Design of Microstrip Patch Antenna on Liquid Crystal Polymer (LCP) for Applications at 70GHz

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September 2008

Master’s Thesis
To my parents and grand parents
Acknowledgements

“In the Name of Allah, the most Beneficent and the most Merciful”

The thesis work has been carried out in Information and Communication Technologies Centre of Commonwealth Scientific and Industrial Research Organization (CSIRO), Sydney Australia, and presented in the Department of ITB/Electronics, University of Gävle, Sweden.

I wish to express my sincere gratitude to my supervisor Dr. Thomas Merkle for his guidance throughout the project. His generous support and valuable advice throughout the work is remarkable. My special thanks to Dr. Andrew Weily at ICT Centre CSIRO, Sydney, for his technical support to improve the work. Many thanks to Dr. Stephanie Smith at ICT Centre CSIRO, Sydney, for her valuable research suggestions to add the quality to my thesis.

I would like to thank my teachers specially Prof. Claes Beckman, staff members in the ITB/Electronics Department and colleagues in University of Gavle, Sweden. Particularly I would like to thank Mohammad Afzal Hussain for his continues help during the entire course of the work. Also, I cannot forget Maaz Rasheed, Mohammad Siddiq Ali Musab, Md. Maruf Hossain and Zahir Al-Asad for their moral support and availability during the thesis.

To all my family members and friends who contributed to this thesis in one way or another, I want to express my deepest respect. Particularly I would like to thank my uncle Gulraiz Khan for his continuous encouragement during the course of this project. Thanks to Ghaffer Iqbal Kiani, a PhD scholar at Macquarie University Sydney, for helping in accommodation matters and providing technical support in the thesis. Also, many thanks to Ms Vicky Deane, Student Services Manager at Robert Menzies College, Sydney, for providing assistance in educational matters.
Abstract

The demand of small size electronic systems has been increasing for several decades. The physical size of systems is reduced due to advancements in integrated circuits. With reduction in size of electronic systems, there is also an increasing demand of small and low cost antennas. Patch antennas are one of the most attractive antennas for integrated RF front end systems due to their compatibility with microwave integrated circuits. To fulfil the demand of integrated RF front end systems, a design of microstrip patch antenna with optimum performance at 70GHz is investigated. The procedure could be extended to design other planar antennas that act in a similar way.

In this work, three different design methods to design patch antennas for applications at 70GHz are investigated that include use of analytical models, numerical optimization, and numerical variation of dimensions. Analytical models provide a basic understanding of the operation of a patch antenna and they also provide approximate dimensions of a patch antenna for a targeted frequency without using numerical simulations. However, as the operating frequencies of RF systems reach mm-wave frequencies, we expect that the accuracy of analytical models become less accurate. For example, the excitation of substrate modes and effect of ground size are not predicted in simple analytical models.

Due to these expected limitations of the analytical design methods, the accuracy of these models is investigated by numerical electromagnetic field simulations. In this work, CST Microwave Studio Transient Solver is used for that purpose. In order to make sure that the appropriate settings of the solver are applied, the simulation settings such as mesh density, boundary conditions and the port dimensions are investigated. The simulation settings may affect computation time and convergence of the results. Here, in this work, the accuracy of the simulator for a specific design of inset feed rectangular patch antenna is verified. The patch dimensions obtained from analytical calculations are optimized at 70GHz by using the optimizer of the transient solver. The patch dimensions obtained from optimizer are verified by varying the patch dimensions in equidistant steps around the found result of the optimizer.

In a rectangular microstrip patch antenna design, the use of a width of 1.5 times the length is an approximate rule of thumb [1] for low dielectric constant substrates. It is also investigated how the performance properties of a microstrip patch antenna are affected by varying the width to length ratio of the patch. There are occasions where a different ratio is required because of space limitations, or to change the input impedance. The patch designs having various width to length ratios were optimized with the feed location.

The analytically calculated dimensions provided good initial values of the rectangular patch antenna for further optimization using more accurate techniques. The design have been optimized at 70GHz for the investigated mesh density, boundary conditions and the port dimensions. The numerical variation of dimensions is found to be most reliable among the investigated design methods but it is more complicated with many parameters.
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<td>CSIRO</td>
<td>Commonwealth Scientific and Industrial Research Organization</td>
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<tr>
<td>CST MWS</td>
<td>Computer Simulation Technology Microwave Studio</td>
</tr>
<tr>
<td>3D</td>
<td>Three Dimensional</td>
</tr>
<tr>
<td>VBA</td>
<td>Visual Basic for Application</td>
</tr>
<tr>
<td>MOM</td>
<td>Methods of Moments</td>
</tr>
<tr>
<td>FEM</td>
<td>Finite Element Method</td>
</tr>
<tr>
<td>FDTD</td>
<td>Finite Difference Time Domain</td>
</tr>
<tr>
<td>GPS</td>
<td>Global Positioning System</td>
</tr>
<tr>
<td>UHF</td>
<td>Ultra high frequency</td>
</tr>
<tr>
<td>LCP</td>
<td>Liquid Crystal Polymer</td>
</tr>
<tr>
<td>MICs</td>
<td>Microwave Integrated Circuits</td>
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<tr>
<td>TEM</td>
<td>Transverse electromagnetic mode</td>
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<tr>
<td>RF</td>
<td>Radio Frequency</td>
</tr>
<tr>
<td>mm-wave</td>
<td>Millimetre wave</td>
</tr>
<tr>
<td>dB</td>
<td>Decibel</td>
</tr>
<tr>
<td>$v_o$</td>
<td>Speed of light (3 * 10^8 m/s)</td>
</tr>
<tr>
<td>Lp</td>
<td>Length of patch</td>
</tr>
<tr>
<td>Wp</td>
<td>Width of patch</td>
</tr>
<tr>
<td>W</td>
<td>Width of microstrip feed line</td>
</tr>
<tr>
<td>h</td>
<td>Height of substrate</td>
</tr>
<tr>
<td>$\varepsilon_r$</td>
<td>Dielectric constant of the substrate</td>
</tr>
<tr>
<td>$\varepsilon_{\text{reff}}$</td>
<td>Effective dielectric constant</td>
</tr>
<tr>
<td>$\lambda_o$</td>
<td>Free space wavelength.</td>
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<tr>
<td>$f_o$</td>
<td>Resonant frequency</td>
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Chapter 1

Introduction

In this research, the design and analysis of a rectangular microstrip patch antenna is presented. A microstrip patch antenna consists of a conducting radiator patch printed onto a ground substrate. The elements of patch antenna are usually flat; hence their name, planar antennas. The objective is to investigate and analyse the design of rectangular microstrip patch antenna at 70GHz. To accomplish the objective, the CST MWS Finite Difference Time Domain (FDTD) software package is used.

The study includes the development of a rectangular patch antenna model, antenna simulation, and analysis of results based on various outputs of the CST Microwave Studio Transient Solver software package. Transient Solver [2] is a very flexible time domain simulation module that is capable of solving antenna problems. It stimulates the structure at a previously defined port using a time domain signal with broad frequency. A broadband simulation enables us to receive the S-parameters for our entire frequency range and, optionally, the electromagnetic field patterns at various desired frequencies from only one simulation run.

1.1 Aim of Thesis

The primary goal of the research is to determine the dimensions of rectangular microstrip patch antenna to obtain the optimal performance at 70GHz. It is also desired to select port dimensions such that the selected port dimensions do not affect the operation of the antenna. The same procedure could be applied to design other planar antennas to act in the same way.

1.2 Outline of Thesis

Chapter 2 reviews the theoretical aspects and summarizes the specifications of patch antenna. The basic antenna theory is discussed in this Chapter that would be applied to the work. In order to feed RF power to microstrip patch antenna, different feeding techniques are presented along with their advantages and disadvantages. In addition a brief description about the substrate material, patch and ground material is presented. Advantages and disadvantages of patch antenna are also discussed in terms of some of the practical applications. Some of the figure of merits of patch antenna are discussed that would be used to analyse the performance of the antenna. Here, in this work, different design methods of microstrip patch antenna are presented that are applied to design the antenna. Analytical method is discussed in detail together with the analytical formulas for calculating the effective dielectric constant, the patch
length and the patch width. A brief overview of some of the widely used numerical techniques is presented. The parameter variation of dimensions of the rectangular patch is also discussed. The project setup of CST MWS is briefly presented.

In Chapter 3, the accuracy of the numerical simulations is discussed. In CST MWS, various settings produce different results. The optimizer does not automatically converge to the best result for all type of problems. Here, in this work, the convergence of the simulator results has been verified at 70GHz. The boundary conditions, the port dimensions and the mesh density are investigated to get convergence in results.

Chapter 4 provides the design of inset-fed microstrip patch antenna. The rectangular microstrip patch antenna is designed using the analytical formulas presented in Chapter 2. By using the calculated parameters, the patch is simulated in CST MWS. The accuracy settings as investigated in Chapter 3 are applied to the transient solver. The simulated results of analytically calculated dimensions are found to be less accurate. The parameters are then optimized for 70GHz by keeping the optimization goal of return loss ≤ -30dB. During this optimization, the width of the patch is kept 1.5 times the patch length. At the end, parameter variation method is used to verify the simulated results. It is found that if the substrate height and the substrate material are specified, then, the important factors affecting the antenna performance are the patch length, the patch width and the inset feed point of rectangular microstrip patch antenna. In parameter variation one, out of the three, parameter was varied linearly in equidistant steps while the other two parameters were kept constant and the respective results for return loss, directivity, antenna gain and realized gain are noticed and analysed.

In a rectangular microstrip patch antenna design, the use of a width of 1.5 times the length is an approximate rule of thumb [1] for low dielectric constant substrates. There are occasions where a different ratio is required because of space limitations, or to change the input impedance. In Chapter 5, the performance properties of the microstrip patch antenna are investigated with various width to length ratios of the microstrip patch. For this purpose, six patch designs having various width to length ratios are optimized with the feed location. In each case the performance properties are analysed.

Finally, in chapter 6, some conclusions and future work consideration of this thesis work is presented.
Chapter 2

Patch Antenna Theory

This Chapter provides background information regarding the structure and operation of microstrip patch antenna. The materials generally used to fabricate patch antennas are discussed. In order to feed RF power to patch antennas, some of the feeding techniques are presented along with advantages and disadvantages. The characteristics of antenna are also discussed that will be analysed in this work. In addition three different design methods of microstrip patch antenna are presented which will be applied to this work. Finally a brief description of the solver setup is presented that will be applied to the patch antenna by using CST Microwave Studio.

2.1 Introduction to Microstrip Patch Antenna

A microstrip antenna in its simplest form consists of a sandwich of two parallel conducting layers separated by a single thin dielectric substrate [3]. The lower conductor functions as a ground plane and the upper conductor functions as radiator. A microstrip patch antenna in its simplest form is shown in Figure 2.1.

![Figure 2.1 Structure of microstrip patch antenna [4].](image)

where \( L \) is the patch length, \( W \) is the patch width, \( h \) is height of the substrate and \( t \) is thickness of the patch. The radiating patch may be square, rectangular, circular and triangular or any other configuration. Some of the shapes are illustrated in the Figure 2.2.
Figure 2.2 Different shapes of microstrip patch elements.

Square, rectangular, thin strip (dipole) and circular are the most common because of their attractive radiation characteristics [1], especially low cross-polarization radiation. The rectangular patch is the main research interest in this project. Linear or circular polarizations can be achieved with either single elements or arrays of microstrip antennas.

Microstrip patch can be designed either broadside radiator or end-fire radiator. For broadside radiator, the microstrip patch is designed in such a way that the pattern maximum is normal to the patch while for end-fire radiator the direction of maximum radiation is along the axis of the patch.

There are several approaches to analyse a microstrip patch. The most popular models of analysis of microstrip antennas include transmission line model [1], cavity model and full wave model (which include primarily integral equations/moment Method). The transmission line model is simplest of all, it gives physical insight but it is less accurate. The cavity model is more accurate, gives good physical insight but it is complex in nature. While the full wave models are very accurate, versatile, and can treat single element, finite and infinite arrays, arbitrary shaped elements and coupling but these models are the most complex models.

Here in this work, the transmission line model is investigated which provided a better physical insight of designing rectangular patch antenna and also provided approximate relationships to calculate dimension of the patch. However, it is assumed that the accuracy of transmission line model varies at mm-wave frequencies. The accuracy is investigated by numerical techniques.
2.1.1 Materials for Patch Antennas

There are many different structures of microstrip antennas but basically they consist of four parts [5]. These parts include:

1. The patch;
2. A dielectric substrate;
3. A ground plane, and
4. A feed line.

The patch is a very thin flat metallic region having different shapes and the ground plane is usually of same metal. A feed line supplies the RF power to the patch element. Here in this project, lossy copper is used for the patch element, the ground plane and the feed line.

![Microstrip Patch](image)

Figure 2.3 Side view of microstrip rectangular patch antenna.

The dielectric sheet is usually called the “substrate” [6]. In order to choose a substrate we have to consider its various features like the dielectric constant [7], the dielectric loss tangent, the cost of the material, the dimensional stability with time, the surface adhesion properties for the conductor coatings, the manufacturability (ease of cutting, drilling and shaping) [8]. A wide variety of substrate materials have been found to exist, with mechanical, thermal, and electrical properties which are attractive for use in both planar and conformal antenna configurations. There are many substrates materials on the market today with dielectric constants ranging from 1.17 to about 25 [9].

In this research Liquid Crystal Polymer (LCP) is used as dielectric material. LCP is an emerging dielectric material that has gained attention in recent few years as a potential high performance microwave flexible substrate and packaging material [10]. Important features of LCP are listed below.

1. Liquid Crystal Polymer is much cheaper than other available dielectric materials. Low cost (~$5/ft² for 2-mil single-clad low-melt LCP) [10] make it attractive for high frequency designs at minimum cost.

