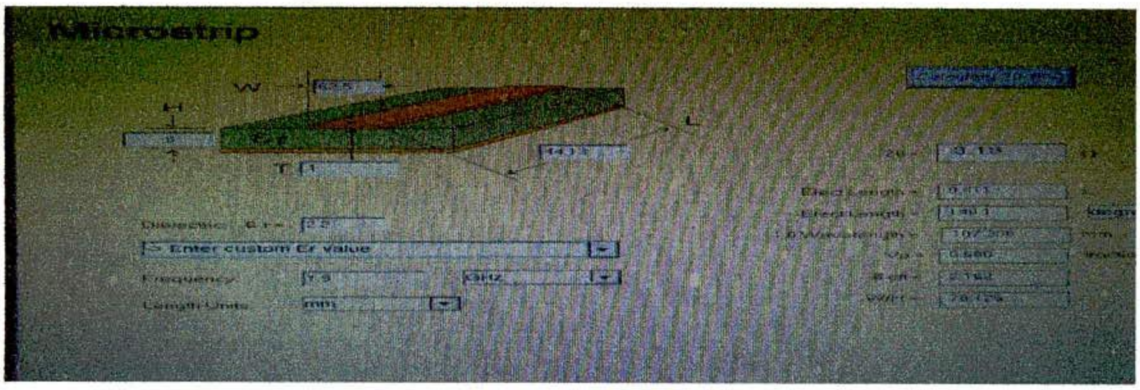


Figure 4.1: AppCad

4.2.1 Commercial Substrates

Taconic, Rogers and FR-4 have been used as commercial substrates. These are commonly used in microwave and RF applications due to cost effective and reliable substrates for long life performance of antenna. However MPAs are designed in this work theoretically using those commercially available substrates.

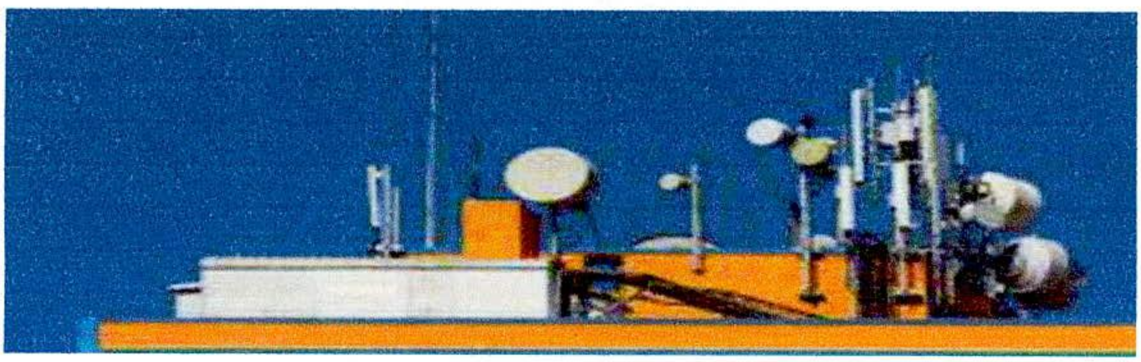


Figure 4.2: Microwave and RF applications

4.2.1.1 Taconic

Taconic is a commercial substrate used in RF applications having different values of dielectric constant. Here initially the lower value of dielectric constant (ε_r) or relative permittivity is selected as 2.2, whose type is TLY(tm) & dielectric loss tangent = 0.0009. So design parameters of MPA are :

a. Width, $W = \dfrac{c}{2f_0\sqrt{\dfrac{\varepsilon_r + 1}{2}}}$ = 62.5mm

b. The effective dielectric constant, $\varepsilon_{eff} = \dfrac{\varepsilon_r + 1}{2} + \dfrac{\varepsilon_r - 1}{2}\left(1 + 12\dfrac{h}{W}\right)^{-\frac{1}{2}}$ = 3.0896

c. The effective length, $L_{eff} = \dfrac{c}{2f_0\sqrt{\varepsilon_{eff}}}$ = 44.91mm

d. The increment of length, $\Delta L = 0.412h\dfrac{(\varepsilon_{eff} + 0.3)\left(\dfrac{W}{h} + 0.264\right)}{(\varepsilon_{eff} - 0.258)\left(\dfrac{W}{h} + 0.8\right)}$ =0.3918mm

e. The actual patch length, L= L_{eff} - 2 ΔL = 44.13mm

f. The length of ground plane, Lg = 6h + L = 6 x 0.8 + 44.13 = 48.93mm

g. The width of ground plane, Wg = 6h + W = 6 x 0.8 + 62.5 = 67.3mm

h. The width of feed and transmission line are calculated by App Cad calculator as 3.14 mm and 0.78 mm respectively.

4.2.1.2 Rogers

Rogers is widely used in many applications. But it has high performance in RF applications. Though it has got different values of dielectric constant, but initially here the lower value of dielectric constant (ε_r) or relative permittivity is selected i.e. ε_r = 2.2 & dielectric loss tangent = 0.0009 same as Taconic whose type is Rogers RT/duroid 5880(tm). So design parameters of MPA are also same with Taconic as follows:

a. Width, W= 62.5mm

b. The effective dielectric constant, ε_{eff} = 3.0896

c. The effective length, L_{eff}= 44.91mm

d. The increment of length, ΔL =0.3918mm

e. The actual patch length, $L = L_{eff} - 2\,\Delta L$ = 44.13mm

f. The length of ground plane, Lg = 6h + L = 6 x 0.8 + 44.13 = 48.93mm

g. The width of ground plane, Wg = 6h + W = 6 x 0.8 + 62.5 = 67.3mm

h. The width of feed and transmission line are 3.14 mm and 0.78mm respectively.

4.2.1.3 FR-4

FR-4 substrates are also used in many microwave & RF applications. Recently square patch antenna has been designed with this substrate. However, it has only one value of dielectric constant (ε_r) or relative permittivity of 4.4 & dielectric loss tangent = 0.02. It's type is FR-4_epoxy project material. So design parameters of MPA are calculated with previous equations as follows:

a. Width, W= 48.04mm

b. The effective dielectric constant, ε_{eff} = 2.8

c. The effective length, L_{eff}= 47.18mm

d. The increment of length, ΔL =0.398mm

e. The patch length, $L = L_{eff} - 2\,\Delta L$ = 46.38mm

f. The length of ground plane, Lg = 6h + L = 6 x 0.8 + 46.38 = 51.18mm

g. The width of ground plane, Wg = 6h + W = 6 x 0.8 + 48.04 = 52.84mm.

h. The width of feed and transmission line are 2.89 mm 0.72mm respectively.

