CHAPTER 2

MICROSTRIP PATCH ANTENNA PARAMETERS AND EXPERIMENTAL SETUP (SIMULATION, FABRICATION AND MEASUREMENT)

2.1 Introduction

The objective of this thesis is to design antennas that are suitable for the multiband and wideband communication systems. Before the design work, it is essential to know about the basics of antenna theory. Some important parameters that are essential to design the antenna are discussed in this chapter. Some general approaches used to achieve wide operating bandwidth of microstrip antenna are also presented.

2.1.1 Definition of Antenna

The antennas play an important role in any wireless system. According to the IEEE standard definitions of terms for antennas, an antenna is defined as “a means for radiating or receiving radio waves” [125]. In other words, a transmitting antenna is a device that takes the signals from a transmission line, converts it into electromagnetic waves and then broadcasts it into free space, while operating in receiving mode, the antenna collects the incident electromagnetic waves and converts it back into signals.
2.2 Antenna Parameters

There are several antenna parameters that are useful to describe the performances of microstrip patch antenna. Some of these are as follows:

2.2.1 Frequency Bandwidth

Frequency bandwidth is the range of frequencies within which the performance of the antenna, with respect to some characteristic, conforms to a specified standard. The bandwidth can be considered to be the range of frequencies, on either side of the centre frequency, where the antenna characteristics are within an acceptable value of those at the centre frequency. In wireless communications, the antenna is required to provide a return loss less than -10dB over its frequency bandwidth.

The frequency bandwidth of an antenna can be expressed as either absolute bandwidth (ABW) or fractional bandwidth (FBW). The $f_H$ and $f_L$ denote the upper edge and the lower edge of the antenna bandwidth, respectively. The ABW is defined as the difference of the two edges and the FBW is designated as the percentage of the frequency difference over the center frequency, as given in equation 2.1 and 2.2, respectively.

\[
ABW = \frac{f_H - f_L}{f_H + f_L} \tag{2.1}
\]

Where,

$f_H =$ higher frequency, $f_L =$ lower frequency
For broadband antennas, the bandwidth can also be expressed as the ratio of the upper to the lower frequencies, where the antenna performance is acceptable, as shown in equation 2.3

\[ BW = \frac{f_H}{f_L} \]  

(2.3)

### 2.2.2 Return Loss

Return loss is a measure of the effectiveness of power delivery from a transmission line to a load such as an antenna. If the power incident on the antenna under test is \( P_{\text{in}} \) and the power reflected back to the source is \( P_{\text{ref}} \), the degree of mismatch between the incident and reflected power in the travelling waves is given by the ratio \( P_{\text{in}}/P_{\text{ref}} \). The higher this power ratio is, the better the load and line are matched. Return loss is the negative of the magnitude of the reflection coefficient in dB. Since power is proportional to the square of the voltage, return loss is given by:

\[ RL = 10 \log_{10} \frac{P_{\text{in}}}{P_{\text{ref}}} \text{ dB} \]  

(2.4)

which is positive quantity if \( P_{\text{ref}} < P_{\text{in}} \).

### 2.2.3 Radiation Pattern

Radiation pattern defines the variation of the power radiated by an
antenna as a function of the direction away from the antenna. It is a graphical representation of the radiation properties of the antenna as a function of space coordinates. Also the antenna radiation pattern is a measure of its power or radiation distribution with respect to a particular type of coordinates. We generally consider spherical coordinates as the ideal antenna is supposed to radiate in a spherically symmetrical pattern. Almost in all cases the radiation pattern is determined in the far field.

2.2.4 Antenna Gain

The most important figure of merit that describes the performance of an antenna radiator is the gain. The term antenna gain describes how much power is transmitted in the direction of peak radiation to that of an isotropic source.

OR

The relative gain is the ratio of the power gain in a given direction to the power gain of a reference antenna in its referenced direction. In most of cases the reference antenna is a lossless isotropic source. When the direction is not specified, the power gain is usually taken in the direction of maximum radiation.