2. LCP have low dielectric constant (2.9-3.2 for \( f < 105\, \text{GHz} \)) and low loss tangent (0.002-0.0045 for \( f < 105\, \text{GHz} \)). Later on, the researchers at Georgia Institute of Technology, Atlanta Georgia, characterized [10] the permittivity of LCP up to 110GHz.
(3) LCP has a unique property of low moisture absorption (water absorption<0.004%) which makes it stable across a wide range of environments by preventing changes in relative dielectric constant \(\varepsilon_r\) and loss tangent \(\tan\delta\) [10].

(4) LCP material can be laminated without using additional adhesive layers [11] owing to its thermoplastic nature.

So in general LCP offers an excellent combination of electronic, thermal, mechanical and chemical properties that make it as a promising substrate for electronics packaging [12].

Specifications of [10] Liquid Crystal Polymer (LCP) along with other design parameters are presented in Table 2.1.

<table>
<thead>
<tr>
<th>Specification</th>
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<td>Operating frequency (GHz)</td>
<td>70</td>
</tr>
<tr>
<td>Dielectric constant (\varepsilon_r) of LCP</td>
<td>3.16</td>
</tr>
<tr>
<td>Loss tangent (\tan\delta) of LCP</td>
<td>0.004</td>
</tr>
<tr>
<td>Substrate height (h) in µm</td>
<td>100</td>
</tr>
<tr>
<td>Thickness of the ground plane (t) in µm</td>
<td>9</td>
</tr>
<tr>
<td>Thickness of the patch in µm</td>
<td>9</td>
</tr>
<tr>
<td>Conductivity of copper in S/m</td>
<td>5.8 \times 10^7</td>
</tr>
</tbody>
</table>

Table 2.1 The design specifications of microstrip patch antenna.

Table 2.1 gives the design specifications that would be used to design the rectangular patch in this work.
2.1.2 Feeding Techniques for Microstrip Patch Antennas

There are many ways to feed RF power to patch antennas. Some of the popular feed techniques are microstrip line, coaxial probe, aperture coupling and proximity coupling. These four methods along with advantages and disadvantages are summarized in Table 2.2 [13].

The feeding techniques are required in order to match the characteristic impedance of the feedline to that of the patch antenna. When the characteristic impedance of the antenna is same as the feed line, the antenna is said to be matched to the line. If the antenna is not matched, maximum power transfer will not take place [23]. In general, however, the impedance of the antenna is not the same as that of the feed line. The antenna can be matched depending on the design impedance. Here, in this work, we are using 50Ω input impedance of the patch. The standard characteristic impedance is 50Ω.

In microstrip feed line patch, a conducting microstrip is connected directly to the microstrip patch and the inset feed point is chosen in such a way that feed line impedance is matched to that of patch impedance. When the patch antenna is fed by a microstrip line the input impedance of the patch antenna also exhibits some dependence on the substrate thickness and permittivity, but it is strongly dependant on the location of the connection between the feed line and the patch [13]. The purpose of inset cut in the patch is to match feedline impedance to the patch without adding any additional matching element. Microstrip line feeding is the simplest and has an advantage that the feed can be fabricated on the same substrate as a single layer to provide a planar structure. A disadvantage is potential feed radiation [14]. Microstrip line feeding is suitable for developing high-gain microstrip array antennas.

A patch can also be fed with a probe through ground plane. The probe position can be inset for matching the patch impedance with the input impedance. This insetting minimizes probe radiation. The ease of insetting and low radiations are advantages of probe feeding as compared to microstrip line feeding [14].

“Proximity coupling [13] offers some opportunity to reduce feedline radiation while maintaining a relatively thick substrate for the radiating patch. The input impedance of antenna is affected by the overlap of the patch and the feedline, and by the substrates. This feature adds degree of freedom in the design, but may complicate the task of selecting an optimum design”. However, due to multilayer fabrication, the antenna thickness increases.

Aperture coupling [13] has gained attraction as a means of producing patch arrays. Aperture coupling is centred under the patch. No spurious radiation escapes to corrupt the side lobes or polarization of the antenna because of the feed lines behind the ground plane. Low levels of cross polarization can be achieved with aperture coupling. However, due to multilayer fabrication, the antenna thickness increases.

The main interest in this project is to use microstrip feed line to feed the RF power to the radiating patch. Maximum power transfer would occur if feedline impedance is matched to impedance of the patch antenna [15]. For a microstrip-line-fed patch antenna, impedance matching can be done by choosing different feed
positions. The goal is to match the antenna input impedance to the characteristic impedance of the connecting transmission line. The feed position determines the input impedance [16].

<table>
<thead>
<tr>
<th>Technique</th>
<th>Advantage</th>
<th>Disadvantage</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Microstripline</strong></td>
<td>(1) Radiating edge</td>
<td>Single layer Good polarization</td>
</tr>
<tr>
<td></td>
<td>(2) Non Radiating edge</td>
<td>Impedance matching is easier</td>
</tr>
<tr>
<td></td>
<td><img src="image" alt="Diagram" /></td>
<td>Spurious radiation. Must be inset or use transformer to match impedance.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Excites cross polarization</td>
</tr>
<tr>
<td><strong>Coaxial probe</strong></td>
<td><img src="image" alt="Diagram" /></td>
<td>Probe location is used for impedance matching.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Low radiation.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>The location of probe can selectively excite some additional modes.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>It can be used with plated vias for multilayer circuits.</td>
</tr>
<tr>
<td></td>
<td><img src="image" alt="Diagram" /></td>
<td>Impedance is highly inductive when thick substrates are used.</td>
</tr>
<tr>
<td><strong>Proximity Coupling</strong></td>
<td>(1) Single layer</td>
<td>No dc contact between feed and radiating patch.</td>
</tr>
<tr>
<td></td>
<td><img src="image" alt="Diagram" /></td>
<td>Direct radiation from coupling region. Dimensional tolerance.</td>
</tr>
<tr>
<td></td>
<td>(2) Multilayer</td>
<td>Can have large effective thickness for patch substrate and much thinner feed</td>
</tr>
<tr>
<td></td>
<td><img src="image" alt="Diagram" /></td>
<td>substrate. There are several degrees of freedom available for matching/tune</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Direct radiation from coupling region. Dimensional tolerance.</td>
</tr>
<tr>
<td></td>
<td><img src="image" alt="Diagram" /></td>
<td>Multilayer fabrication is required. Optimization is difficult.</td>
</tr>
<tr>
<td><strong>Aperture coupling</strong></td>
<td><img src="image" alt="Diagram" /></td>
<td>Independent choice of substrates for feed and radiators.</td>
</tr>
<tr>
<td></td>
<td><img src="image" alt="Diagram" /></td>
<td>Multilayer fabrication is needed.</td>
</tr>
<tr>
<td></td>
<td><img src="image" alt="Diagram" /></td>
<td>No spurious radiation from feed.</td>
</tr>
<tr>
<td></td>
<td><img src="image" alt="Diagram" /></td>
<td>No via connectors.</td>
</tr>
</tbody>
</table>

*Table 2.2 Feeding techniques for microstrip antenna [13].*
2.1.3 Operation of Microstrip Patch Antenna

Microstrip antennas radiate primarily because of the fringing fields between the patch edge and the ground plane. The patch length is approximately half the wavelength ($\lambda/2$) in conventional microstrip patches. If it is assumed that there are no variations of electric field along the width and the thickness of the patch, then the electric field configuration along the length can be illustrated as shown in Figure 2.4.

If the fringing fields are resolved into its parallel and tangential components with respect to the ground plane, the normal components will be out of phase with each other and would cancel out each other. The tangential components are in phase with each other therefore the resulting tangential field components would combine to give maximum radiated field in a direction normal to the patch i.e., the broadside direction.

The trade off in microstrip antennas is to design a patch with loosely bound fields extending into space while keeping the fields tightly bound to the feeding circuitry. This has to be accomplished with high radiation efficiency and with the desired polarization, impedance, and bandwidth [7].

The rectangular patch is usually operated near resonance in order to obtain real-valued input impedance [7]. If the substrate parameters are specified, there are three design parameters; the patch length, the patch width and the inset feed point that controls the resonant frequency and the resonant resistance. Here in this work we will investigate the effect of these parameters. Top view of a microstrip patch antenna with edge feed is shown in Figure 2.5.
The resonant nature of microstrip antennas also means that at frequencies below UHF, the size of the antennas become excessively large. The microstrip antennas are typically used at frequencies from 1 to 100 GHz.

2.1.4 Advantages and Disadvantages of Microstrip Patch Antennas

Microstrip antennas have several advantages and therefore are widely used in many practical applications. The main advantages include the following:

(1) They are low weight and low profile antennas. Microstrip antennas are small in size which makes them easy to integrate into package, so these antennas are used as efficient radiators in many [17] communication systems e.g., nowadays GPS are proving to be a major user of microstrip antennas.

(2) Due to low fabrication cost and ease of manufacturability, microstrip antennas are most suitable for mass production [5].

(3) They can be integrated with other microwave integrated circuits (MICs) [13].

(4) “Microstrip antennas are versatile in the sense that they can be designed to produce a wide variety of patterns and polarizations, depending on the mode excited and the particular shape of the patch used” [5].

(5) Feed line and matching networks are fabricated along with antenna structure. If the substrate is flexible, conformal antennas are possible. Etching is done with the standard photolithographic processes. The accuracy of etching process also ensures uniformity of different parts over a production run [14].

(6) The main reason for using microstrip patches is the ability to construct array antennas with the feed network and the radiating elements on a single surface. This arrangement means that the antennas are fed by a microstrip connected directly to the patch [13].

There are certain disadvantages of microstrip patch antennas. Some of the short comings are listed below.

(1) The major limitation in microstrip antenna is the narrow bandwidth [14], which can be stated in terms of antenna’s quality factor, Q. Microstrip antennas are high-Q devices [5] with Qs sometimes exceeding 100 for the thinner elements. High-Q elements have small bandwidths [5]. Also the higher the Q of an element the lower is its efficiency.

(2) Microstrip antennas have poor isolation between feedlines and radiating elements. There is always possibility of generation of surface waves at the air-dielectric interface and these results in dielectric losses [8].

(3) Finally, microstrip feed line losses result in low overall efficiency.
However, it is possible to find solution of some of these disadvantages by using suitable designs. Increasing the height of the dielectric substrate will reduce the Q of the microstrip element and thereby increase its bandwidth and efficiency. But there are limitations, as the height increases more surface waves are produced which usually are not desirable because they extract power from the total available power for direct radiation. These surface waves are counted as unwanted power loss [5] since these waves are ultimately scattered at dielectric discontinuities.

Microstrip antennas have been used in many civilian and government applications despite of their advantages and disadvantages. Sometimes disadvantages are counted as advantage e.g., for narrow band applications the antenna itself can act as a filter for unwanted frequency components, so small bandwidth [5] is counted as an advantage.

2.2 Characteristics of Patch Antenna

The performance of an antenna can be gauged from a number of parameters. Here in this work some necessary parameters are presented that characterize the performance of the designed patch antenna. The same definitions are applied in Chapter 3, 4 and 5, and these definitions are consistent with the definitions used in the text book [1].

2.2.1 Reflection Coefficient

The reflection coefficient of a line is the ratio of the power reflected back from the line to the power transmitted into the line. If the power transmitted by the source is $P_T$ and the power reflected back is $P_R$, then the reflection coefficient [18] is given by

$$\Gamma = \frac{P_R}{P_T} = \frac{Z_L - Z_O}{Z_L + Z_O} \tag{2-1}$$

where $\Gamma$ is called the reflection coefficient, $Z_L$ is the load impedance and $Z_O$ is characteristic impedance of the transmission line. A load is said to be matched to the line if there is no reflection of the incident wave i.e. $\Gamma = 0$, there is no reflected wave. In order to obtain $\Gamma = 0$, the load impedance must be matched to the characteristic impedance of the transmission line. If the antenna is mismatched, then, not all the available power from the feedline is delivered to the antenna. This loss is called Return Loss (RL) and is defined [18] as

$$RL = -20\log|\Gamma| \tag{2-2}$$

Return loss is usually expressed in decibels. For maximum power transfer the reflected signal [18] should be as small as possible, meaning that the ratio $P_R / P_T$ should be as small as possible, or expressed in dB, the return loss as large number as possible e.g., a return loss of 40dB is better than one of 20dB.
2.2.2 Directivity

Directivity of an antenna is defined as “the ratio of the radiation intensity in a given direction from the antenna to the radiation intensity averaged over all directions. The radiation intensity is given by the total power radiated by the antenna divided by $4\pi$.” Mathematically, directivity [1] can be expressed as

$$Directivity = 4\pi \frac{\text{power radiated per unit solid angle}}{\text{total radiated power}} \quad (2-3)$$

The same definition is presented in CST Microwave Studio. If the direction is not specified; the direction of maximum radiation intensity is implied. The directivity is defined with respect to an isotropic source and hence has the unit dBi. An isotropic source radiates an equal amount of power in every direction.

2.2.3 Antenna Gain

Antenna gain is related to input or accepted power of the antenna structure. Absolute gain of an antenna in a given direction is defined as “the ratio of the radiation intensity, in a given direction to the radiation intensity that would be obtained if the power accepted by the antenna were radiated isotropically. The radiation intensity corresponding to the isotropically radiated power is equal to the power accepted by the antenna divided by $4\pi$.” [1]. According to the IEEE standards, “gain does not include losses arising from impedance mismatches (reflection losses) and polarization mismatches (losses) [1]”. Mathematically antenna gain can be expressed as

$$Gain = 4\pi \frac{\text{power radiated per unit solid angle}}{\text{input (accepted) power}} \quad (2-4)$$

Antenna gain is expressed in decibels. The CST Microwave Studio utilizes the same definition to obtain antenna gain. In case of loss free antenna having no conductor losses, the gain is equal to directivity. Antenna gain considers dielectric and conductor losses and doesn’t consider mismatch losses.