4.2.1.4 Analysis for Commercial Substrates

Above commercial substrates are analyzed and main design parameters are accumulated in following table.

Table 4.1 : Theoretical design parameters for commercial substrates

Name of Substrate	ε_r	Calculated patch size(LxW)mm	Feed line width(mm)	Transmission line width(mm)	Ground plane size(LxW)mm
Teconic	2.2	44.13x62.5	3.14	0.78	48.93x67.3
Rogers	2.2	44.13x62.5	3.14	0.78	48.93x67.3
FR-4	4.4	46.38x48.04	2.89	0.72	51.18x52.84

a. Patch size is larger. It may be reduced increasing the value of ε_r for Taconic & Rogers. For FR=4 only patch size may be optimized.
b. Very high or very low width/height ratio may affect the accuracy of antenna matching which may be increased optimizing the value of patch width.
c. Width of feed line may be optimized for perfect impedance matching, length of the substrate and size of ground plane may be increased for better antenna performance parameters.
d. Putting the quarter wave transmission line between patch and feed line may be the better option for good antenna matching.

4.2.2 III- Nitride Substrates

MPAs are designed theoretically using following III-Nitride substrates.

4.2.2.1 Indium Nitride (InN)

For InN, the value of dielectric constant (ε_r) or relative permittivity is 8.4, density = 6.81 gm/cc & dielectric loss tangent = 0.001. So design parameters of MPA are calculated as follows:

a. Width, W= 16.7mm
b. The effective dielectric constant, ε_{eff} = 8.446
c. The effective length, L_{eff}= 27.16mm
d. The increment of length, ΔL =0.343mm
e. The patch length, $L= L_{eff} - 2\,\Delta L = 26.57$mm
f. The length of ground plane, Lg = 6h + L = 6 x 0.8 + 26.57 = 31.37mm
g. The width of ground plane, Wg = 6h + W = 6 x 0.8 + 16.7 = 21.5mm
h. The width of feed and transmission line are 5.67 mm and 1.41mm respectively.

4.2.2.2 Aluminium Nitride(AlN)

For AlN, the value of dielectric constant (ε_r) or relative permittivity = 8.8, density = 3.26 gm/cc, thermal conductivity = 140-180 W/m•k, hardness = 1100 kg/mm^2 & dielectric loss tangent = 0. So design parameters are calculated with previous equations as follows:

a. Width, W= 35.67mm

b. The effective dielectric constant, ε_{eff} = 9.25
c. The effective length, L_{eff}= 25.96mm
d. The increment of length, ΔL =0.345mm
e. The patch length, L= L_{eff} - 2 ΔL = 25.26mm
f. The length of ground plane, Lg = 6h + L = 6 x 0.8 + 25.26 = 30.06mm
g. The width of ground plane, Wg = 6h + W = 6 x 0.8 + 35.67 =40.47 mm.
h. The width of feed and transmission line are calculated by App Cad calculator i.e.2.75 mm and 0.69mm respectively.

4.2.2.3 Galium Nitride (GaN)

For GaN, the value of dielectric constant (ε_r) = 5.3(for high temp), density = 6.15 gm/cc, relative permeability = 1 & dielectric loss tangent = 0. So design parameters are calculated as follows:

a. Width, W= 44.48mm
b. The effective dielectric constant, ε_{eff} = 6.007
c. The effective length, L_{eff}= 32.23mm
d. The increment of length, ΔL =0.36mm
e. The patch length, L= L_{eff} - 2 ΔL = 31.58mm
f. The length of ground plane, Lg = 6h + L = 6 x 0.8 + 31.58 = 36.38mm
g. The width of ground plane, Wg = 6h + W = 6 x 0.8 + 44.48 = 49.28 mm
h. The width of feed and transmission line are 2.84 mm and 0.71mm respectively.

4.2.2.4 Analysis for III- Nitride Substrates

Considering the above calculations, III-Nitride substrates are analyzed and main design parameters are accumulated in following table.

Table 4.2 : Theoretical design parameters for III-Nitride substrates

Name of Substrate	ε_r	Calculated patch size(LxW)mm	Feed line width(mm)	Transmission line width(mm)	Ground plane size(LxW)mm
InN	8.4	26.57x16.7	5.67	1.41	31.37x21.5
AlN	8.8	25.26x35.67	2.75	0.69	30.06x40.47
GaN	5.3	31.58x44.48	2.84	0.71	36.38x49.28

a. Patch size is smaller for InN & AlN. But the size of GaN is comparatively larger. It may be reduced by optimizatio.
b. Feed line width is found smaller than that of commercial substrates. For perfect impedance matching, length of the substrate and size of ground plane may be increased than minimum value which should not have any effect.
c. Putting the quarter wave transmission line between patch and feed line may be the better option for good antenna matching.

4.3 Simulations

An application software Ansoft HFSS (High Frequency Structure Simulator) is used for simulations. Many researchers found that it is the most precise antenna simulation software. Antenna performance parameters are simulated in detail. Validation check of design setting, mesh operation, analysis set up, radiation etc are carried out systematically. All results or data are analyzed very sincerely with this software. By using Ansoft HFSS simulation software, all design parameters or calculated data from section 4.2.1 are inputed into simulation model for following commercial and III-nitride substrates. For perfect impedance matching, size of ground plane and vacuum are increased upto 100x90 mm and 110x98 mm in simulation model respectively. And then necessary optimization for the size of patch, feed, transmission line etc are carried out for getting best result. Figure 4.3 shows the layout for Ansoft HFSS.