A transmitting antenna gain of 3 dB means that the power received far from the antenna will be 3 dB higher than what would be received from a lossless isotropic antenna with the same input power. Similarly, a receiving antenna with a gain of 3 dB in a particular direction would receive 3 dB more power than a lossless isotropic antenna.
2.2.5 Group Delay

Group delay is one of the important parameter while discussing the wideband microstrip antenna. Group delay provides the pulse-handling capability. It represents the degree of distortion in the pulse signal. It is a useful measure of time distortion which is usually calculated by differentiating phase with respect to frequency. It evaluates non dispersive behaviour of antenna as a derivative of far field response with respect to frequency. If group delay variation exceeds more than 1 ns, phases are no more linear in far field and phase distortion occurs which can cause a serious problem for wideband applications.

2.2.6 Efficiency

Antenna radiation efficiency is defined as the ratio of power radiated to the input power. It relates the gain and directivity. Radiation efficiency also takes into account conduction and dielectric losses.

2.2.7 Polarization

Polarization of an antenna in a given direction is defined as “the polarization of the wave transmitted or radiated by the antenna”. When the direction is not defined then the polarization is taken to be in the direction of maximum gain. The polarization of the radiated energy varies with the direction from the center of the antenna, so that different parts of the pattern
may have different polarizations. Polarization describes the time varying direction and relative magnitude of the E-field.

At each point on the radiation sphere the polarization is resolved into a pair of orthogonal polarizations, the co-polarization and cross-polarizations. Co-polarization represents the polarization the antenna is intended to radiate while cross-polarization represents the polarization orthogonal to a specified polarization.

2.2.8 Input Impedance

Input impedance is defined as the “the impedance presented by an antenna at its terminals, or ratio of the voltage to current at a pair of terminals, or the ratio of the appropriate components of the electric to magnetic fields at a point.

2.3 Methods of Analysis of Microstrip Patch Antennas

Various models and methods are used for the analysis of microstrip antenna but the preferred methods for the analysis of microstrip patch antennas are the transmission line model and cavity model, that are discussed below:
2.3.1 Transmission Line Model

Transmission line method is the easiest method as compared to the rest of the methods. The transmission line model gives good physical insight, but is less accurate and it is more difficult to model coupling. The transmission line model is used to predict the input characteristic of rectangular microstrip antennas, due to its accuracy and numerical efficiency. It also plays an important role in the modeling of arrays. Its great drawback is its inability to predict the input characteristic much beyond a fundamental resonance.

In transmission line model the interior region of the patch antenna is modeled as a section of transmission line. The transmission line model treats the rectangular patch radiator as a strip line resonator with no transverse field variation and assumes the radiation to occur from the two transverse open edges. It is also known that the dominant mode of propagation in a strip line is the transverse electric magnetic (TEM) mode having negligible variation of fields in the transverse direction.

The transmission line model represents the microstrip antenna by two slots of width $W$ and and height $h$ separated by a transmission line of length $L$. From figure 2.1 it can be seen that most of the electric field lines reside in the substrate and parts of some lines in air. Thus transmission line cannot support TE mode of transmission. Hence, an effective dielectric constant ($\varepsilon_{\text{reff}}$) is obtained for the fringing and wave propagation in transmission line. The value of $\varepsilon_{\text{reff}}$ is slightly less than $\varepsilon_r$ due to the fringing fields. Fringing fields at the border of the patch are not limited to
the dielectric substrate but also extend in the air.

![Electric Field Lines](image)

**Figure 2.1 Electric Field Lines [125]**

The expression for $\varepsilon_{\text{reff}}$ is given as:

$$\varepsilon_{\text{reff}} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2} \left[ 1 + 12 \frac{h}{W} \right]^{3/2} \tag{2.5}$$

Where,

$\varepsilon_{\text{reff}}$ = effective dielectric constant

$\varepsilon_r$ = dielectric constant of the substrate

$h$ = height of the dielectric

$W$ = width of the patch

Consider a rectangular microstrip patch antenna of length $L$, and width $W$ placed on a substrate of height $h$ as shown in figure 2.2. The length of the patch is along $x$ direction, width is along $y$ direction and height is along $z$ direction.
In fundamental mode i.e. \( \text{TM}_{10} \) mode, the length of the patch is less than \( \lambda/2 \) where \( \lambda \) is the wavelength in the dielectric medium and is equal to \( \lambda_0/\sqrt{\varepsilon_{\text{reff}}} \) where \( \lambda_0 \) is the free space wavelength. \( \text{TM}_{10} \) mode implies that field varies only along the length by \( \lambda/2 \) and it does not varies along the width of the patch.