2.2.4 Realized Gain

Realized gain is an important factor for analysis of antenna properties as it takes into account the losses due to dielectric, conductor and impedance mismatch. The realized gain [2] is defined by the relation.

$$Realized\ Gain = Gain \times (1 - S_{11}^2) \quad (2-5)$$

where $S_{11}$ is the input reflection coefficient. Realized gain is expressed in decibels.
2.2.5 Radiation Pattern of Patch Antennas

The radiation pattern of an antenna is a plot of the far-field radiation properties as a function of spatial coordinates which are specified by angle (θ) and (ϕ). The radiation pattern shows that the patch radiates more power in certain direction than in other. The rectangular patch antenna excited in its fundamental mode has a maximum directivity in the direction perpendicular to the patch (broadside). The directivity decreases when moving away from broadside towards lower elevations.

The coordinates used by CST Microwave Studio are shown in Figure 2.6; the far field is represented by two components at spherical coordinates theta and phi. The angle theta is defined in xz-plane, measured clockwise from z axis, while the angle phi is defined in xy-plane, measured anti-clockwise from x-axis. Radiation pattern for the rectangular patch antennas is designed in such a way that the broadside is taken along z-axis. The z-axis direction coincides with θ = 0 axis.

![Figure 2.6 Coordinates for the Radiation pattern of the designed rectangular patch antenna.](image)

Here, in this work the same set of coordinates are used as illustrated in the Figure 2.6.

2.3 Design Methods

There are several approaches to design a rectangular patch. Here, in this work, three design approaches are applied to design rectangular patch antenna.

(1) Transmission line model.
(2) Numerical techniques.
(3) Parameter variation.

The transmission line model is an analytical model. The transmission line model maintains simplicity at the expense of accuracy. It provides analytical relationships to calculate the patch dimensions. The numerical techniques are used for more complex and real life problems. In parameter variation, the dimensions of the patch are varied to verify the results.

2.3.1 Transmission Line Model

Rectangular patch antenna is analysed by using transmission line model. In this analytical model, it is assumed that some of the waves travel in air some in
substrate, the fields at the ends undergo fringing [1], therefore an effective dielectric constant ($\varepsilon_{\text{eff}}$) is introduced to account for fringing and the wave propagation in the line. The effective dielectric constant is given by [1]

$$\varepsilon_{\text{eff}} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2} \left[ 1 + 12 \frac{h}{W} \right]^{\frac{1}{2}} \text{ for } W/h > 1 $$ (2-6)

Where $\varepsilon_r$ is the relative permittivity of the substrate, $h$ is the height of the substrate and $W$ is the width of the patch. The value of $\varepsilon_{\text{eff}}$ is slightly less than $\varepsilon_r$ because the fringing fields around the patch are not confined to the dielectric substrate but spread in the air as well. For a line with air above the substrate, the effective dielectric effective has values in the range of $1 < \varepsilon_{\text{eff}} < \varepsilon_r$.

Most of the electric field lines reside in the substrate and some parts of lines in air. Due to two different kinds of mediums, this transmission line cannot support pure Transverse Electro-Magnetic (TEM) since the phase velocities would be different in the air and the substrate. Instead the dominant mode of propagation is the quasi-TEM mode. The amount of fringing is a function of the dimensions of the patch and the height of the substrate; it must be taken into account because it influences the resonant frequency of the antenna. In fact, the patch looks electrically a bit larger than its physical dimensions due to fringing fields as illustrated in Figure 2.7. A practical width [1] that leads to good radiation efficiencies is:

$$W = \frac{v_o}{2f_r} \sqrt{\frac{2}{\varepsilon_r + 1}}$$ (2-7)

where $v_o$ is the free-space velocity of light.

![Figure 2.7](image)

**Figure 2.7** Top view of the physical and effective lengths of rectangular patch.

The length of the rectangular microstrip antenna is [1] determined by

$$L = \frac{v_o}{2f_r\sqrt{\varepsilon_{\text{eff}}}} - 2\Delta L $$ (2-8)
where $\Delta L$ is the normalized extension of the length. The dimensions of the patch along its length have been extended by a distance $\Delta L$ and is [1] determined by

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

(2-9)

$\Delta L$ is a function of the effective dielectric constant $\epsilon_{\text{eff}}$ and the width-to-height ratio ($W/h$). As the length of the patch has been extended by $\Delta L$ on each side the effective length of the patch for dominant $TM_{\text{lo}}$ mode with no fringing is given by [1]

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

(2-10)

After selecting the patch length and the width for a given substrate, the next task is to determine the feed point (d) to get good impedance match between the feed line impedance and the input impedance of the patch element. Matching between the patch and the feed line can be achieved by selecting the position of feed line. The feed point must be located at a point on patch where the input impedance is 50$\Omega$. Here in this work, the return loss is compared for different locations of the feed points and that feed point is selected where the return loss has minimum value.

In transmission line model, a cut in the inset made to provide matching without need of any additional matching elements. The location of the inset feed is calculated empirically by using analytical formulas [1]. The inset feed point is calculated by using equations through 2-11 – 2-13. The free space wavelength [1] is given by

$$\lambda_o = \frac{v_o}{f_r}$$

(2-11)

where $\lambda_o$ is the free space wavelength and $v_o$ is the speed of light. The wave number [1] is given by

$$k_o = \frac{2\pi}{\lambda_o}$$

(2-12)

The transmission line model represents the microstrip antenna by two slots, separated by a transmission line of length L. The conductance of a single slot can be obtained [1] by using

$$G_i = \frac{1}{120\pi^2} \int_{\theta_0}^{\pi} \sin^2 \left( \frac{k_o W}{2 \cos \theta} \right) \sin^3 \theta d\theta$$

(213)
Ideally the two slots should be separated by $\lambda/2$ where $\lambda$ is the wavelength in the dielectric substrate. But in reality, the separation of slots is slightly less than $\lambda/2$ because the length of the patch is electrically longer than the actual length due to fringing. The mutual conductance $G_{12}$ can be calculated by using [1]

$$G_{12} = \frac{1}{120\pi^2} \int_{0}^{\pi} \sin^2\left(\frac{k_x W \cos \theta}{2 \cos \theta}\right) J_0(k_x L \sin \theta) \sin^3 \theta \, d\theta$$

(2-14)

Input resistance [1] is calculated by using

$$R_{in} = Z_{in} = \frac{1}{2(G_{1} + G_{12})}$$

(2-15)

$$Z_o = R_{in} \cos^2\left(\frac{\pi d}{L}\right)$$

(2-16)

Where $d$ is the inset distance from the radiating edge, and $R_{in}$ is the resonant input resistance when the patch is fed at a radiating edge. The inset distance ($d$) is selected such that $Z_o$ is equivalent to the feedline impedance. Here, in this work we used feedline impedance of 50Ω. Due to use of microstrip feed in many applications, microstrip feedline is used to provide RF feed power to the antenna.

Transmission line model is an analytical model which provides a better physical insight of designing rectangular patch antenna and also provides approximate relationships to calculate dimension of the patch. The transmission line model gives good starting values. However, as the operating frequencies of RF systems reach mm-wave frequencies, we expect that the accuracy of analytical models become less accurate. In analytical models excitation of substrate modes and effect of ground size are not predicted. We will also investigate the design with numerical optimization and parameter variation of the patch dimensions.

### 2.3.2 Numerical Techniques

In fact only a few simple problems in electromagnetics can be solved analytically. For more complex and real life problems the numerical techniques are used, for approximate solution of Maxwell’s equations. Full wave numerical techniques can provide analysis of microstrip antennas in which the effects like space wave radiation, surface wave loss and coupling, fringing fields, mutual coupling between the edges do not have to be modelled [25]. These features are all integrated in numerical analysis techniques. Some of the widely used numerical techniques are listed below:

1. Method of Moments (MOM).
2. Finite Element Method (FEM).
MOM is an integral equation based method in frequency domain [7]. “Method of Moment discretizes the integral equation-solution forms of a given problem. This integral-solution approach is widely used in time-harmonic problems, e.g., to calculate the radiating properties of antennas or scattering characteristics of dielectric and metal bodies” [19]. However this method involves the calculation of the Green’s function for the given structure, which can be quite tedious for few types of geometry. MOM is inadequate for problems involving pulsed excitations and various transient phenomenon [7]. These kinds of problems require data to be computed over a wide range of frequencies.

The Finite Element Method (FEM) is a numerical technique for finding approximate solutions for partial differential equations. The concept of FEM lies in discretizing the given structure into elements described by element-shape functions [20]. The basic concept is that a structure may be divided into smaller elements. These elements can be chosen as triangles, trapezoids or any suitable shape which helps in the discretizing process. The original structure is then considered as an assemblage of these elements connected at a finite number of joints called nodes. The properties of elements are formulated and combined to obtain the properties of entire structure. In this method attention is mainly paid to the formulation of properties of the constituent elements instead of solving the problem for the entire structure. A common procedure is adopted for combining the elements. This scheme exploits the fact that all systems work on the principle of least energy path.

FDTD is a differential equation based method in time domain. The antenna structure is excited with a pulsed time domain signal, and the response is calculated in time domain. With one simulation in the time domain, one wide frequency range can be covered in frequency domain via Fourier transformation. In this work, the CST MICROWAVE STUDIO is available which offers FDTD transient solver and is widely used among antenna engineers at CSIRO. Transient solver in CST MICROWAVE STUDIO offers some other possibilities like calculation of antenna radiation patterns and relevant antenna parameters, electromagnetic field distributions at various frequencies, S-parameter calculation, and structure design by using optimizer and parameter sweep. Owing to these possibilities, FDTD is chosen to analyse the characteristics of the rectangular patch antenna and to determine parameters that will give optimal results. The FDTD method is one of the most popular techniques used for solving electromagnetic problems and it has been successfully applied to an extremely wide variety of problems [21]. It is capable of analysing structures using different types of materials, e.g., lossy dielectrics and magnetized ferrites [25].

2.3.3 Parameter Variation

The simulated results obtained from a numerical optimizer can be verified by using parameter variation of dimensions. In this approach a parameter variation is performed around the found result of the optimizer. In parameter variation of a rectangular patch antenna the patch length, the patch width and the inset feed point are varied linearly in equidistant steps. Here in this work two of these three parameters are kept constant while the third one is varied linearly to analyse the
characteristics of the antenna. The dimensions of the rectangular patch that have been used in this work are shown in Figure 2.8.

![Figure 2.8 The basic dimensions of a microstrip patch antenna](image)

From Figure 2.8, $W_p$ is the width of the patch, $L_p$ is the length of the patch, $W$ is the width of the microstrip line, $d$ is the inset feed point and $g$ is the gap between the microstrip line and the patch. The resonant length determines the resonant frequency [22] for a rectangular patch. Location of the connection of inset feed point controls the resonant resistance of patch antenna [13]. Feed point should be chosen in such a way that the patch impedance is matched with the feed line impedance. The important dimensions that should be investigated include the patch length, the patch width, and the inset feed location of the patch. These dimensions have different effects on the performance properties of the patch antenna as described in Section 2.2.

### 2.4 Project Setup

Here in this work for high frequency simulation, CST Microwave Studio have been used a numerical electromagnetic solver with an optimizer. CST Microwave Studio is a specialized tool for fast and accurate three dimensional electromagnetic simulations of high frequency problems. It possesses key features like VBA compatibility, automatic macro recording, automatic multi-dimensional parameter sweeps and optimizers, electrostatic and magnetostatic solvers. The software provides manual meshing and adaptive mesh refinement options. The post processing template includes farfield broadband calculations, smith chart plots, 2D and 3D plots and polar radiation pattern plots. Applications of CST include antenna design [2], resonator and filter designs.

The microstrip patch antenna is generated by three bricks, one for radiating plate, one for the ground plane and one for the substrate. The rectangular patch is designed using CST Microwave Studio and is illustrated in Figure 2.9.
Figure 2.9 Design of microstrip rectangular patch in CST Microwave studio.

Top view of the designed rectangular patch is shown in Figure 2.9. The Figure is taken from CST Microwave studio. The patch width is extended along x-axis, the length along y-axis and the height along z-axis.

LCP is used as substrate material having dielectric constant $\varepsilon_r = 3.16$, and is defined by using brick creation tool. The substrate, which is usually much larger then the patch, is chosen to be a square of having dimensions of 2000µm*2000µm. The height of the substrate (100µm) is created along z-axis.

The patch is created in the middle of the square shaped substrate. Lossy copper metal is used as patch material and for ground plane. Lossy copper metal having conductivity of $5.8 * 10^7 S/m$ is loaded from the material library of CST Microwave studio. Here, we are using 50Ω characteristic impedance for the patch. Ground plane is created by using extrude option of CST Microwave studio, again lossy copper material is loaded from the material library for the ground plane.

The width of microstrip feed line is calculated using the line calc [24] tool. Using the dielectric constant of LCP ($\varepsilon_r = 3.16$) at 70GHz frequency, and a characteristic impedance of 50Ω, the width of microstrip feed-line is calculated to be 234µm.

A waveguide port is defined for excitation at the beginning of the microstrip line. The dimensions of the port are chosen in such a way that they should not affect the performance of the antenna. Ports are used to calculate the reflection parameters. In this work, the S-parameters are calculated for a frequency range of 55-85GHz.

The main result of interest of an antenna is the farfield distribution at given frequency. A farfield monitor at one of the resonance frequencies allows the visualization of the farfield after the simulation. In this work, farfield pattern plots are obtained from the CST Microwave Studio FDTD software. For this purpose template based post-processing option of CST Microwave Studio is used and various field monitors are defined for 55-85GHz in step size of 0.5GHz.
In this work accuracy of numerical simulations is investigated because accuracy of the results is critical at high frequency applications, such as mm-wave applications. Wrong numerical simulation may lead to wrong conclusions. The correct settings for a specific problem lead to the accurate solution.

The accuracy of numerical simulations mainly depends on boundary conditions, port dimensions, and mesh density. Here, in this work, certain boundary conditions have been chosen which have influence on the simulation system. Port dimensions are investigated such that the designed dimensions of the port do not affect the accuracy of the simulated results. The mesh density is also investigated to achieve the convergence in results for the patch antenna.