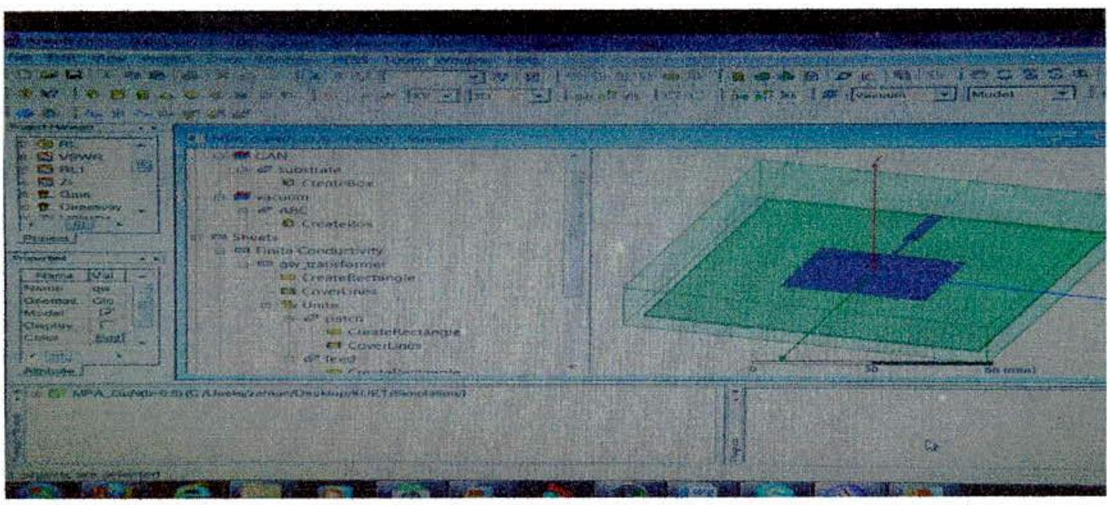


Figure 4.3: Layout of Ansoft HFSS

4.3.1 Simulation Model for Commercial substrates based MPAs

4.3.1.1 Taconic

First of all, I put the calculated data in simulation model and it shows the peak value of VSWR and R_L as 3.329 and -36.92 dB respectively at $f_0 =$ 3.4 GHz. Here VSWR value is out of range which should be approx unity for the perfect matching. And f_0 must be around 1.9 GHz (operating freq). Now as per design analysis, the value of ε_r is increased upto maximum value for Taconic substrate. As a result patch sizes are reduced satisfactorily in calculation, but simulation models do not show any better performance result of VSWR, RL etc. Then width of patch is optimized at 52.5mm and performance parameters are found from simulation model as VSWR=1.53 & RL -13.534dB respectively at $f_0 = 2.21$ GHz. Now again for reducing f_0 to set 1.9 GHz , patch size is increased and at same time other values are change like VSWR = 1.93, RL = -4.26 etc. Finally patch size becomes 52.13x70mm shown in simulation model below.

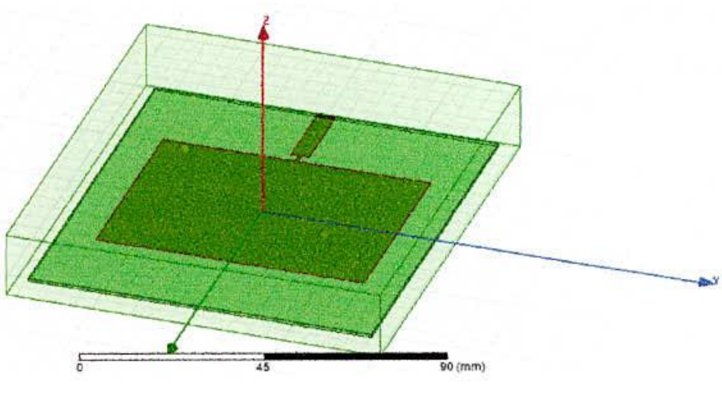


Figure 4.4: Simulation model of Taconic substrate based MPA

4.3.1.2 Rogers

Putting the calculated data in simulation model, I get the peak value of VSWR and RL as 2.63 at 2.46 GHz and -4.2dB at 3.62 GHz respectively. Here VSWR value is out of range which should be approx unity for the perfect matching. And f_0 must be around 1.9 GHz (set operating freq). Now as per design analysis, the value of ε_r is increased upto maximum value. Patch sizes are reduced satisfactorily in calculation, but simulation models do not show any better performance result of VSWR, RL etc. After necessary optimization simulation model shows the peak value of VSWR=1.18 & RL = -13.534 dB respectively at f_0 = 2.22 GHz. Now for setting f_0 = 1.9 GHz, patch size is increased and other values are also changed as VSWR = 2.08, RL = -9.65 dB etc. Finally patch size becomes 52.13x70.5 mm shown in simulation model below.

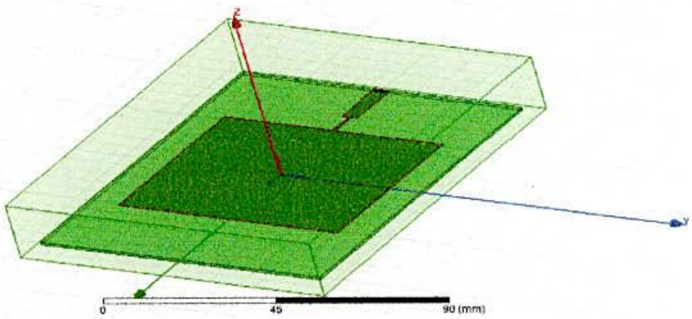


Figure 4.5: Simulation model of Rogers substrate based MPA

4.3.1.3 FR-4

Putting the calculated data in simulation model, it shows the peak value of VSWR and RL as 0.8 at 1.52 GHz and - 28dB at 1.5 GHz respectively. Here VSWR value is within the range. But f_0 must be around 1.9 GHz (set operating freq). Now as per design analysis, the patch size is optimized to increase the f_0 at 1.9 GHz. After necessary optimization simulation model shows VSWR=1.56 & RL = -13.18dB respectively at f_0 = 1.9 GHz. Now patch size is reduced and becomes 38x26mm shown in simulation model below.

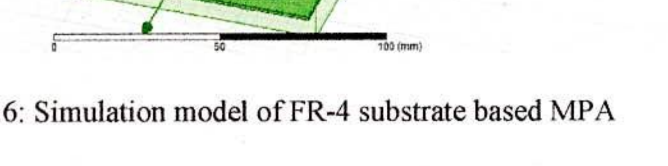


Figure 4.6: Simulation model of FR-4 substrate based MPA

4.3.2 Simulation Model for III-Nitride substrates based MPAs

4.3.2.1 InN

Putting the calculated data in simulation model, it shows the peak value of VSWR and RL as 3.82 and -4.5dB respectively at $f_0 =$ 1.88 GHz. Here VSWR value is out of range which should be approx unity for the perfect matching, R_L value should be around -20dB and f_0 must be around 1.9 GHz(set operating freq). Now width of patch & feed are optimized at 22mm & 4.84mm. Finally patch size becomes 26.57x22mm shown in simulation model below.

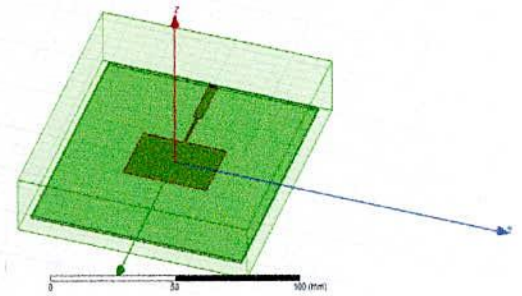


Figure 4.7: Simulation model of InN substrate based MPA

4.3.2.2 AlN

Putting the calculated data in simulation model, I get the peak value of VSWR and RL as 2.04 and -11.34dB respectively at $f_0 = 1.92$ GHz. Here VSWR, RL & f_0 values are comparatively better. Then fine tuning gives the values more accurate. Finally patch size becomes 25.5x35.5mm shown in simulation model below.