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

(2.5)
The effective length of the patch is

\[ L_{eff} = L + 2\Delta L \]  \hspace{1cm} (2.6)

For a resonance frequency \( f_0 \), the effective length is

\[ L_{eff} = \frac{c}{2f_0\sqrt{\varepsilon_{reff}}} \]  \hspace{1cm} (2.7)

For a rectangular microstrip patch antenna, the resonance frequency for any \( \text{TM}_{mn} \) mode is given as:

\[ f_r = \frac{c}{2f_0\sqrt{\varepsilon_{reff}}} \left[ \left( \frac{m}{L} \right)^2 + \left( \frac{n}{W} \right)^2 \right]^{1/2} \]  \hspace{1cm} (2.8)

Where \( m \) and \( n \) are the modes along \( L \) and \( W \) respectively.

The width of the patch is calculated as:

\[ W = \frac{c}{2f_0\sqrt{\frac{1}{\varepsilon_{reff}} - \frac{1}{\varepsilon_{reff}+1}}}} \]  \hspace{1cm} (2.9)
2.3.2 Cavity Model

The earlier discussed transmission line model is easy to use, but it has some disadvantages. Specifically, the transmission line model is useful for the patches that are in rectangular in shape and it ignores field variations along the radiating edges. While cavity model does not have these type of disadvantages.

The cavity model is a general model of the patch that imposes open-end conditions at the side edges of the patch. It represents the patch as a dielectric loaded cavity with electric walls and magnetic walls.

In this model, the inside portion of the dielectric substrate is modeled by a cavity that is bounded by the electric walls on the top and bottom while magentic fields around the cavity. When the microstrip patch is energized, a charge distribution is established on the upper and lower surfaces of the patch, as well as on the surface on the ground plane which is shown in figure 2.3. The charge distribution is controlled by the attractive and a repulsive mechanism. Attractive mechanism is in between the opposite charges on the bottom of the patch and the repulsive mechanism is in between like charges on the bottom surface of the patch. Movement of these charges creates correpsonding current densities $J_b$ and $J_t$ at the bottom and top surfaces of the patch.
If the microstrip patch antenna is treated as cavity then the radiation can not be signified because an ideal loss free cavity does not radiate. For the radiation a loss mechanism is introduced by adding an effective loss tangent, $\delta_{\text{eff}}$.

Thickness of the substrate of microstrip patch antenna is very small, therefore there is a reflection of waves at the edge of the patch that are generated in the dielectric substrate. Thus a very small amount of energy is radiated. Since the height of the substrate is very small ($h \ll \lambda$) where $\lambda$ is the wavelength within the dielectric, the field variations along the height will be constant. Also the fringing fields along the edges of the patch are also very small. Thus only TM field configurations are considered within the cavity.
2.3.3 Finite Element Method

The Finite Element Method (FEM) is a very versatile technique because it allows the analysis of complex structures. It has been used in a wide variety of problems like modeling waveguides and transmission lines, cavities etc. The FEM method is suitable for three dimensional structures. This method is important for researchers especially in the field of antennas and other domains of electromagnetic waves. In this method, the region of interest is divided into a number of finite surfaces or volume elements depending upon the planar or volumetric structures to be analyzed. These small divided units generally referred to as finite elements such as triangles and rectangles for two dimensional problems and tetrahedral elements for three dimensional problems. Wave equations with inhomogenous boundary conditions are solved by disintegrating the problem into boundary value problems. This method is also applicable for non uniform shapes.