In this work, hexahedral mesh is used. In general there are three ways to define a hexahedral mesh: manually, automatically and adaptively. In the first stage, the manual mesh properties of CST MWS are investigated. Adaptive mesh refinement is also discussed in which the simulator simulates the structure for a given number of times and improves the mesh from run to run to get convergence in the required results. Accuracy settings of the transient solver are also discussed in which the simulator defines the steady state monitor.

In manual meshing of CST MWS, different mesh properties are used to check the accuracy and reliability of the designed antenna. These properties include mesh type, lines per wavelength, lower mesh limit and mesh line ratio limit. Special properties include edge refinement factor and use of sub-gridding. The mesh density have been investigated to achieve the convergence such that the results no longer significantly change with increase in mesh density.

In adaptive mesh refinement, the settings which are used for high frequency applications to check the accuracy of results of the patch antenna include convergence criteria, frequency range, and refinement settings. In convergence criteria we define maximum delta S, minimum number of passes, and maximum number of passes. In frequency range we can either use full frequency range or define a minimum frequency and maximum frequency. In refinement settings, we can define refinement strategy as energy based or expert system based.

In accuracy settings, the simulator defines the steady state monitor. To get a value for the accuracy, the amplitude of the time signals and the total energy inside the calculation domain are used. The simulation stops when the defined accuracy level is reached. Various accuracy settings influences the duration of the simulation.
3.1 Boundary Conditions

In numerical simulation, certain boundary conditions are chosen that have influences on the simulation system. In CST Microwave Studio, different types of boundary conditions are available like *Electric*, *Magnetic*, *Open*, *Open-add space*, *Periodic* and *Conducting Wall*. These boundary conditions need to be chosen properly.

In this project, all calculation domain boundary conditions are set to *open-add space* except the one with the ground plane. The ground plane is specified by an *electric* boundary condition. *Electric* boundary condition operates like a perfect electric conductor i.e., all tangential electric fields and normal magnetic fluxes are set to zero [2].

*Open-add space* boundary condition operates like free space behind their boundary planes. Free space means that electromagnetic fields are absorbed at these boundaries with virtually no reflections or waves can pass this boundary with minimal reflections. *Open-add space* boundary condition is same as *open* boundary condition but it adds some extra space for farfield calculation. This option in CST Microwave Studio is recommended for antenna problems [2].

3.2 Port Selection

In order to calculate reflection parameters, port is defined for the patch antenna. In the measurement setups, the device under test is connected to the network analyser by using low reflection probes or applying proper de-embedding techniques. Care must be taken with the probe connection because the measured S-parameter will otherwise become inaccurate. For electromagnetic field simulations of patch antenna, the same problems exist. The port connection needs to be loss free and have very low levels of reflection.

In this work, a waveguide port at the beginning of the microstrip line is defined for the excitation. The port is created in such a way that the extension below the microstripline is exactly the height of substrate so that the port may not be connected to the ground plane. The height of the port is set to be 5 times above the substrate height and the width of the port is set equal to 10 times the width of microstrip feed line. The width of the microstrip transmission line is calculated by using *line calc* tool [24] and height of substrate is used as 100µm. With these dimensions of the port, the fundamental microstrip line mode is obtained and is shown in Figure 3.1. The selected port dimensions resulted in creation of the fundamental quasi-TEM mode and the calculated line impedance is 50.3Ω. Now the port size is gradually decreased to 8, 6 and 4 times the width of the microstrip line then the corresponding line impedance is calculated and shown in Table 3.1.
Port modes (in log scale) for 4 times the width of the transmission line and 5 times height of the substrate is shown in the Figure 3.2. With these dimensions, it resulted in creation of higher order modes.

<table>
<thead>
<tr>
<th>Width of port (µm)</th>
<th>Height of port (µm)</th>
<th>Line impedance (Ω)</th>
</tr>
</thead>
<tbody>
<tr>
<td>14*W</td>
<td>5*h</td>
<td>50.327</td>
</tr>
<tr>
<td>12*W</td>
<td>5*h</td>
<td>50.339</td>
</tr>
<tr>
<td>10*W</td>
<td>5*h</td>
<td>50.36</td>
</tr>
<tr>
<td>8*W</td>
<td>5*h</td>
<td>50.428</td>
</tr>
<tr>
<td>6*W</td>
<td>5*h</td>
<td>50.724</td>
</tr>
<tr>
<td>4*W</td>
<td>5*h</td>
<td>51.3</td>
</tr>
</tbody>
</table>

**Table 3.1** Port size and corresponding line impedance.

In Table 3.1, W is the width of the transmission line and h is the height of the substrate. It is seen that the line impedance is converging at 10 times the width of the transmission line.

In general, the size of port is an important consideration. On one side the port needs to be large enough to enclose the significant part of the microstrip line’s fundamental quasi-TEM mode. On other side, the port size should be chosen small enough that the higher order modes cannot propagate and only one mode should exist at the port [2]. The higher order modes of the microstrip line are very similar to modes in rectangular waveguide. The larger the port the lower the cut off frequency of these modes. If higher order modes are propagating in microstrip line, this normally results in very slow energy decays in the transient simulations. In other case, choosing the port size too small will cause degradation of the S-parameter’s accuracy or even instabilities of transient solver.
3.3 Mesh Generation

The mesh influences the accuracy and the simulation time of the solver [2]. In CST Microwave Studio, the FDTD solver uses a hexahedral mesh and there are three ways to define hexahedral mesh:

(1) Manual Meshing.
(2) Automatic Mesh Generation with Expert System.
(3) Adaptive Mesh Refinement (Energy based or Expert System Based).

Manual Meshing can be defined at any time even before the model is generated [2]. In CST Microwave Studio different parameters are defined for manual meshing like lines per wavelength, lower mesh limit, mesh lines ratio limit and edge refinement factor. All of these parameters have some effects on S-parameters accuracy. By increasing the mesh density to a certain limit ensures the accuracy in S-parameters and gives converging results. Manual meshing gives a deeper insight to check the accuracy and reliability of the designed antenna.

Automatic mesh generation with expert system determines the important features of the structure and automatically creates a mesh, which represents the structure and fields. This means that the frequency ranges and dielectrics, metallic edges are considered by the expert system but certain mesh properties [2] can also be selected manually.

In adaptive mesh refinement, the regions with high field concentration or field gradients are recognized where the mesh needs to be locally refined [2]. Adaptive meshing procedure simulates the structure according to specified maximum number of passes and improves the mesh from run to run. If the deviation in results falls below the given accuracy level, the adaptation terminates. This approach improves the start solution at the expense of simulation time. In this work, the adaptive mesh refinement has been used to obtain the most accurate solution. Transient Solver calculation is performed using hexahedral mesh.

3.4 Manual Mesh Settings

Inaccuracies can arise from the finite mesh resolution and are difficult to estimate. By increasing the mesh resolution to a certain limit and again calculating S-parameters ensures accuracy. In manual mesh settings, different mesh settings are used to check the accuracy and reliability of the designed antenna; these settings for a specific design dimensions are presented in Table 3.2.
<table>
<thead>
<tr>
<th>Chapter No.</th>
<th>Serial number</th>
<th>Lines per wavelength</th>
<th>Lower mesh limit</th>
<th>Mesh line ratio limit</th>
<th>Number of mesh cells</th>
<th>Antenna gain (dB)</th>
<th>Realized gain (dB)</th>
<th>Total simulation time of the solver (s)</th>
</tr>
</thead>
<tbody>
<tr>
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<td>10</td>
<td>10</td>
<td>10</td>
<td>21573</td>
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<tr>
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<td>2</td>
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<tr>
<td></td>
<td>4</td>
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<td>10</td>
<td>10</td>
<td>40920</td>
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<td>6.46</td>
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<td>10</td>
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<td>6.13</td>
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<td>383500</td>
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<td>21573</td>
<td>6.98</td>
<td>6.98</td>
<td>23</td>
</tr>
</tbody>
</table>

Table 3.2 Mesh density control parameters for hexahedral mesh.

In manual meshing, the accuracy of the results is analysed by simulating various combinations of lines per wavelength, lower mesh limit, and mesh lines ratio limit, and the simulated results are noticed. The total simulator time and the number of mesh cells in each case are also noticed. In order to get converging results, the density of mesh is increased and the results are analysed both quantitatively and qualitatively. The time shown by the solver log file is recorded but in reality it takes 4-5 minutes longer than the solver recorded time, this may be due to a delay in updating the results.

At metal edges, singularities occur in electromagnetic fields this means electromagnetic fields vary significantly near edges and must be sampled more than elsewhere [2]. In special mesh properties, the Refine at PEC/lossy metal edges by factor option forces the system to refine the mesh at critical edges by a given factor. The default setting is 2, but here we are using a project template in which we will use edge refinement factor of 4. This option increases the spatial sampling at the metal edges.

### 3.4.1 Lines Per Wavelength

*Lines per wavelength* determine the maximum step width of the mesh. *Lines per wavelength* are related to wavelength of highest frequency set for simulation. *Lines per wavelength* is a frequency dependant factor. “A lines per wavelength setting of 10 means [2] that a plane wave propagating along one of the coordinate axis is sampled at least 10 times”.
In this simulation, open-add space boundary conditions are used and the wavelengths are calculated. Two criteria are used to define the space between the structure and the applied open-add space boundaries: The first criterion defines the minimum number of mesh lines as a limit for the space. Here, in this work 5 mesh lines are defined for the space. The second criterion determines the minimum distance to the open boundary in part of the wavelength, considered either at the centre frequency or at a user defined value. Here, in this work an 8th part of a wavelength at the centre frequency is considered.

In quantitative analysis, manual meshing is evaluated for various values of lines per wavelength. Starting with a minimum value, lines per wavelength are increased to a certain limit in order to achieve converging results. In the first stage, different lines per wavelength are simulated and respective results for return loss, antenna gain and realized gain are plotted. The simulated results are shown in Table 3.3.

<table>
<thead>
<tr>
<th>Sr. No</th>
<th>Lines per wavelength</th>
<th>Lower mesh limit</th>
<th>Mesh line ratio limit</th>
<th>Number of mesh cells</th>
<th>Antenna gain at 70 GHz (dB)</th>
<th>Realized gain at resonance frequency (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10</td>
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<td>10</td>
<td>21573</td>
<td>6.98</td>
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<td>10</td>
<td>233640</td>
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<td>6.42</td>
</tr>
</tbody>
</table>

Table 3.3 Analysis of various lines per wavelength and computed results.

From the Table 3.3, it is seen that for an increase in lines per wavelength, the number of mesh cells also increases. Mesh settings have some effects on S-parameters accuracy. The plot for $S_{11}$ against various lines per wavelength is shown in Figure 3.3.
From the Figure 3.3, it is seen that with an increase in lines per wavelength, the resonant frequency shifts away from 70GHz. There is a resonance shift of 0.5GHz when lines per wavelength is increased from 10 to 14. This is because when mesh lines per wavelength are increased, mesh density is increased and this affected the accuracy of matching. $S_{11}$ minimum is plotted against number of lines per wavelength, and is shown in Figure 3.4. In Figure 3.4, it is observed that $S_{11}$ minimum remains constant for 25 lines per wavelength and do not vary significantly up to 40 lines per wavelength. A plot of resonance frequency against various lines per wavelength is shown in Figure 3.5.

From Figure 3.5, it is observed that resonance frequencies do not vary significantly for lines per wavelength equal to 25-35. A plot of antenna gain against various lines per wavelength is shown in the Figure 3.6.
From Figure 3.6, it is seen that the antenna gain for 10 lines per wavelength is 6.98dB and it drops with increase in lines per wavelength from 10 to 18. Antenna gain seems to saturate at 25 to 30 lines per wavelength. Realized gain is plotted against various lines per wavelength and shown in Figure 3.7. Realized gain continues to drop with increase in lines per wavelength. It is due to the fact that with increase in lines per wavelength, the mesh density is increased which in turn affected the accuracy of matching. Realized gain saturates with 30-35 lines per wavelength. A plot of lines per wavelength against realized gain at resonant frequencies is plotted and shown in Figure 3.8.

From the Figure 3.8, it is seen that with an increase in the number of lines per wavelength, the realized gain drops continuously up to 25 lines per wavelength and saturates on 30 lines per wavelength.

In qualitative analysis, the antenna structure is presented in form of pictures. By using Table 3.3, for a setting of 10 lines per wavelength, the mesh cells structure as shown in the Figure 3.9 is obtained.
From Figure 3.9, it is seen that there are 5 mesh lines for the space between the structure and the bounding box. For the designed structure, we have 40 mesh lines. Here an edge refinement factor of 4 is used. When the lines per wavelength are increased to 18, a structure of mesh cells as shown in Figure 3.10 is obtained. In this case, the number of lines that fill the added open space stay the same while the open space gap gets smaller. There are 5 mesh lines for the space between the structure and bounding box while 60 mesh lines for the antenna structure. It is observed that with the increase in line per wavelength the number of mesh cells is increased and hence mesh density is increased.

3.4.2 Lower Mesh Limit

*Lower mesh limit* determines the maximum step width of the mesh. This option is used to define the lower limit of mesh lines to be used for mesh creation regardless of the settings in *lines per wavelength*. *Lower mesh limit* has direct effects on mesh steps. “The diagonal of the calculation domain’s smallest boundary face is divided by the value of the *lower mesh limit* parameter. The resulting value \( [2] \) will then be taken as a maximum mesh step width”.

In the quantitative analysis, the manual meshing for various values of *lower mesh limit* is evaluated. Here in this work, when the value of *lower mesh limit* is increased from 10-50, mesh density is also increased. For a value of *lower mesh limit* of 50 we have 651496 mesh cells for the given structure. Starting with minimum value, various values of *lower mesh limit* are simulated and respective results for antenna gain and realized gain are obtained. The total number of mesh cells is determined in each case and the simulated results are given in Table 3.4.
Table 3.4 Analysis of various lower mesh limit and simulated results.