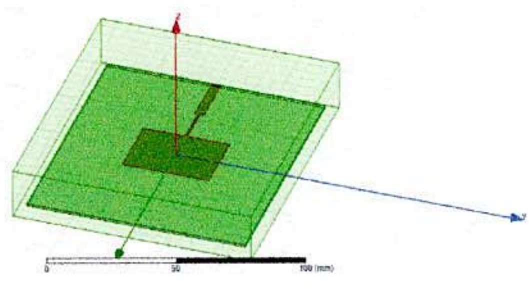


Figure 4.8: Simulation model of AlN substrate based MPA

4.3.2.3 GaN

Putting the calculated data in simulation model, I get the peak value of VSWR and RL as 1.16 and -22.36dB respectively at $f_0 = 1.965$ GHz. Here VSWR & RL values are absolutely perfect. But f_0 should be 1.9 GHz. Then fine tuning of air boundary and patch size optimization give the best results. Finally patch size becomes 33.5x38 mm shown in simulation model below.

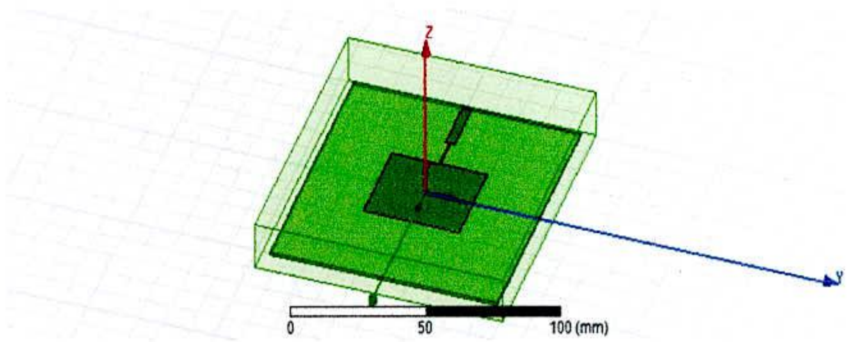


Figure 4.9: Simulation model of GaN substrate based MPA

CHAPTER V

Results and Discussions

In this chapter simulation results of Microstrip patch antenna (MPA) models are discussed and the substrate with best result is proposed to use in MPA design.

5.1 Introduction

Theoretical design provides the dimension of patch, ground plane and related feed or transmission lines which are applied in simulation models. Then the results of various performance parameters and wave shapes are produced through the simulation process of Ansoft HFSS. In this chapter those results are compiled and discussed.

5.2 Simulation Results

From simulation models of different substrates, the recorded simulation results are shown below separately & also combined for commercial substrates & III-nitride substrates.

5.2.1 Commercial Substrates

Simulation results (final) for Taconic, Rogers & FR-4 are recorded in following table and necessary curves & figures are shown accordingly.

Table 5.1 : Simulation results for commercial substrates

Name of Substrate	ε_r	patch size (LxW) mm	Z_i Ω	VSWR	RL dB	f_0 GHz	BW MHz	ή (%)
Taconic	2.2	52.13x70	52.89	4.15	-4.26	1.92	140	85.2
Rogers	2.2	52.13x70.5	46.91	2.08	-9.65	1.9	120	81.2
FR-4	4.4	38x26	41.72	1.56	-13.18	1.89	70	19.78

a. Zi

Input impedance (Zi) is an important parameter for antenna. It is the impedance presented by the antenna at its terminals. Zi is having two parts, real and imaginary. The real or resistive part, R_{in} again consists of two components, the radiation resistance R_R and the loss resistance R_L. The power associated with R_R is the power actually radiated by the antenna, while the power dissipated in the R_L is lost as heat in the antenna itself due to dielectric or conducting losses. The imaginary part, X_{in} of the input impedance represents the power stored in the near field of the antenna. As such, input impedance (Real part) vs operating frequency (f_0) curves for commercial substrates are shown in figure 5.1.

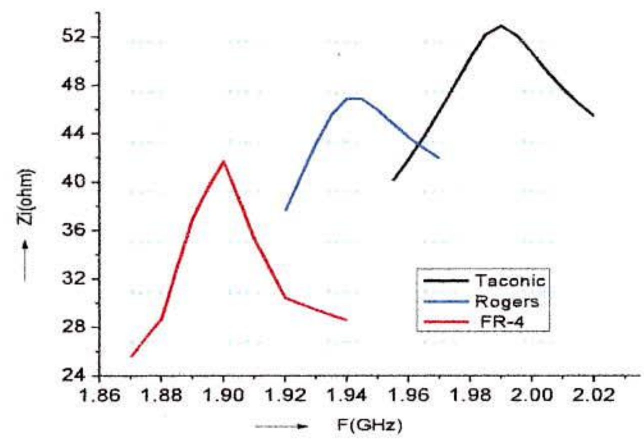


Figure 5.1: Input impedance for commercial substrates

The input impedance (peak value) are found 52.89 Ω at 1.99 GHz, 46.91 Ω at 1.94 GHz and 41.72 Ω at 1.9 GHz respectively for Taconic, Rogers and FR-4. Values of Taconic & Rogers are approximately equals to standard value i.e. 50 ohm, but operating frequencies are not around 1.9 GHz. Value of FR-4 is in little far away, but its operating frequency is perfect.

b. VSWR

Voltage standing wave ratio (VSWR) is the key parameter to analyze the antenna performance. The minimum VSWR which corresponds to a perfect match is unity. As such, VSWR vs operating frequency (f_0) curves for commercial substrates are shown in figure 5.2. The calculated minimum values of VSWR are 4.15, 2.08, 1.56 respectively for Taconic, Rogers and FR-4. Here FR-4 is the best one to accept.

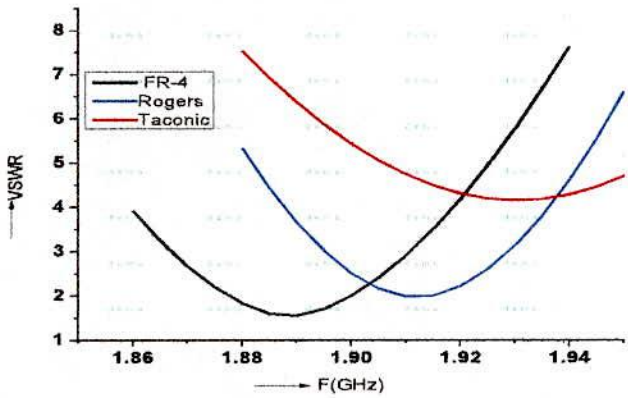


Figure 5.2: VSWR for commercial substrates

c. RL

The peak values of return loss (RL) are found -4.26 dB,-9.65 dB, and -13.18 dB respectively for Taconic, Rogers and FR-4 from figure 5.3 (RL vs frequency curve). Here again the peak value of RL for FR-4 is better than others.