2.4 Simulation and Optimization

The use of simulation software is an essential part to achieve the goal. The simulation of the microstrip patch antenna is done through Ansoft’s HFSS tool. HFSS is a commercial finite element method (FEM) solver for electromagnetic structures from Ansys. The acronym HFSS stood for High Frequency Structural Simulator. It is one of the finest applications used for the designing of microstrip patch antenna, complex RF electronic circuit elements
including filters, transmission lines, and packaging. It is an interactive simulation system, whose basic mesh element is a tetrahedron that allows solving any arbitrary 3D geometry, especially those with complex curves and shapes in a fraction of time. Different port schemes are available in this simulation software such as lumped port, wave port etc. The accurate simulation results of microstrip feed with coplanar waveguide are coming out through wave port. The optimization of the antenna parameters through HFSS is very useful and easy to optimize the parameters accurately. In the first step of simulation through HFSS, it is to define the geometry of the system by putting the material properties and boundaries available in HFSS window. Suitable excitation port is assigned to microstrip antenna. A radiation boundary filled with air box is then defined in which five edges are to select except the lower phase of the box. Now, the frequency range and the number of frequency points are putting in the simulation software. Finally, if all the parameters are validated through validation check, then simulation results such as S-parameters, VSWR, gain, group delay and far field radiation pattern can be displayed. There are many kinds of boundary schemes and excitation techniques available in HFSS. Radiation boundary and PEC (perfect electric conductor) boundary are widely used in this work.

2.5 FR4 Substrate

"FR" stands for flame/fire retardant. FR-4 is a grade designation assigned to glass-reinforced epoxy laminate sheets, tubes, rods and printed circuit boards. It is a composite material composed of woven fiber glass cloth with
an epoxy resin binder that is flame resistant. FR-4 glass epoxy is famous and flexible high-pressure thermoset plastic laminate material with high strength to weight ratios.

If the material has to be flame or fire retardant, there are certain requirements to be fulfilled for the material to be certified, as FR. When an equipment using FR4 grade PCB and if there is some kind of overvoltage or short circuit in the equipment, then the PCB made of organic material can catch fire but it should have the ability to retard the fire by itself; that means, it should have a self-extinguishing property.

The FR4 substrate is manufactured by compressing an epoxy resin at high pressure and a glass fiber mat (or mats) is embedded within the structure. The glass fiber gives the strength to substrate and increases the dielectric constant of the composite material. The weave is usually more densely packed in the one direction, and so the material is inherently anisotropic, with a small variation in the dielectric constant in different planes. Furthermore, the manufacturing technique employed introduces inconsistency in board thickness, which can cause variation in microstrip circuit parameters. Typical FR4 board characterisation is generally carried out by the manufacturers at 1MHz. At microwave frequencies, the bulk dielectric constant value is typically similar to the value at 1 MHZ, decreasing slightly at the frequencies above a few GHz.

FR4 epoxy glass substrates are the material of choice for most PCB applications. The material is of low cost and has excellent mechanical properties, making it ideal for a wide range of electronic equipments. As more and more microwave systems are developed for consumer market, there is a
considerable interest in minimising the cost of these systems.

Commercial substrate materials are promptly available for the use at RF and microwave frequencies for the design of microstrip and printed antennas. The substrate can be preferred based on the desired material characteristics for optimal performance over the specific frequency range. Dielectric constant, thickness and loss tangent are the commonly used parameters. Normally the dielectric constant ranges from 2.2 to 12 for the operations at frequencies ranging from 1 to 100 GHz.

The microstrip patch antenna design depends upon the substrate thickness. The thick substrates with low dielectric constants are the desired ones to obtain the larger bandwidth and higher efficiency due to loosely bound fringing fields. While thin substrates with large dielectric constants reduce the overall size of the antenna, however due to high loss tangents thin substrates are less efficient that results with narrow bandwidth. Therefore substrate selection is an important matter which has to be done in the beginning to get the desirable features for a given application.