From the Table 3.4, it is seen that for an increase in lower mesh limit, the number of mesh cells increases. The total simulation time of the solver also increases with increase in value of lower mesh limit. The effect on S-parameters is shown in the Figure 3.11.

![Plot of various lower mesh limits against reflections](image1.png)

**Figure 3.11** $S_{11}$ for various values of lower mesh limit.

![Lower Mesh Limit Vs $S_{11}$ (minimum)](image2.png)

**Figure 3.12** Plot of lower mesh limit against $S_{11}$ minimum.

From the Figure 3.11, it is seen that as we increase the lower mesh limit, the centre frequency deviates from the resonance value. When a lower mesh limit is increased from 10 to 20 there is a resonance shift of 0.5GHz. Another shift of 0.5GHz is observed for lower mesh limit of 30, but its value starts to converge with lower mesh limit of 40. As compared to lines per wavelength, lower mesh limit has more effects on resonance frequency. From the Figure 3.12, it is seen that lower mesh limit of 40 is sufficient for converging $S_{11}$. A plot of resonance frequency for various values of lower mesh limit is shown in Figure 3.13.
Figure 3.13 Plot of resonance frequency for different values of lower mesh limit.

From the Figure 3.13, it is observed that there is a rapid deviation in resonance frequency for lower mesh limit of 10-30 and resonance frequency saturates for a lower mesh limit of 30-40. A Plot of antenna gain for various values of lower mesh limit is shown in Figure 3.14.

Figure 3.14 Plot of antenna gain for various values of lower mesh limit.

From the Figure 3.14, it is observed that if lower mesh limit is set to 30 or 40, the antenna gain starts to converge to 6.6dB. Antenna gain converges when lower mesh limit is set to 30 or above 30. It is concluded that, in order to achieve converging gain we require 180320 mesh cells and for this purpose the solver time is 162s. From the Figure 3.15, it is seen that the realized gain continues to decline with increasing the lower mesh limit and starts to saturate at lower mesh limit of 40. For converging realized gain, 383500 mesh cells are required for which solver time is 381s which is almost double the time compared to time required for 180320 mesh cells. A plot of realized gain at the respective resonance frequencies for each of the lower mesh limit is shown in the Figure 3.16.
Figure 3.16 Plot of lower mesh limit for antenna gain at 70GHz and realized gain at the resonant frequencies.

It is seen that with increase in the number of lower mesh limit from 10 to 50 in steps of 10, the realized gain drops significantly. The realized gain continues to drop from lower mesh limit of 10 to 30 and its value drops with fewer ratios up to lower mesh limit of 40.

In qualitative analysis of lower mesh limit, the antenna structure is presented in form of pictures. In special mesh properties, edge refinement factor is set equal to 4. By using Table 3.4, for a setting of lower mesh limit of 10 the mesh cells arrangement is shown in the Figure 3.17.

Figure 3.17 Antenna structure cells for lower mesh limit of 10.

Figure 3.18 Antenna structure for lower mesh limit of 30.

For a setting of lower mesh limit of 30 and edge refinement factor of 4, mesh cells arrangement is shown in the Figure 3.18. The open added space stays the same with increase in lower mesh limit; only the number of mesh cells is increased. By comparing Figure 3.17 and 3.18, it is observed that lower mesh limit is directly related to the size of mesh step. The higher the value of lower mesh limit the denser is the structure.
3.4.3 Analysis of Mesh Line Ratio Limit

Mesh line ratio limit parameter limits the creation of small mesh steps relative to the size of large mesh steps. This option is used in case of small details resulting in clustered fix points, mesh lines may not be placed at all fix points positions. Fix points are the critical points at which the expert system finds it necessary to set mesh lines, fix points are shown by red dots in Figure 3.18. From Table 3.2 it is seen, when mesh line ratio limit parameter is increased from 10 to 50, the number of mesh cells remains same. It is also seen that with increase in mesh line ratio limit from 10 to 50, number of mesh cells and simulation time remained the same. Simulated results showed that by increasing the mesh line ratio limit, the return loss, antenna gain and realized gain also remained the same.

3.4.4 Conclusions

The above discussion on manual mesh analysis motivates the need of defining the mesh in such a way that the simulations give us more accurate and converging results. Although starting the simulation with finer mesh resolution gave more accurate results, these also increased the simulation time. From the above discussions, it is concluded that the convergence in simulated antenna gain and realized gain depends on the number of mesh cells. From Table 3.3, it is seen that a convergence in antenna gain and realized gain can be achieved if we use 30 lines per wavelength. Similarly from Table 3.4, it is observed that a lower mesh limit of 30 produces converging antenna gain and realized gain. A convergence in $S_{11}$ can be achieved if lower mesh limit is set equal to 30, this can be seen in Figure 3.13.

The above analysis is a manual analysis of mesh settings, the same structure can be analysed by adaptive mesh refinement analysis in which CST Microwave Studio uses various passes and estimates the best suitable converging value of the parameters until it reaches a specified accuracy limit.

3.5 Adaptive Mesh Refinement

Adaptive meshing procedure simulates the structure a few times and improves the mesh from run to run. In adaptive meshing, the regions with high field concentration or field gradients are recognized where the mesh needs to be locally refined. If the deviation in results falls below the given accuracy level, the adaptation terminates. This approach always improves the start solution at the expense of simulation time. By using the adaptive mesh refinement option of CST Microwave Studio, the best suitable converging values of the parameters can be achieved. Initially simulation is done without adaptive meshing; the results are shown in Figure 3.19.
In the Figure 3.19, antenna gain, realized gain and \( S_{11} \) are shown without adaptive mesh refinement. These are simulated results for 10 lines per wavelength, lower mesh limit of 10 and mesh line ratio limit having a value of 10.

Special properties of adaptive mesh refinement include maximum delta \( S \), minimum number of passes and maximum number of passes. Maximum delta-\( S \) quantity is defined as a maximum deviation of the \( S \)-parameters between two subsequent passes. It is set to 0.02. The mesh adaptation stops once the \( S \)-parameter converges such that the Delta \( S \) value falls below 2%. Minimum number of passes determines the minimum number of passes which will be performed. In this simulation minimum number of passes is set equal to 2. Maximum number of passes determines the maximum number of passes to be performed for the mesh adaptation in order to converge to a final solution. In this simulation maximum number of passes is set equal to 6. The progress of the procedure is watched in the CST 1D Results/Adaptive meshing folder. With adaptive meshing, the simulated antenna gain, realized gain and number of mesh cells are shown in Table 3.5.

<table>
<thead>
<tr>
<th>Number of passes</th>
<th>Number of mesh cells</th>
<th>Antenna gain at 70GHz (dB)</th>
<th>Realized gain at 70GHz (dB)</th>
<th>Solver time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>21600</td>
<td>6.98</td>
<td>6.98</td>
<td>24</td>
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<tr>
<td>2</td>
<td>40300</td>
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<td>6.842</td>
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</tr>
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<td>6.63</td>
<td>5.96</td>
<td>265</td>
</tr>
</tbody>
</table>

**Table 3.5** Simulated results for adaptive mesh refinement.

From the Table 3.5, it is seen that the solver time increases with increase in number of passes. Here in this work the Maximum number of passes is set equal to 6 but the simulation stopped after the 5\(^{th}\) pass. This implies that the results converged to an optimum solution after the 5\(^{th}\) pass. The maximum number of passes is a useful setting to limit the total simulation time to a reasonable amount. The achieved antenna gain is shown in Figure 3.20.
From the Figure 3.20, it is seen that with adaptive mesh subsequent passes, the antenna gain decreases a little fraction, but it converges to 6.6 dB on the 4th and 5th pass. The simulator stopped on the 5th pass. From the Figure 3.21 it is concluded that realized gain also converged to 5.9 dB on the 5th pass.

Here, in this *adaptive mesh refinement* the simulator runs in five different passes and calculates the best estimated value for the $S_{11}$. In each pass, the number of cells is varied to achieve convergence in simulated parameters. It is observed that with subsequent passes, the resonant frequency shifts away from 70 GHz and it converges after 5 passes. The respective $S_{11}$ with *adaptive mesh refinement* is shown 3.22.

Now by using the Table 3.5, a graph of the number of cells against number of passes is plotted and is shown in Figure 3.23. From the Figure 3.23, it is observed that in adaptive meshing the number of cells are increased with each pass in order to meet converging results. In the first pass, the number of cells is 21600 and in the 5th pass the number of cells is increased to 213000. Solver time also increases with subsequent passes; this can be seen in the Table 3.5.
A plot of the number of mesh cells against antenna gain and realized gain is shown in Figure 3.24. The antenna gain converged for 150000 mesh cells while realized gain converged for 150000-200000 cells.

Finally, if the results of adaptive meshing are compared with manual meshing, it is observed that they are in very close relationship with each other. In manual meshing 200000 mesh cells are required to get converging gain while in adaptive meshing 150000-250000 cells resulted in converging antenna gain. Similarly for converging realized gain, manual meshing requires 233640 mesh cells while adaptive meshing requires 250000 mesh cells. From the above discussions, it is observed that the converging antenna gain and realized gain depends on number of mesh cells.

### 3.6 Accuracy Settings

The transient S-parameter calculation is mainly affected by two sources of numerical inaccuracies i.e., numerical truncation errors due to finite simulation time intervals and inaccuracies due to finite mesh resolution. The transient solver calculates the time varying field distribution that results from excitation with Gaussian pulse at the input port. The signals at ports are the fundamental results from which the S-parameters are derived using a Fourier Transform. Numerical inaccuracies can be introduced by the Fourier Transform that assumes the time signals have completely decayed to zero at the end. If this is not the case then a ripple is introduced into the S-parameters that affect the accuracy of the results. This does not move the location of maxima or minima in the S-parameter curves [2]. The amplitude of the excitation signal at end of the simulation time is called the truncation error. The level of truncation error can be controlled by the accuracy settings in the transient solver dialog box. A plot of antenna gain for various accuracy settings is shown in the Figure 3.25.
For an *accuracy* setting of -30dB, large ripples in antenna gain are observed, while for -40dB ripples are reduced and they are observed smoother for -50dB. By increasing the accuracy limitation the truncation error is limited and large ripple is reduced.

The realized gain is plotted against different *accuracy* limits and is shown in Figure 3.26. Realized gain remains almost the same for 70GHz for all the three accuracy settings. There is a minor difference of 0.04dB for -30 to -40 dB while 0.01dB difference for -40 to -50dB. At 71GHz a maximum realized gain of 6.79dB is seen for accuracy settings of -50dB, and it reduces a small fraction of 0.02dB for -40dB and gives least value of 6.6db for an accuracy setting of -30dB. A plot of $S_{11}$ for various *accuracy* settings is shown in Figure 3.27.

From Figure 3.27 it is seen that the $S_{11}$ minimum is achieved at 71GHz. In order to observe ripples in $S_{11}$ an enlarged picture is shown in the Figure 3.28. From Figure 3.28, it is seen that there are more ripples in the S parameters for an *accuracy* setting
of -30dB, while for -40dB ripples are reduced and for -50dB an almost smooth curve for \( S_{11} \) is obtained. All the above results are tabulated in Table 3.6.

<table>
<thead>
<tr>
<th>Accuracy settings</th>
<th>Lines per wavelength</th>
<th>Lower mesh limit</th>
<th>Mesh line ratio limit</th>
<th>Antenna gain at 70GHz (dB)</th>
<th>Realized gain at 70GHz (dB)</th>
<th>( S_{11} ) at 70GHz (dB)</th>
<th>Total Simulation time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-30dB</td>
<td>10</td>
<td>30</td>
<td>10</td>
<td>6.66</td>
<td>6.13</td>
<td>-9.43</td>
<td>136</td>
</tr>
<tr>
<td>-40dB</td>
<td>10</td>
<td>30</td>
<td>10</td>
<td>6.73</td>
<td>6.17</td>
<td>-9.21</td>
<td>155</td>
</tr>
<tr>
<td>-50dB</td>
<td>10</td>
<td>30</td>
<td>10</td>
<td>6.74</td>
<td>6.15</td>
<td>-9.12</td>
<td>192</td>
</tr>
</tbody>
</table>

Table 3.6 Accuracy settings and the respective simulated results.

In CST Microwave Studio an accuracy setting of -30dB is considered as moderate, -40dB as high and -50dB as very high accuracy level. When accuracy setting is changed from -30 dB to -40dB, a reduction of 0.13dB in antenna gain is noticed and antenna gain remained almost constant for -50dB. Similarly for realized gain, when an accuracy setting is changed from -30 to -40dB, a reduction of 0.04dB in realized gain in noticed which is negligible. However, the simulation time increases when the accuracy setting is changed from -30 to -50dB.

In order to achieve lowest ripples in S-parameters and antenna gain, an accuracy setting of -50dB is required for the transient solver particularly at 70GHz. However, more simulation time is required for this accuracy setting.

### 3.7 Conclusions

In this Chapter the accuracy of the numerical simulator is investigated. The boundary conditions and the port dimensions are also investigated that would be applied to design the microstrip patch antenna. The effect of manual mesh density on the accuracy of simulations is also studied. In this Chapter, the accuracy of the numerical simulator is verified both by manual meshing and by adaptive mesh refinement. The results shown by both type of meshing are close to each other. However, in the case of adaptive meshing, it is observed that CST Microwave Studio transient solver converges the results after 5 passes. The simulation time of the 5 passes in adaptive mesh refinement takes longer than manual meshing. In general Adaptive mesh refinement can be used for the electromagnetic simulation but it takes much more time for completion of the specified number of passes. It is also shown that an accuracy setting of -50dB produced the lowest ripples in \( S_{11} \) and antenna gain. However, the simulation time for the accuracy settings of -50dB is higher than -40dB. In future in this thesis work we will use accuracy setting of -40dB. An accuracy setting of -50dB can be applied to get smoother results at later stages.