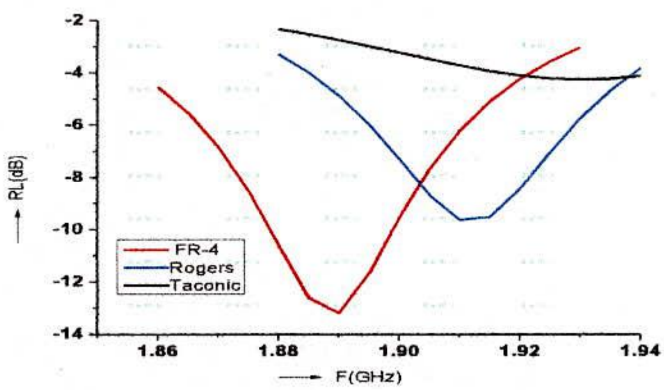
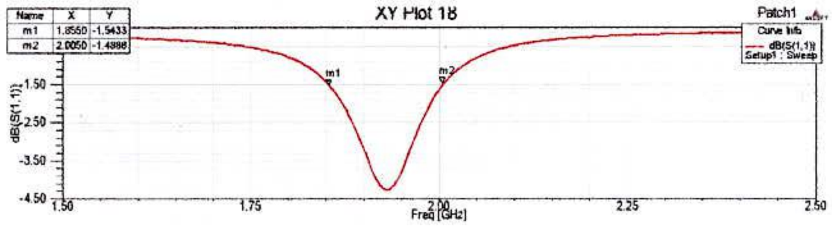


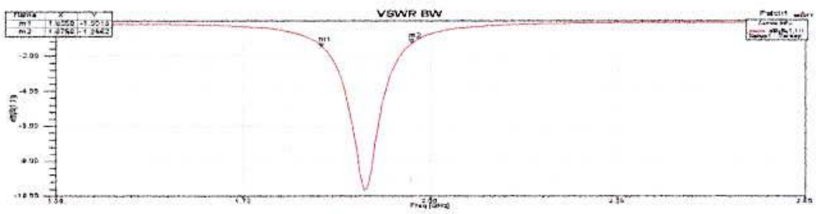
Figure 5.3 RL for commercial substrates

d. BW

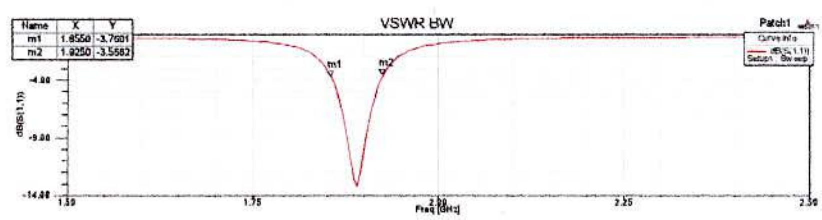
Bandwidth is a limitation for MPA. Generally this type of antenna possess narrow bandwidth. This limitation has been overcome in some cases. However, bandwidth measurement for commercial substrates are shown in figure 5.4.



BW for Taconic=2005-1855=140MHz



BW for Rogers = 1975-1855=120MHZ



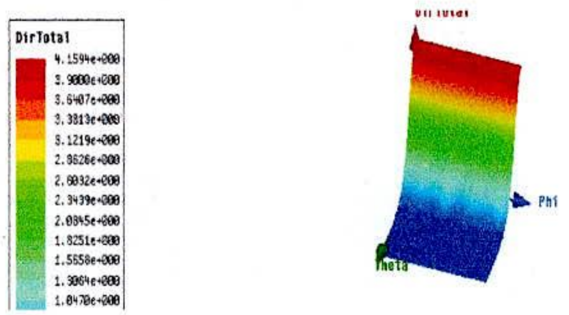
BW for FR-4 = 1925-1855= 70MHz

Figure 5.4: Bandwidth measurement for commercial substrates

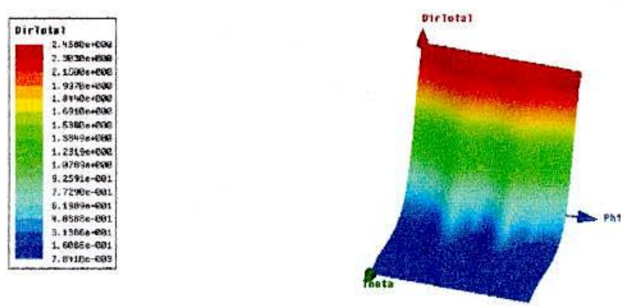
The bandwidth is found 140MHz, 120MHz and 70MHz respectively for Taconic, Rogers and FR-4. These values may be accepted.

e. Directivity

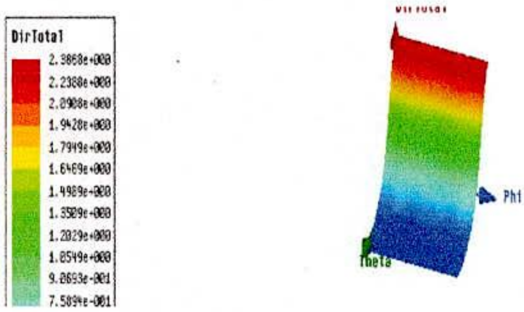
It is the ratio of radiation intensity in the given direction from the antenna to the radiation intensity averaged over all direction. Rectangular microstrip patch antenna and ground plane radiating slots form a broadside radiation pattern in the principal E-plane ($\theta = 90^{0}$) and H-plane ($\varphi = 0$). However total directivity for commercial substrates are shown in figure 5.5 (Rectangular plots).



Directivity for Taconic (Ratio = 4.16)



Directivity for Rogers (Ratio = 2.45)



Directivity for FR-4 (Ratio = 2.38)

Figure 5.5: Directivity for commercial substrates

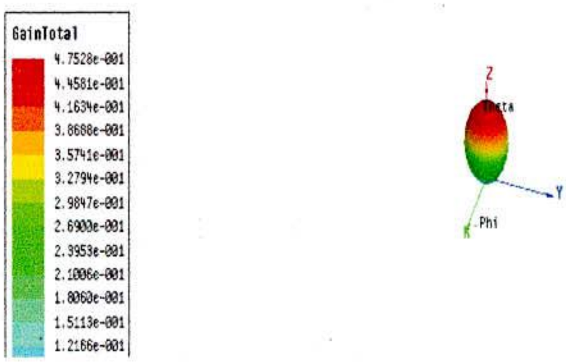
The total directivity is found in 'z' (upper) direction which is red color shown in Fig.5.5. The prescribed ratios are 4.16, 2.45 and 2.38 respectively for Taconic, Rogers and FR-4. Here Taconic substrate shows the maximum antenna radiation.

f. Gain

It is closely related to the directivity of an antenna. Gain does not include losses arising from impedance and polarisation mismatch. The gain is the amount of power that can be achieved in one direction at the expense of the power lost in the others. The gain is always related to the main lobe and is specified in the direction of maximum radiation unless indicated. However total gain for commercial substrates are shown in figure 5.5 (polar plots).