2.6 Antenna Fabrication

Printed antennas are usually fabricated on microwave substrate materials using standard photolithographic techniques or milling techniques through machines. Selection of proper substrate material is the essential part in antenna design. The dielectric constant, loss tangent, homogeneity, isotropicity and dimensional strength of the substrate all are of importance. High loss tangent substrate adversely affects the efficiency of the antenna especially at high frequencies. The selection of dielectric
constant of the substrate depends on the application of the antenna and the radiation characteristics specifications. High dielectric constant substrates cause surface wave excitation and low bandwidth performance.

In photolithographic process a computer aided design of the geometry is initially made and a negative mask of the geometry to be generated is printed on a butter paper. A single side or double sided copper cladded substrate of suitable dimension is properly cleaned using acetone and dried in order to avoid the discontinuity caused by the impurities. Any disparity in the etched structure will shift the resonant frequency from the predicted values, especially when the operating frequency is very high. A thin layer of negative photo resist material is coated using dip coating technique on copper surfaces and it is dried. The mask is placed onto the photo resist and exposed to UV light. After the proper UV exposure the layer of photo-resist material in the exposed portions hardens which is then immersed in developer solution for few minutes. The hardened portions will not be washed out by the developer. The board is then dipped in the dye solution in order to clearly view the hardened photo resist portions on the copper coating. After developing phase the unwanted copper portions are etched off using Ferric Chloride (FeCl₃) solution to get the required antenna geometry on the substrate. The etched board is rinsed in running water to remove any etchant. FeCl₃ dissolves the copper parts except underneath the hardened photo resist layer after few minutes. The laminate is then cleaned carefully to remove the hardened photo resist using acetone solution.

While, in milling process the removal of extra copper on FR4 sheet
is done through machine without using any chemical as shown in figure 2.5 and 2.6. Milling process is typically a non-chemical process and it can be completed in a lab environment without exposure to hazardous chemicals. High quality circuits boards can be produced by using this process. CNC machine prototyping can provide a fast-turn around board production process without the need for wet processing. This single machine could carry out both parts of the process, milling and cutting. PCB milling has advantages for both prototyping and some special PCB designs. Probably the biggest benefit is that one doesn't have to use chemicals to produce PCB's. The flow chart of the process through machine is shown below:
Figure 2.4 Flow chart of the fabrication process of microstrip patch antenna through milling machine.
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Figure 2.5 Milling machine (MITS, Eleven Lab) used for the fabrication of antenna (Available at Department of Electronics & Communication Engineering, Rohilkhand University, Bareilly, India).

Figure 2.6 Computer system used for the operation of machine used for the fabrication process.
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Table 2.1 illustrates the details of milling machine available at Department of Electronics & Communication Engineering, Rohilkhand University, Bareilly, India.

Table 2.1 [131] Specifications of MITS ELEVEN LAB milling machine

<table>
<thead>
<tr>
<th>Specifications</th>
<th>Dimensions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Company Name</td>
<td>MITS (Japan)</td>
</tr>
<tr>
<td>Machine Model</td>
<td>Eleven Lab</td>
</tr>
<tr>
<td>Minimum pattern width (mm)</td>
<td>0.1 (4 mil)</td>
</tr>
<tr>
<td>Minimum milling width (mm)</td>
<td>0.1 (4 mil)</td>
</tr>
<tr>
<td>Working area (X/Y/Z) (mm)</td>
<td>229 x 320 x 10 <em>7 (30</em>6) (9.0&quot; x 12.6&quot; x 0.4&quot;)</td>
</tr>
<tr>
<td>Table size (mm)</td>
<td>296 x 396 (11.6&quot; x 15.6&quot;)</td>
</tr>
<tr>
<td>Control axis</td>
<td>X, Y, Z</td>
</tr>
<tr>
<td>Control motor</td>
<td>Stepper Motor</td>
</tr>
<tr>
<td>Resolution (µm) *3</td>
<td>0.625 (0.0246 mil)</td>
</tr>
<tr>
<td>Maximum Travel Speed (mm/sec.) *1</td>
<td>55 (2.17&quot;)</td>
</tr>
<tr>
<td>Spindle speed min⁻¹ (rpm)/Spindle motor</td>
<td>5,000 - 41,000/DC Spindle</td>
</tr>
<tr>
<td>Drilling (mm)</td>
<td>0.2 - 3.175 (8 - 125 mil)</td>
</tr>
<tr>
<td>Maximum drilling cycle (cycles/min.) *2</td>
<td>55</td>
</tr>
<tr>
<td>Maximum thickness of processed material (mm) *4</td>
<td>10 (0.4&quot;)</td>
</tr>
<tr>
<td>Tool change</td>
<td>Manual / Single step tool change</td>
</tr>
<tr>
<td>Power consumption</td>
<td>100 - 240 V, 50-60 Hz, 150VA</td>
</tr>
<tr>
<td>Machine dimensions W x D x H (mm)</td>
<td>435 x 575 x 430 (17.2&quot; x 23&quot; x 17&quot;) With cabinet: 500 x 580 x 450 (19.7&quot; x 23&quot; x 18&quot;)</td>
</tr>
<tr>
<td>Machine weight (kg)</td>
<td>Approx. 28 (62 lbs) With cabinet: Approx. 38 (84 lbs)</td>
</tr>
<tr>
<td>Interface</td>
<td>One USB or one RS-232C port</td>
</tr>
</tbody>
</table>