Finally, it is decided to use manual mesh settings with 10 lines per wavelength, a lower mesh limit of 30 and mesh line ratio limit of 10 with an accuracy settings of -40dB for the proceeding simulations. For a lower mesh limit of 30, resonance frequency does not vary significantly; this can be seen in Figure 3.13. Also realized gain drops with fewer ratios for a mesh limit of 30 and above 30.
Chapter 4

Design of Inset-feed Rectangular Patch Antenna

In this Chapter, the design of an inset feed patch antenna for operation at 70GHz is presented. The patch antenna design is analysed by using analytical method, numerical optimization method and parameter sweep of the dimensions as introduced in Chapter 2. The results obtained from these three design methods are compared and discussed. The procedure involved in the design of the microstrip patch antenna is shown in Figure 4.1.

In order to get converging results, it has been suggested in Chapter 3 to use manual mesh settings with 10 lines per wave length, a lower mesh limit of 30 and mesh line ratio limit of 10 with an accuracy settings of -40dB for the proceeding simulations. For a lower mesh limit of 30, the resonance frequency does not vary significantly. Also the realized gain drops with fewer ratios for a mesh limit of 30. Adaptive mesh refinement is not used for this work.

4.1 Analytical Method

The dimensions of the patch have been calculated by using the analytical formulas presented in Chapter 2. The design parameters given in Table 2.1 are used to calculate the dimensions of the patch. The width of the microstrip feed line have been calculated by using line calc [24] tool. The equations through (2,6 – 2,9) are used to calculate the width and the length of the patch while the equations through (2,11 – 2,16) are used to calculate the position of the inset feed point. The calculations are given in Appendix-A and the programming code for these calculations is given in Appendix-B. The calculated dimensions are tabulated in Table 4.1.

<table>
<thead>
<tr>
<th>Effective dielectric constant ($\varepsilon_{\text{eff}}$)</th>
<th>2.88</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length of the patch (Lp) in µm</td>
<td>1166</td>
</tr>
<tr>
<td>Width of the patch (Wp) in µm</td>
<td>1486</td>
</tr>
<tr>
<td>Position of inset feed point (d) in µm</td>
<td>418</td>
</tr>
<tr>
<td>Width of the microstrip feed line (W) in µm</td>
<td>234</td>
</tr>
</tbody>
</table>

Table 4.1 Calculated design dimensions of the microstrip patch.

The dimensions of the patch obtained from the analytical calculations are numerically verified in CST Microwave Studio. Manual mesh is defined having 10 lines per
wavelength, lower mesh limit of 30, mesh line ratio limit of 10, and an edge refinement factor of 4. An accuracy setting of -40dB is used to simulate the structure.

**Figure 4.1** Procedure involved in the design of the microstrip patch antenna.
For the analytically calculated dimensions the simulated return loss is shown in Figure 4.2. The simulated directivity, antenna gain and realized gain are shown in Figure 4.3.

From the Figure 4.2, it is seen that the patch antenna resonates at 69.3GHz with return loss of 11.9dB. Here the resonance frequency is not exactly at 70GHz as expected. There is a shift of 0.7GHz in these analytical calculated dimensions. The patch size and feed point is required to be optimized further in order to get resonance at 70GHz and a matched impedance. The simulation results for the analytically calculated patch dimensions are presented in Table 4.2.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resonant frequency (GHz)</td>
<td>69.3</td>
</tr>
<tr>
<td>Directivity (dBi)</td>
<td>7.2</td>
</tr>
<tr>
<td>Antenna gain (dB)</td>
<td>6.5</td>
</tr>
<tr>
<td>Realized gain (dB)</td>
<td>5.7</td>
</tr>
<tr>
<td>$S_{11}$ (dB)</td>
<td>-11.9</td>
</tr>
</tbody>
</table>

Table 4.2 Simulated results for analytically computed patch dimensions.

The results obtained from Table 4.2 indicate that the simulated results from analytically calculated patch dimensions show a deviation of 0.7GHz from the resonance frequency of 70GHz. The analytical method does not necessarily produce the accurate result but it provides a good starting value. This motivates to use a more accurate method to achieve the desired results. Numerical simulation have been used for this purpose.

4.2 Numerical Optimization

Here in this work, CST Microwave Studio have been used as a numerical electromagnetic solver. Using the optimization tool of CST Microwave Studio transient solver and setting the goal of $S_{11} \leq -30$dB, the length of patch (Lp) and inset feed point (d) is optimized while width of the patch (Wp) is kept 1.5 times the length of the patch. The use of Wp=1.5*Lp is an approximate rule of thumb for low
dielectric constant substrates [1]. LCP is used as a substrate in this work and it has [10] low dielectric constant (2.9-3.2 for $f < 105$GHz).

By using the macros option in CST Microwave Studio, Broadband Farfield Monitors are defined for 55-85GHz in step-size of 0.5GHz. Hexahedral Mesh is used having 10 lines per wavelength, lower mesh limit of 30, and mesh line ratio limit of 10. The template based post processing option of CST Microwave Studio is used to define far field pattern plots. The plot range of each of the directivity, antenna gain and realized gain is chosen to be in the broadside direction and a scaling component is selected as Absolute. In cutplane window, fixed angle for theta and phi is entered as 0-degree in order to get the broadside radiation. In the transient solver parameters settings, accuracy of (-40dB) is used as investigated in Chapter 3. The Interpolated Quasi Newton Optimizer is used in which the number of passes is set equal to 1. Then by using the optimize option of the transient solver, the goal for $S_{11}$ is defined as ≤-30dB at 70GHz. The length of the patch and inset feed point are optimised for 70 GHz. The optimized results are presented in Table 4.3.

<table>
<thead>
<tr>
<th>Length of the patch (Lp) in µm</th>
<th>1150</th>
</tr>
</thead>
<tbody>
<tr>
<td>Width of the patch (Wp) in µm</td>
<td>1725</td>
</tr>
<tr>
<td>Position of Inset feed point (d) in µm</td>
<td>308</td>
</tr>
<tr>
<td>Gap between microstrip feed line and the patch (g) in µm</td>
<td>100</td>
</tr>
</tbody>
</table>

Table 4.3 Optimized dimensions at 70 GHz.

The gap (g) between the microstrip feedline and the patch is kept constant. The simulated directivity, antenna gain, realized gain at 70GHz can be seen from Figure 4.4. A plot of the optimized return loss is shown in the Figure 4.5.

In Figure 4.4, the simulated directivity is 7.3dBi and the simulated antenna gain and realized gain are equal to 6.7dB at 70GHz. By comparison of Figure 4.2 with 4.5, it is concluded that the return loss is much improved with optimized dimensions as
compared to that of the analytically calculated dimensions. Plotted results of numerical optimization are tabulated in Table 4.4.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resonant frequency (GHz)</td>
<td>70GHz</td>
</tr>
<tr>
<td>Directivity (dBi)</td>
<td>7.3</td>
</tr>
<tr>
<td>Antenna gain (dB)</td>
<td>6.7</td>
</tr>
<tr>
<td>Realized gain (dB)</td>
<td>6.7</td>
</tr>
<tr>
<td>$S_{11}$ (dB)</td>
<td>-34.4</td>
</tr>
<tr>
<td>-10dB Bandwidth (GHz)</td>
<td>1.85</td>
</tr>
</tbody>
</table>

**Table 4.4** Results of numerical optimization.

By comparing Table 4.2 and 4.4, we can conclude that by optimization of length and inset feed point we can achieve the goal of resonance at 70 GHz and can also improve the return loss. A plot of the calculated and the optimized return loss is shown in Figure 4.6.

![Figure 4.6](image)

**Figure 4.6** A comparison of return loss for analytically calculated and optimized dimensions of the patch.

Figure 4.6 shows a comparison between the calculated and the optimized results for return loss. A better return loss is achieved for numerically optimized dimensions. The radiation patterns with the with the broadside direction are shown in the Figure 4.7. The E-field is shown in the Figure 4.8. The patch is operated in the fundamental mode with the maximum fields along the width corners.

![Figure 4.7](image)
![Figure 4.8](image)
4.3 Parameter Variation

The simulated results can be verified by using a parameter variation of the patch dimension. In this method, a parameter variation is performed around the already found result of the optimizer. Here in this work, the patch length, the patch width and the inset feed point of the rectangular patch antenna are varied in equidistant steps. Two parameters are kept constant and the third one is varied to see the respective variations in return loss, directivity, antenna gain and realized gain. The optimized dimensions at 70GHz are used from Table 4.3 for this parameter variation. The parameter sweep option of the CST Microwave Studio is used in order to investigate how performance parameters are affected. The converging results of numerical optimizer are verified.

4.3.1 Analysis of Inset Feed Point

The inset feed point is varied around the optimized value of 308µm. By using the parameter sweep option of CST MWS, the value of the inset feed point is varied from 250-370µm in 7 equidistant samples while the optimized length 1150µm and the optimized width 1725µm are kept constant. The return loss, directivity, antenna gain and realized gain are analysed. A plot of return loss for the variation in inset feed point is shown in the Figure 4.9.

![Figure 4.9](image)

**Figure 4.9** $S_{11}$ versus frequency for different values of inset feed point.

From the Figure 4.9 it is seen that with increasing inset feed point from 250-310µm the return loss decreases up to 36.3dB and then increases again. The values of the resonant frequency for various inset feed points taken from graph are shown in Table 4.5.
<table>
<thead>
<tr>
<th>Inset feed point (µm)</th>
<th>Resonant frequency ( f_0 ) (GHz)</th>
<th>Realized gain (dB)</th>
<th>( S_{11} ) (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>250</td>
<td>70.27</td>
<td>6.58</td>
<td>-13.59</td>
</tr>
<tr>
<td>270</td>
<td>70.18</td>
<td>6.64</td>
<td>-16.33</td>
</tr>
<tr>
<td>290</td>
<td>70.09</td>
<td>6.71</td>
<td>-21.36</td>
</tr>
<tr>
<td>310</td>
<td>69.97</td>
<td>6.74</td>
<td>-38.55</td>
</tr>
<tr>
<td>330</td>
<td>69.85</td>
<td>6.75</td>
<td>-22.93</td>
</tr>
<tr>
<td>350</td>
<td>69.64</td>
<td>6.56</td>
<td>-15.74</td>
</tr>
<tr>
<td>370</td>
<td>69.46</td>
<td>6.36</td>
<td>-11.6</td>
</tr>
</tbody>
</table>

Table 4.5 Resonant frequencies for inset feed points.

From the Table 4.5 it is seen that the inset feed point has more effects on return loss as compared to resonance frequency. When the value of inset feed point is increased from 250-370µm, the return loss value decreases up to 310µm and then increases again. This is expected, because the inset feed point is the primary tool used to match the antenna, and the resonant properties of the antenna are not altered drastically by changing this parameter.

Similarly, for the same variation of the inset feed point, a plot of simulated directivity is shown in Figure 4.10.

Figure 4.10 Directivity versus frequency for different inset feed points.

Directivity does not change significantly with inset feed point to a good approximation between 250-370µm distance. There is a variation of 0.1dB for the entire parameter sweep, this implies directivity does not change significantly with inset feed point. Directivity is plotted against the inset feed point at 70GHz and is shown in Figure 4.11. It is observed that maximum directivity is at 250µm and it decreases slightly with increase in the value of the inset feed point.

Figure 4.11 Directivity versus inset feed point at 70GHz.

A plot of antenna gain against frequency is shown in Figure 4.12 for the same variation in the inset feed point.
Figure 4.12: Antenna gain versus frequency for various inset feed points.

From the Figure 4.12, it is seen that with the variation in inset feed point, there is no major variation in antenna gain. A maximum antenna gain of 6.75dB is observed at an inset feed point of 270µm. A plot of antenna gain against different inset feed points at 70GHz is shown in Figure 4.13. There is a negligible variation of 0.05dB for the entire sweep. When compared with optimized result, it is noticed that the manual sweep value of the inset feed point of 310µm is very close to the optimized value i.e., 308µm, so by parameter variation the same value of antenna gain is verified.

Similarly, for the same variation of the inset feed point, a plot of realized gain is shown in Figure 4.14.

From the Figure 4.14, it is seen that the realized gain increases from 6.5dB to a maximum value of 6.75dB for an inset feed distance of 250-310µm. The variations in realized gain are seen due to variations in $S_{11}$. This maximum value is very close to
the value obtained in numerical optimization. The realized gain is plotted as a function of variable inset feed point at resonance frequency by using Table 4.5 and the plot is shown in Figure 4.15. It is seen that maximum realized gain is achieved at an inset feed position of 310µm and this value verifies the optimized realized gain which is obtained at 308µm. The results of the above graphs for return loss, directivity, antenna gain and realized gain at 70GHz are tabulated in Table 4.6.

<table>
<thead>
<tr>
<th>Inset feed point (µm)</th>
<th>Directivity (dB)</th>
<th>Antenna gain (dB)</th>
<th>Realized gain (dB)</th>
<th>$S_{11}$ (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>250</td>
<td>7.33</td>
<td>6.74</td>
<td>6.52</td>
<td>-13.1</td>
</tr>
<tr>
<td>270</td>
<td>7.33</td>
<td>6.75</td>
<td>6.63</td>
<td>-15.75</td>
</tr>
<tr>
<td>290</td>
<td>7.33</td>
<td>6.75</td>
<td>6.71</td>
<td>-20.95</td>
</tr>
<tr>
<td>310</td>
<td>7.33</td>
<td>6.75</td>
<td>6.75</td>
<td>-36.32</td>
</tr>
<tr>
<td>330</td>
<td>7.32</td>
<td>6.74</td>
<td>6.70</td>
<td>-20.4</td>
</tr>
<tr>
<td>350</td>
<td>7.31</td>
<td>6.73</td>
<td>6.52</td>
<td>-13.21</td>
</tr>
<tr>
<td>370</td>
<td>7.29</td>
<td>6.70</td>
<td>6.14</td>
<td>-9.71</td>
</tr>
</tbody>
</table>

Table 4.6 Directivity, antenna gain, realized gain and return loss for different values of the inset feed point at 70GHz.