Gain for Taconic (Ratio = 3.5)

Gain for Rogers (Ratio = 3.54)



Gain for FR-4 (Ratio = 4.75)

Figure 5.6 : Gain for commercial substrates

The total gain is found in 'z' (upper) direction which is red color shown in Fig.5.6. The prescribed ratios of power are 3.5, 3.54 and 4.75 respectively for Taconic, Rogers and FR-4 Here antenna Gain for FR-4 substrate is higher than other two.

5.2.2 III-Nitride Substrates

III-Nitride substrates are considered with their available physical parameters like relative permeability, density, thermal conductivity etc in addition to dielectric constant. However simulation results for InN, AlN & GaN are recorded in following table and curves:

Table 5.2: Simulation results for III-Nitride substrates

Name of Substrate	ε_r	patch size(LxW)mm	Z_i Ω	VSWR	RL dB	f_0 GHz	BW MHz	ή (%)
InN	8.4	26.57x22	47.52	2.5	-13.51	1.91	75	72.8
AlN	8.8	25.5x35.5	49.15	2.2	-11.45	1.915	85	80.6
GaN	5.3	33.5x38	50.06	1.11	- 25.31	1.91	100	87.5

a. Zi

Input impedance vs operating frequency (f_0) curves for III-Nitride substrates are simulated by using Ansoft HFSS (High Frequency Structure Simulator) which are shown in figure 5.7.

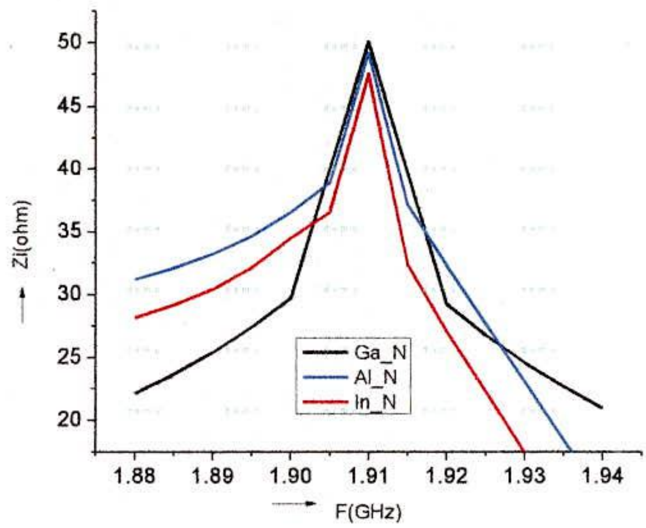


Figure 5.7: Input impedance for III-Nitride substrates

The input impedance are found 47.52 Ω, 49.15 Ω and 50.06 Ω respectively for InN, AlN and GaN shown in Fig. 5.7 at the centre frequency 1.9 GHz.

b. VSWR

Voltage standing wave ratio (VSWR) is the key parameter to analyze the antenna performance. As such, VSWR vs operating frequency (f_0) curves for III-Nitride substrates are shown in figure 5.8.

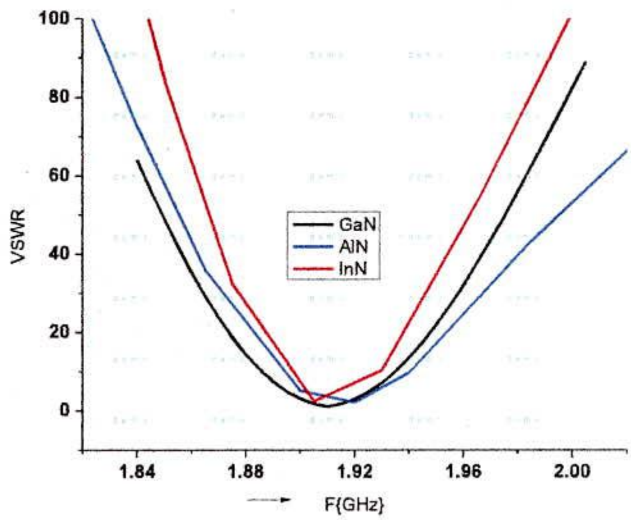


Figure 5.8: VSWR for III-Nitride substrates

The minimum VSWR which corresponds to a perfect match is unity. The calculated values of VSWR are 2.5, 2.2, 1.11 respectively for InN, AlN and GaN which is shown in Fig. 5.8. Here the value of GaN is more accurate.

c. RL

Return loss (RL) is an important performance parameter of antenna. Peak values of RL are calculated from simulation. The calculated value of *RL* is good agreement with the reported values for the conventional wireless antennas. GaN gives the best result within all the substrates simulated . As such, RL vs f_0 curves for III-Nitride substrates are simulated by using Ansoft HFSS which are shown in figure 5.9.

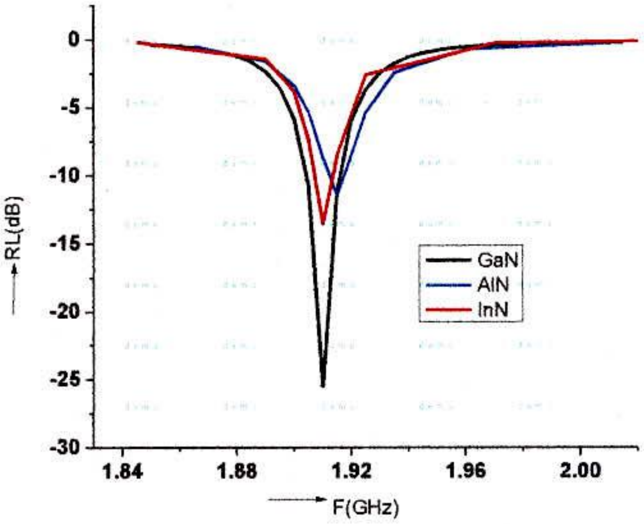
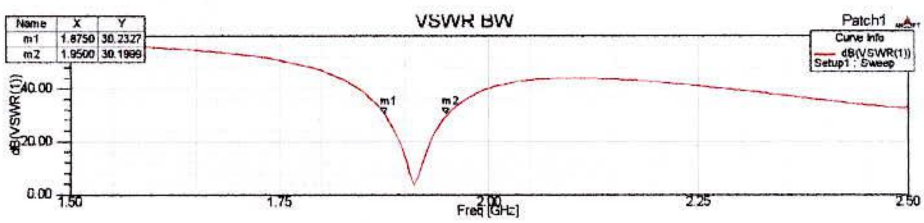