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2.7 Antenna Measurement

A concise explanation of equipments and facilities used for the measurements of antenna characteristics is presented in this section.

2.7.1 Agilent 8757E scalar network analyzer

The Agilent 8757E scalar network analyzer shown in figure 2.7, allows to measure insertion loss, gain, return loss, SWR, and power quickly and accurately. With high-performance detectors and directional bridges, this analyzer becomes the basis of a complete measurement system with superb performance.

The 8757E features three detector inputs and two independent display channels, allowing simultaneous ratioed or non-ratioed measurement of device's transmission and reflection characteristics.

The operation frequency of the system is from 10 MHz to 110 GHz. It has 101 to 401 measurement points per channel with extended amplitude display range from +16 to –60 dBm. It has the ability to measure a detector off-set with the power calibrator to compensate for RF attenuators.
Figure 2.7 Measurement setup of agilent 8757E scalar network analyzer at Vidyut Kendra, Modinagar, U.P, India.

Table 2.2 Specifications of Agilent 8757E scalar network analyzer

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating Band</td>
<td>10 MHz to 110 GHz.</td>
</tr>
<tr>
<td>Display channel</td>
<td>Two</td>
</tr>
<tr>
<td>Detector inputs</td>
<td>Three</td>
</tr>
<tr>
<td>Temperature Range</td>
<td>0°C to 55°C</td>
</tr>
<tr>
<td>Measurement points/trace</td>
<td>101 to 401</td>
</tr>
<tr>
<td>Power requirement</td>
<td>48 to 66 Hz, 220 V</td>
</tr>
<tr>
<td>Dual directional coupler</td>
<td>2 to 18 GHz</td>
</tr>
<tr>
<td>Output Accuracy</td>
<td>1 dB</td>
</tr>
</tbody>
</table>
2.7.2 Anechoic Chamber

An antenna is a device that operates in a free space environment. This type of operating conditions are not achieved in a simple laboratory environment. The power reflected from the walls and other devices of the instrument may hinder the power radiated from test antenna and disrupt the radiation pattern. For free space environment an anechoic chamber is used to measure the antenna characteristics accurately. However, exact free space conditions may not be achieved but the chamber minimizes the false signals coming from other instruments during pattern measurements. The anechoic chamber consists of microwave absorbers fixed on the walls, roof and floor to avoid electromagnetic reflections. The general photograph of anechoic chamber is shown in figure 2.8.

![General photograph of the anechoic chamber used for the antenna measurements.][132]
The entire interior surface of anechoic chamber is loaded with polyurethane foam based microwave absorbers. The tapered shapes of the absorber provide good impedance matching for the microwave power impinges upon it. Aluminium sheets are used to protect the chamber from electromagnetic interference of surroundings. To avoid any possible interaction with outer environment, a metallic lining is also put on the exterior. The test antenna is mounted on a turntable, which is kept in the quiet zone of the chamber. The turntable is controlled remotely from the control room.