From Table 4.6 it is concluded that variation in the inset feed point has more effect on the return loss compared to directivity, antenna gain and realized gain. It is seen that when the value of inset feed point is increased from 250-370µm, return loss is decreased and at a certain point it gave a minimum value of return loss (-36.3dB). It is also seen that the realized gain has lowest value as compared to directivity and gain while gain has a bit higher value as compared to realized gain.

### 4.3.2 Analysis of Patch Length

The length of the patch is varied around the optimized value of 1150µm. The length of the patch is varied from 1085-1205µm in 7 equidistant sample points, while the optimized width of the patch and the optimized inset feed point are kept constant. The simulated return loss, directivity, antenna gain and realized gain are analysed. A plot of the simulated return loss for the variation in length of patch is shown in Figure 4.16.

![Figure 4.16: Graph between return loss and frequency.](image)
From the Figure 4.16, it is seen that with increasing the patch length from 1085-1205µm, the resonance frequency shifts almost 1GHz for every 20µm increase in length. These values of resonance frequencies taken from Figure 4.16 are tabulated in Table 4.7.

<table>
<thead>
<tr>
<th>Lp (µm)</th>
<th>Resonant frequency ( (f_o) ) (GHz)</th>
<th>Realized gain (dB)</th>
<th>( S_{11} ) (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1085</td>
<td>73.42</td>
<td>6.83</td>
<td>-15.67</td>
</tr>
<tr>
<td>1105</td>
<td>72.34</td>
<td>6.84</td>
<td>-19.83</td>
</tr>
<tr>
<td>1125</td>
<td>71.29</td>
<td>6.82</td>
<td>-26.8</td>
</tr>
<tr>
<td>1145</td>
<td>70.24</td>
<td>6.71</td>
<td>-43.59</td>
</tr>
<tr>
<td>1165</td>
<td>69.22</td>
<td>6.62</td>
<td>-25.44</td>
</tr>
<tr>
<td>1185</td>
<td>68.26</td>
<td>6.52</td>
<td>-20.3</td>
</tr>
<tr>
<td>1205</td>
<td>67.3</td>
<td>6.45</td>
<td>-17.32</td>
</tr>
</tbody>
</table>

**Table 4.7** Return loss for different values of the patch length.

As the length of the patch is increased from 1085-1145µm, the return loss values increase from 15.67dB to 43.59dB but with further increase in length of patch to 1205µm, the return loss decreases to 17.32dB. Also the resonant frequency shifts in big steps for small changes in the patch length. It is concluded that length of the patch greater effects on resonant frequency.

Similarly, a plot of directivity for the same variation in the patch length is shown in the Figure 4.17.

Maximum value of directivity of 7.33dBi is seen at a length of 1165µm and this is very close to the optimized value of 1150µm. In Figure 4.18, the directivity is plotted as a function of variable patch length for 70GHz. Figure 4.17 and 4.18 shows that directivity varies to approximation of 0.2dB for the entire sweep in length. A maximum value of directivity can be obtained when length is between 1145-1165µm.
Similarly, antenna gain is plotted for variations in the patch length. A plot of antenna gain against frequency is shown in Figure 4.19.

![Plot of antenna gain versus frequency for various patch lengths.](image1)

![Plot of realized gain versus frequency for different patch lengths.](image2)

When the patch length is varied, maximum value of antenna gain is observed at a length of 1165µm. In Figure 4.20, the antenna gain is plotted as a function of variable patch length for 70GHz. It is observed that maximum antenna gain is achieved if the length of patch is 1185µm and this value is a bit away from optimized length. Antenna gain varies approximately 0.6dB for the entire sweep in length.

Similarly realized gain is analysed for the same variation in the patch length. The simulated realized gain is shown in Figure 4.21.

![Plot of realized gain versus variable patch length at f0.](image3)

The maximum value of realized gain is achieved at length of 1145µm, if we further increase the patch length, realized gain decreases. The realized gain is plotted as a
function of variable patch length at resonance frequency by using Table 4.7 and the plot is shown in Figure 4.22. From Figure 4.22, it is observed that the maximum value of realized gain obtained from the length variation is very close to the optimized realized gain. In tabular form, the above graphs of return loss, directivity, antenna gain and realized gain are presented in Table 4.8.

<table>
<thead>
<tr>
<th>Patch length (µm)</th>
<th>Directivity (dB)</th>
<th>Antenna gain (dB)</th>
<th>Realized gain (dB)</th>
<th>$S_{11}$ (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1085</td>
<td>7.12</td>
<td>6.33</td>
<td>1.813</td>
<td>-1.89</td>
</tr>
<tr>
<td>1105</td>
<td>7.21</td>
<td>6.66</td>
<td>3.98</td>
<td>-3.4</td>
</tr>
<tr>
<td>1125</td>
<td>7.28</td>
<td>6.75</td>
<td>5.82</td>
<td>-7.1</td>
</tr>
<tr>
<td>1145</td>
<td>7.32</td>
<td>6.74</td>
<td>6.71</td>
<td>-21.3</td>
</tr>
<tr>
<td>1165</td>
<td>7.33</td>
<td>6.77</td>
<td>6.46</td>
<td>-11.5</td>
</tr>
<tr>
<td>1185</td>
<td>7.32</td>
<td>6.81</td>
<td>5.39</td>
<td>-5.55</td>
</tr>
<tr>
<td>1205</td>
<td>7.33</td>
<td>6.69</td>
<td>3.98</td>
<td>-3.33</td>
</tr>
</tbody>
</table>

**Table 4.8** Directivity, antenna gain, realized gain and return loss for various patch lengths at 70 GHz.

From Table 4.8 it is seen that variations in patch length at 70GHz have more effects on the return loss and realized gain as compared to directivity and gain. It is observed that by increasing the length of the patch from 1085-1145µm, $S_{11}$ decreases from -1.8dB to -21.3dB. With further increase in length from 1145 to 1205µm, $S_{11}$ starts increasing. If Table 4.7 and 4.8 are compared, it is seen the patch length has greater effects on resonant frequency.

### 4.3.3 Analysis of Patch Width

The width of the patch is varied around the optimized value of the width (1725µm) while the optimised patch length and the optimised inset feed point are kept constant. The width of the patch antenna is swept from 1670-1790µm by taking 7 equidistant samples. A plot of return loss against various patch widths is shown in Figure 4.23.

**Figure 4.23** $S_{11}$ versus frequency for various values of patch width.
From the Figure 4.23, it is seen that by increasing the patch width the return loss decreases to a certain limit and then increases again. The resonance frequency does not vary significantly for the entire sweep in the patch width. In tabular form the resonant frequencies for the variation in the patch width are presented in Table 4.9.

<table>
<thead>
<tr>
<th>Patch width (µm)</th>
<th>Resonant frequency ($f_r$) (GHz)</th>
<th>Realized gain (dB)</th>
<th>$S_{11}$ (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1670</td>
<td>70.21</td>
<td>6.66</td>
<td>-17.32</td>
</tr>
<tr>
<td>1690</td>
<td>70.15</td>
<td>6.71</td>
<td>-20.92</td>
</tr>
<tr>
<td>1710</td>
<td>70.06</td>
<td>6.73</td>
<td>-27.06</td>
</tr>
<tr>
<td>1730</td>
<td>69.97</td>
<td>6.75</td>
<td>-48.52</td>
</tr>
<tr>
<td>1750</td>
<td>69.88</td>
<td>6.76</td>
<td>-26.01</td>
</tr>
<tr>
<td>1770</td>
<td>69.82</td>
<td>6.75</td>
<td>-20.18</td>
</tr>
<tr>
<td>1790</td>
<td>69.73</td>
<td>6.38</td>
<td>-16.31</td>
</tr>
</tbody>
</table>

**Table 4.9** Return loss and resonant frequencies for different patch widths.

From the Table 4.9 it is seen that with increase in value of patch width from 1670-1730µm, the return loss increases and reaches to 48.5dB and resonant frequency is shifted from 70.2GHz to 69.9GHz. If the Table 4.9 is compared with Table 4.7, it is observed that the resonant frequency shifts in bigger steps for variation in patch length as compared to variation in patch width. In case of variation in patch width there is a minor shift in resonant frequency.

Now, a plot of directivity for the same variation in patch width is shown in Figure 4.24.

**Figure 4.24** Directivity versus frequency for different patch widths.

Directivity does not vary significantly for the entire sweep in the patch width. A plot of directivity versus patch width at 70GHz is shown in the Figure 4.25. The optimized width of the patch is verified by the manual sweep. The directivity at the width of 1730µm is close to the optimized patch width of 1725µm as can be seen in the Figure 4.25.

**Figure 4.25** Plot of directivity versus width of the patch at 70GHz.
Similarly, for antenna gain analysis, the width of the patch is varied with the same ratio. A graph of antenna gain against frequency is shown in the Figure 4.26.

From the Figure 4.26 it is observed that the antenna gain stays almost the same for the entire sweep in the patch width. Antenna gain varies approximately 0.06dB for the entire sweep in the patch width. For the whole sweep the gain stays between 6.71-6.77dB, so patch width variation does not have a large effect on gain. At 70GHz, a plot of antenna gain for various patch widths is shown in Figure 4.27. Figure 4.27 also indicates a comparison between optimized patch width and manual patch widths.

Similarly, for realized gain analysis, a plot of the same variable width of the patch against frequency is shown in Figure 4.28.

Realized gain varies approximately 0.1dB for the entire sweep in the width. It is noticed that maximum realized gain is achieved at a patch width of 1750µm. The
realized gain is plotted as a function of variable patch width at resonance frequency by using Table 4.9 and the plot is shown in Figure 4.29. From the Figure 4.29, the optimized realized gain is verified by using the manual sweep of the width. Maximum value of realized gain is seen as 6.76dB at the patch width of 1750µm and this value is close to the optimized value of realized gain. So the realized gains for manual sweep and for optimized values are in close agreement with each other. All the above graphs for return loss, directivity, antenna gain and realized gain are tabulated in Table 4.10.

<table>
<thead>
<tr>
<th>Patch width (um)</th>
<th>Directivity (dBi)</th>
<th>Antenna gain (dB)</th>
<th>Realized gain (dB)</th>
<th>$S_{11}$ (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1670</td>
<td>7.30</td>
<td>6.71</td>
<td>6.60</td>
<td>-19.8</td>
</tr>
<tr>
<td>1690</td>
<td>7.31</td>
<td>6.72</td>
<td>6.70</td>
<td>-22.92</td>
</tr>
<tr>
<td>1710</td>
<td>7.32</td>
<td>6.73</td>
<td>6.73</td>
<td>-27.9</td>
</tr>
<tr>
<td>1730</td>
<td>7.33</td>
<td>6.74</td>
<td>6.75</td>
<td>-34.5</td>
</tr>
<tr>
<td>1750</td>
<td>7.33</td>
<td>6.76</td>
<td>6.76</td>
<td>-27.9</td>
</tr>
<tr>
<td>1770</td>
<td>7.34</td>
<td>6.77</td>
<td>6.75</td>
<td>-22.9</td>
</tr>
<tr>
<td>1790</td>
<td>7.34</td>
<td>7.78</td>
<td>6.73</td>
<td>-19.6</td>
</tr>
</tbody>
</table>

Table 4.10 Directivity, antenna gain, realized gain and return loss variation in the patch width at 70GHz.

By increasing the width of the patch from 1670-1790µm the directivity, antenna gain and realized gain do not change significantly. However, some variations in return loss are seen. A maximum value of antenna gain and directivity is observed at 1770µm while maximum realized gain is seen at 1750µm.

4.4 Conclusion

A rectangular patch antenna have been designed by the using transmission line model. The patch dimensions are calculated by using analytical relationships. The dimensions of the patch obtained from analytical equations give good starting values and these dimensions are used as initial values in the numerical optimizer. The analytically calculated dimensions provide a good quantitative understanding but later on these dimensions are found to be less accurate.

Due to this low accuracy of analytical design method, the patch antenna is investigated by CST Microwave Studio which is a 3D electromagnetic field simulator. The patch antenna is optimised for the investigated mesh density, the boundary conditions and the port dimensions at 70GHz.

The convergence of the optimized results have been verified by using the parameter sweep of dimensions. Parameter sweep of dimensions is found to be most reliable but it is more complicated with so many parameters. One example is presented for the investigated mesh density, the boundary conditions and the port dimensions. In this example, it is found that with a small variation of the length of the patch, there is a large shift in resonant frequency as it can be seen in Table 4.7. If Table 4.7 and 4.9 are compared, it is seen that the patch length has large effects on resonant frequency while patch width has small effects on resonant frequency.
Resonant frequency decreases abruptly from 73.42GHz to 67.3 GHz when length is increased from 1085-1205µm. On the other hand, the resonant frequency decreases in smaller steps for from 70.21-69.73GHz when the patch width is increased from 1670-1790µm.

By comparing the Tables 4.6, 4.8 and 4.10, it is deduced that the dimensions of the rectangular patch to get minimum return loss and maximum realized antenna gain are inset feed point of 310µm, length of 1145µm and width of 1730µm. On the other hand, the dimensions to get maximum antenna gain are: an inset feed point of 310µm, the patch length of 1185µm and the patch width of 1790µm. These conclusions are presented in Table 4.11.