Figure 5.9: RL for III-Nitride substrate

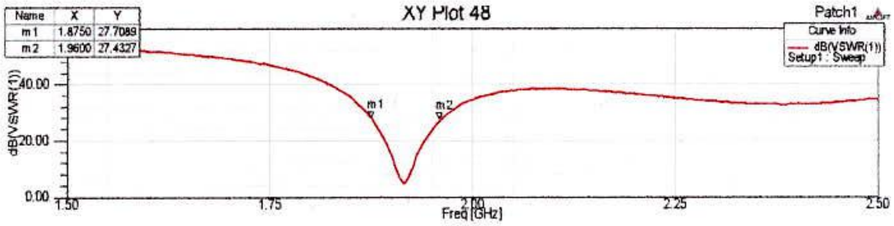
The return loss (peak value) is found -13.51 dB,-11.45dB, and -25.31dB at centre frequency 1.9 GHz shown in Fig.5.9 respectively for InN, AlN and GaN.

d. BW

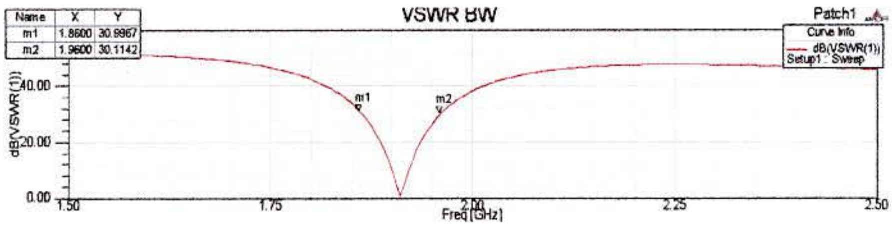
Bandwidth for III-Nitride substrates are calculated and shown in figure 5.10.



InN = 1950-1875 = 75 MHz.



AlN = 1960-1875= 85 MHz.



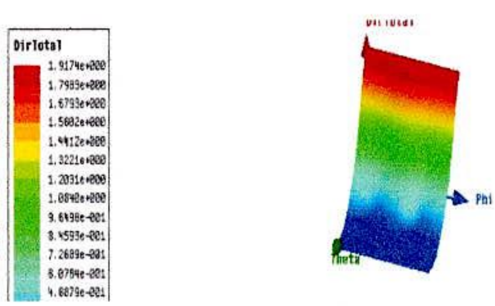
GaN= 1960-1860 =100 MHz

Figure 5.10: Bandwidth measurement for III-Nitride substrates

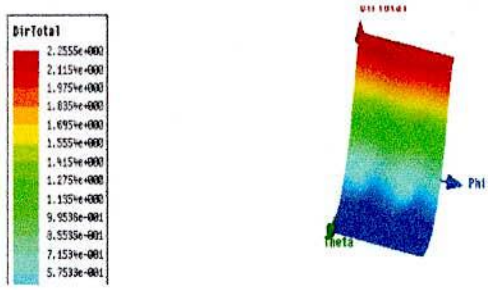
The bandwidth is found 75MHz, 85MHz and 100MHz respectively for InN, AlN and GaN centered at 1.9 GHz which is shown in Fig.5.10. These values may be acceptable.

e. Directivity

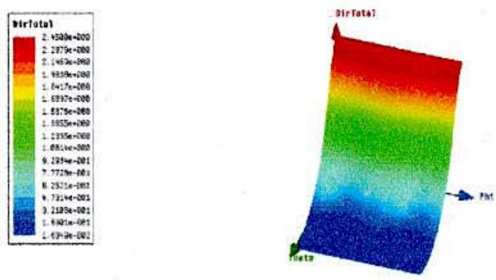
It is the ratio of radiation intensity in the given direction from the antenna to the radiation intensity averaged over all direction. Directivity for III-Nitride substrates are shown in figure 5.11(Rectangular plots).



Directivity for InN (Ratio = 1.92)



Directivity for AlN (Ratio = 2.25)



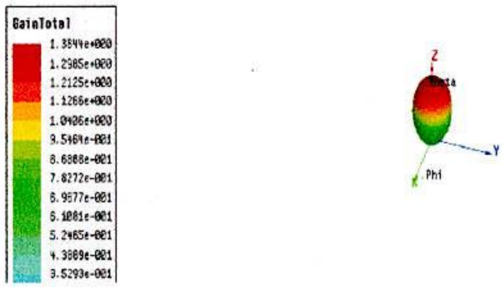
Directivity for GaN (Ratio = 2.45)

Figure 5.11: Directivity for III-Nitride substrates

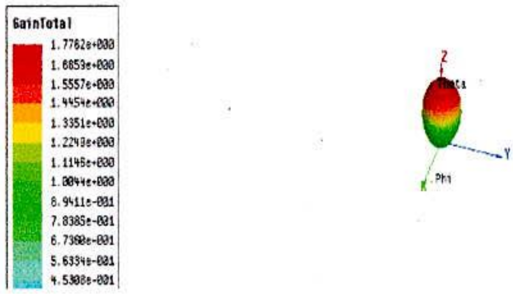
The total directivity is found in 'z' (upper) direction which is red color shown in Fig.5.11. The prescribed ratios are 1.92, 2.25 and 2.45 respectively for InN, AlN and GaN. Here performance of GaN is the best one.

f. Gain

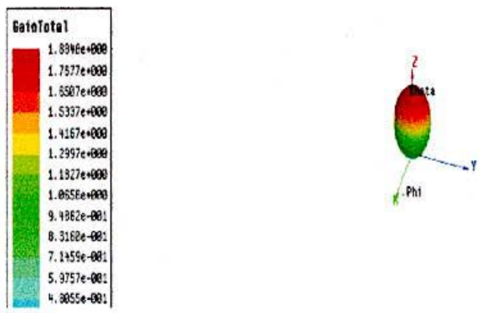
Antenna gain is a parameter which is closely related to the directivity of the antenna. The gain of patch antennas has been the goal of many researchers. The total gain of antenna is shown in figure 5.12 (polar plots) for III-Nitride substrates.



Gain for InN (Ratio = 1.38)



Gain for AlN (Ratio = 1.77)



Gain for GaN (Ratio = 1.88)

Figure 5.12 : Gain for III-Nitride substrates

The total gain is found in 'z' (upper) direction which is red color shown in Fig.5.12. The prescribed power ratios are1.38, 1.77 and 1.88 respectively for InN, AlN and GaN. Here antenna Gain for GaN substrate is higher than other two.

g. Efficiency

The quality factor, bandwidth, and efficiency are antenna figures of merit, which are interrelated and there is no complete freedom to independently optimize each one. Therefore, there is always a trade-off between them in arriving at an optimum antenna performance. Considering the antenna performance parameters like Zi, VSWR, RL etc, the efficiency of III nitride substrates specially GaN based patch antenna is higher. This may be more useful for a mobile handset or wireless applications. Comparing any other substrates, GaN shows the optimum antenna performance at the efficiency of 87.5 %. However radiation efficiency of all the substrates are simulated by HFSS and values are recorded in table 5.3 shown below.

5.3 Discussion from Simulation Results

Simulation results for commercial and III-Nitride substrates are analyzed and discussed with various curves and data thoroughly which are compiled and shown in table 5.3.

Table 5.3: Simulation results for commercial and III-Nitride substrates

S.no.	Name of Substrate	ε_r	patch size (LxW) mm	Z_i Ω	VSWR	RL dB	f_0 GHz	BW GHz	ή (%)
1	Taconic	2.2	52.13x70	52.89	4.15	-4.26	1.92	140	85.2
2	Rogers	2.2	52.13x70.5	46.91	2.08	-9.65	1.9	120	81.2
3	FR-4	4.4	38x26	41.72	1.56	-13.18	1.89	70	19.78
4	InN	8.4	26.57x22	47.52	2.5	-13.51	1.91	75	72.8
5	AlN	8.8	25.5x35.5	49.15	2.2	-11.45	1.915	85	80.6
6	**GaN**	**5.3**	**33.5x38**	**50.06**	**1.11**	**- 25.31**	**1.91**	**100**	**87.5**

Discussion reveals following points which may be considered during design of MPA:

a. Patch size is inversely proportional to operating frequency (f_0).
b. Patch width is directly proportional to return loss.
c. Commercial substrates may be better for the higher frequency than 1.9 GHz.
d. Antenna performance parameters are interrelated and there is no complete freedom to optimize each one.
e. Dielectric constant of semiconductor substrate is frequency dependant. So these parameters may be selected accordingly.
f. Physical parameters of a substrate like dielectric loss tangent, thermal conductivity, density, relative permeability etc may be considered during design of MPA.
g. Impedance matching can be done through suitable feeding techniques.
h. Feed and transmission lines are the fine tuning tools for antenna matching which are to be optimized very carefully.
i. During design of MPA with commercial substrates, all the merits and optimum antenna performance are not present. It may be further researched and study.
j. During design of MPA with III-Nitride substrates, almost all the optimum antenna performance parameters are present. Specially GaN shows the best result in all aspect which may be proposed for Rectangular MPA.

Chapter VI

Conclusion

6.1 Conclusion

This thesis has focused on the optimization, design and analysis of the performance parameters of the rectangular microstrip patch antenna (MPA) using commercial substrates (Taconic, Rogers & FR-4) and III-Nitride based substrates (InN, AlN & GaN). Detailed simulation has been carried out to achieve the progress and applicability of those substrates in rectangular MPA design using Ansoft High Frequency Structure Simulator (HFSS). In this work, we have theoretically designed rectangular MPA for different substrates. The performances of above commercial and III-Nitride substrates based MPA have been evaluated. These include the theoretical analysis and calculation of input impedance (Zi), voltage standing wave ratio (VSWR), return loss (RL), directivity, gain, and efficiency. The dielectric constant for different substrates has a great influence on antenna performance. The substrate posses the best result in all aspect has been proposed for the rectangular MPA design.

The input impedance are found to be 52.89 Ω, 46.91 Ω and 41.72 Ω for commercial substrates (Taconic, Rogers and FR-4) and 47.52 Ω, 49.15 Ω and 50.06 Ω for III-Nitride substrates (InN, AlN & GaN) respectively at the centre frequency 1.9 GHz and substrate height 0.8mm. The input impedance is 50 Ω for the proper matching between antenna and transmission line ($\lambda/4$). The effect of VSWR is also important parameter for transmission system. The values of VSWR are found to be 4.15, 2.08 and 1.56 for commercial substrates (Taconic, Rogers and FR-4) and 2.5, 2.2 and 1.11 for III-Nitride substrates (InN, AlN & GaN) respectively. Return loss (RL) plays an important role for the proposed rectangular patch antenna. The peak values of return loss (RL) is found to be -4.26 dB,-9.65dB, and -13.18dB for commercial substrates (Taconic, Rogers and FR-4) and -13.51dB, -11.45dB and -25.31dB for III-Nitride substrates (GaN, AlN and InN) respectively. Comparing the values of above commercial and III-Nitride substrates, it is found that the values of III-Nitride substrates are more acceptable and specially GaN is good agreement with the reported values for the conventional wireless antennas.

The total directivity is found 1.92, 2.25 and 2.45 with corresponding total gain of a single patch are 1.38, 1.77 and 1.88 respectively for InN, AlN and GaN. The efficiency of proposed antenna with substrate of InN, AlN and GaN are 72.8%, 80.6%, and 87.5% respectively, at substrate height of 0.80 mm and operating frequency 1.9 GHz.

The above calculated results, discussions, design and analysis indicate that the proposed III-Nitride substrates especially GaN based rectangular micro strip patch antenna may be promising for the wireless application in mobile communication.

6.2 Future Works

The research described in this thesis was concerned with the theoretically designed III-Nitride substrates based rectangular microstrip patch antenna. The proposed antenna has been theoretically designed with many exciting results. These have created the way for future work with a goal to fabricate practical III-Nitride based high performance patch antenna. The main problem of III-Nitride substrates specially with GaN technology is cost. An extra process is required to grow a GaN crystal or wafer on which transistors and integrated circuits (ICs) can be fabricated. Once the process is implemented on a large scale, the cost might come down. There are many areas where further work is required. The works remaining for future study are discussed as follows.

The bandwidth limitations of the designed antenna can be improved by employing aperture coupled feeding technique or stacked patch configuration. Instead of single patch, array with required number of patches may be used for optimum antenna performance. Surface waves responsible for reducing the performance of the designed antenna can be improved by using substrates or ground planes with photonic bandgaps. The double or triple-frequency design may be implemented by using the similar substrate. A WLAN antenna may be versatile and perform without prior alignment in order to reach the optimum performance. This attribute of the antennas may be ideal for WLAN applications.

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