<table>
<thead>
<tr>
<th>Result</th>
<th>Inset feed point (d) in µm</th>
<th>Length of the patch (Lp) in µm</th>
<th>Width of the patch (Wp) in µm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum return loss</td>
<td>310</td>
<td>1145</td>
<td>1730</td>
</tr>
<tr>
<td>Maximum antenna gain</td>
<td>310</td>
<td>1185</td>
<td>1790</td>
</tr>
<tr>
<td>Maximum realized gain</td>
<td>310</td>
<td>1145</td>
<td>1730</td>
</tr>
</tbody>
</table>

**Table 4.11** Optimum parameters for minimum return loss, maximum antenna gain and maximum realized gain.

When these values are compared with the optimized results as shown in the Table 4.3, it is observed that these dimensions are in close relationship with the manual sweep values. This implies that the optimized dimensions are verified by manual sweep solution. During the parameter sweep, it is observed that the resonance frequency shifts in bigger steps with variation in patch length as compared to variation in patch width. It is also observed during the parameter variation that the patch length has major effects on radiation properties of the antenna, while the patch width has smaller effects. The three approaches have been applied to design a rectangular patch antenna. The results obtained from these design approaches are compared and discussed.
Chapter 5

Investigation of Performance Parameters with Variation in the Patch Width

In Chapter 4, the performance properties of the patch antenna have been investigated with a width of 1.5 times the patch length. The use of a width of 1.5 times the patch length is an approximate rule of thumb [1] for low dielectric constant substrates. The design is numerically optimized and further verified by parameter sweep of dimensions of the patch. However, there are occasions where a different ratio is required because of space limitations, or to change the input impedance. In this Chapter, the performance properties of the microstrip patch antenna for various width to length ratios of the patch at 70GHz are investigated. In order to obtain an optimum solution, each design of the microstrip patch antenna having various width to length ratios is optimized with the inset feed location. Starting with a patch width equal to its length, the patch width is increased in equal steps up to twice the patch length.

5.1 Analysis of Width for a Microstrip Patch with Wp=Lp

The microstrip patch antenna has been analysed by keeping the patch width equal to the patch length. When the width of a patch is equal to its length, the patch becomes a square shaped patch. The calculated dimensions of the patch are used as initial values for optimization. The manual mesh settings as investigated in Chapter 3 are used to simulate the structure. In the transient solver parameters settings, an accuracy setting of -40dB is used as investigated in Chapter 3. The macros option of CST Microwave Studio is used to construct farfield monitors for 55-85GHz in step size of 0.5GHz. The Template Based Postprocessing option of the CST Microwave Studio is used to define the farfield pattern plots. The plot range for the directivity, antenna gain and realized gain is chosen to be in the broadside direction and scaling component is selected as Absolute. In cutplane window, a fixed angle for theta and phi is entered 0-degree in order to get broadside radiation. The Interpolated Quasi Newton Optimizer is used in which the number of passes is set equal to 1. A goal of $S_{11} \leq -30$dB is defined to optimize the structure. The patch width is kept equivalent to its length. The initial patch dimensions are taken from the analytically calculated dimensions. The length and the inset feed point of the patch are optimized for 70GHz. The optimized results are presented in Table 5.1.
Table 5.1 Optimized dimensions at 70 GHz for a microstrip patch with Wp=Lp.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length of the patch (Lp) in µm</td>
<td>1179</td>
</tr>
<tr>
<td>Width of the patch (Wp) in µm</td>
<td>1179</td>
</tr>
<tr>
<td>Position of Inset feed point (d) in µm</td>
<td>438</td>
</tr>
<tr>
<td>Gap between microstrip feed line and the patch (g) in µm</td>
<td>100</td>
</tr>
</tbody>
</table>

The gap (g) between the microstrip feedline and the patch is kept constant. A plot of the optimized return loss is shown in Figure 5.1. By using the Template Based Postprocessing option of CST Microwave Studio 10dB bandwidth is calculated. The simulated directivity, gain and realized gain at 70GHz are shown in Figure 5.2.

From Figure 5.1, it is seen that the simulated return loss is 33.8dB and -10dB bandwidth is 1.37GHz. The results obtained from the optimization show that the resonance is obtained at 70GHz with a directivity of 7.1dBi while the antenna gain and realized gain are equal to 6.4dB.

5.2 Analysis of Patch Width for Wp=1.2*Lp

The microstrip patch antenna is analysed by keeping the patch width of 1.2 times the patch length. By using the same settings as described in Section 5.1, the antenna structure is simulated with an optimization goal of $S_{11} \leq -30$dB. The initial dimensions of the patch are used from the analytically calculated dimensions. The length and the inset feed point are optimized for 70GHz. The optimized dimensions are given in Table 5.2.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length of the patch (Lp) in µm</td>
<td>1165</td>
</tr>
<tr>
<td>Width of the patch (Wp) in µm</td>
<td>1398</td>
</tr>
<tr>
<td>Position of Inset feed point (d) in µm</td>
<td>392</td>
</tr>
<tr>
<td>Gap between microstrip feed line and the patch (g) in µm</td>
<td>100</td>
</tr>
</tbody>
</table>

Table 5.2 Optimized dimensions at 70 GHz for a microstrip patch with Wp=1.2Lp.
A plot of the optimized return loss is shown in the Figure 5.3. The simulated directivity, gain, and realized gain at 70GHz are shown in Figure 5.4.

A return loss of 34.26dB and -10dB bandwidth of 1.55GHz is observed for this optimized solution. With the optimized dimensions, the resonance is obtained at 70GHz with a directivity of 7.2dBi while the antenna gain and realized gain are equal to 6.5dBi. Here, in this case directivity, antenna gain and realized gains are improved by 0.1dB as compared to Wp=Lp. The -10dB bandwidth is also improved as compared to Wp=Lp.

### 5.3 Analysis of Width for a Microstrip Patch with Wp=1.4Lp

Again, the same settings are used as described in Section 5.1 and the microstrip patch antenna is analysed with the patch width of 1.4 times the patch length. The antenna structure is simulated with an optimization goal of $S_{11} \leq -30$dB. The optimized dimensions are given in Table 5.3.

<table>
<thead>
<tr>
<th>Length of the patch (Lp) in µm</th>
<th>1155</th>
</tr>
</thead>
<tbody>
<tr>
<td>Width of the patch (Wp) in µm</td>
<td>1617</td>
</tr>
<tr>
<td>Position of Inset feed point (d) in µm</td>
<td>336</td>
</tr>
<tr>
<td>Gap between microstrip feed line and the patch (g) in µm</td>
<td>100</td>
</tr>
</tbody>
</table>

**Table 5.3** Optimized dimensions at 70 GHz for a microstrip patch with Wp=1.4Lp.

A plot of the optimized return loss is shown in the Figure 5.5. The simulated directivity, antenna gain, and realized gain at 70GHz are shown in Figure 5.6.
Figure 5.5 Plot of return loss against frequency for \( W_p=1.4L_p \).

Figure 5.6 Plot of directivity gain and realized gain for \( W_p=1.4L_p \).

From the Figure 5.5, it is seen that the simulated return loss is 35.5\( \text{dB} \) and the -10\( \text{dB} \) bandwidth is 1.77\( \text{GHz} \). The optimized dimensions resulted in a directivity of 7.3\( \text{dBi} \) while the antenna gain and realized gain are equal to 6.7\( \text{dB} \). Here, higher antenna gain and realized gains are observed as compared to a patch width of 1.2 times the patch length. Also a broader bandwidth is achieved.

5.4 Analysis of Width for a Microstrip Patch with \( W_p=1.6L_p \)

The microstrip patch antenna is analysed by keeping the patch width equal to 1.6 times the patch length. The same settings are used as described in Section 5.1. The patch length and the inset feed point are optimized at 70\( \text{GHz} \) with an optimization goal of \( S_{11} \leq -30\text{dB} \). The optimized dimensions are tabulated in Table 5.4.

<table>
<thead>
<tr>
<th>Length of the patch (Lp) in µm</th>
<th>Width of the patch (Wp) in µm</th>
<th>Position of Inset feed point (d) in µm</th>
<th>Gap between microstrip feed line and the patch (g) in µm</th>
</tr>
</thead>
<tbody>
<tr>
<td>1144</td>
<td>1830</td>
<td>289</td>
<td>100</td>
</tr>
</tbody>
</table>

Table 5.4 Optimized dimensions at 70 \( \text{GHz} \) for a microstrip patch with \( W_p=1.6L_p \).

A plot of the optimized return loss is shown in the Figure 5.7. The simulated directivity, gain, and realized gain at 70\( \text{GHz} \) are shown in Figure 5.8.
A return loss of 32.8 dB is observed with -10 dB bandwidth of 1.84 GHz for this optimized solution. The results obtained from the optimization show that the resonance is obtained at 70 GHz with a directivity of 7.4 dBi while the antenna gain and realized gain are equal to 6.8 dBi. A much broader bandwidth is observed as compared to the previous case.

### 5.5 Analysis of Width for a Microstrip Patch with $W_p=1.8L_p$

The microstrip patch antenna is analysed by making the patch width equal to 1.8 times the patch length. The same settings are used as described in Section 5.1. The initial dimensions of the patch are used from the analytically calculated dimensions. The patch length and the inset feed point are optimized at 70 GHz with an optimization goal of $S_{11} \leq -30$ dB. The optimized results are given in the Table 5.5.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length of the patch (Lp) in µm</td>
<td>1137</td>
</tr>
<tr>
<td>Width of the patch (Wp) in µm</td>
<td>2047</td>
</tr>
<tr>
<td>Position of Inset feed point (d) in µm</td>
<td>202</td>
</tr>
<tr>
<td>Gap between microstrip feed line and the patch (g) in µm</td>
<td>100</td>
</tr>
</tbody>
</table>

**Table 5.5** Optimized dimensions at 70 GHz for a microstrip patch with $W_p=1.8L_p$.

A plot of the optimized return loss is shown in the Figure 5.9. The simulated directivity, gain and realized gain at 70 GHz are shown in Figure 5.10.
From Figure 5.9, it is seen that the simulated return loss is 42.6dB and the 10dB bandwidth is 2.03GHz. The results obtained from the optimization show that the resonance is obtained at 70GHz with a directivity of 7.4dBi while the antenna gain and realized gain are equal to 6.8dBi. Here, in this case the same value of directivity, antenna gain and realized gains are obtained as were obtained for a patch width 1.6 times the patch length. However, a broader bandwidth still is observed for a patch width of 1.8 times the patch length.

**5.6 Analysis of Width for a Microstrip Patch with Wp=2Lp**

The patch is analysed by keeping a width of two times the patch length. The same settings are used as described in Section 5.1. The antenna structure is simulated with an optimization goal of $S_{11} \leq -30$dB. The initial dimensions of the patch are used from the analytically calculated dimensions. The optimized results are presented in Table 5.6.

<table>
<thead>
<tr>
<th>Length of the patch (Lp) in µm</th>
<th>1125</th>
</tr>
</thead>
<tbody>
<tr>
<td>Width of the patch (Wp) in µm</td>
<td>2250</td>
</tr>
<tr>
<td>Position of Inset feed point (d) in µm</td>
<td>23</td>
</tr>
<tr>
<td>Gap between microstrip feed line and the patch (g) in µm</td>
<td>100</td>
</tr>
</tbody>
</table>

**Table 5.6** Optimized dimensions at 70 GHz for a microstrip patch with Wp=2Lp.

A plot of the optimized return loss is shown in the Figure 5.11. The simulated directivity, antenna gain and realized gain at 70GHz are shown in Figure 5.12.
From Figure 5.11, it is seen that the simulated return loss is 16.8dB. The resonance is obtained at 70GHz with a directivity of 6.7dBi while the antenna gain is 6.1dB and the realized gain is 6dB. It is observed that the directivity, antenna gain and the realized gain have least value for this antenna structure. The bandwidth for this structure is 1.71GHz, a reduction over the previous case. The optimisation goal of $S_{11} \leq -30$dB is not achieved in this case as it is observed that when the patch width is increased the inset feed moves towards the edge of the patch. The impedance at the radiating edge is higher as compared to the impedance of microstrip feed line. The impedance matching is worst in this case.

5.7 Conclusion

Starting with a patch width equal to the patch length, six designs of microstrip patch antenna are optimized, up to a patch width equal to twice the patch length. Directivity, antenna gain and realized gain are calculated in broadside direction. For each case the -10dB bandwidth is calculated by using Template Based Postprocessing option of CST Microwave Studio. The optimized results for these designs are tabulated in Table 5.7.

<table>
<thead>
<tr>
<th>Performance properties</th>
<th>Wp=Lp</th>
<th>Wp=1.2Lp</th>
<th>Wp=1.4Lp</th>
<th>Wp=1.6Lp</th>
<th>Wp=1.8Lp</th>
<th>Wp=2Lp</th>
</tr>
</thead>
<tbody>
<tr>
<td>-10dB Bandwidth (GHz)</td>
<td>1.37</td>
<td>1.55</td>
<td>1.77</td>
<td>1.84</td>
<td>2.03</td>
<td>1.71</td>
</tr>
<tr>
<td>Directivity (dBi)</td>
<td>7.1</td>
<td>7.2</td>
<td>7.3</td>
<td>7.4</td>
<td>7.4</td>
<td>6.6</td>
</tr>
<tr>
<td>Antenna gain (dB)</td>
<td>6.4</td>
<td>6.5</td>
<td>6.7</td>
<td>6.8</td>
<td>6.8</td>
<td>6.1</td>
</tr>
<tr>
<td>Realized gain (dB)</td>
<td>6.4</td>
<td>6.5</td>
<td>6.7</td>
<td>6.8</td>
<td>6.8</td>
<td>6</td>
</tr>
<tr>
<td>$S_{11}$ (dB)</td>
<td>-33.82</td>
<td>-34.26</td>
<td>-35.5</td>
<td>-32.8</td>
<td>-42.6</td>
<td>-16.8</td>
</tr>
</tbody>
</table>

Table 5.7 Results of numerical optimization at 70GHz for various width to length ratios.
From the above analysis, it is seen that the highest bandwidth is found in the case of $W_p=1.8L_p$. Directivity, antenna gain and realized gain are highest for $W_p=1.6L_p$ and $W_p=1.8L_p$. While minimum bandwidth is observed for $W_p=L_p$. It is observed that the design of a rectangular patch antenna is a trade-off; there are multiple solutions available.

The patch length does not change significantly with changing width. The patch length is a critical parameter in a patch design and it determines the resonant frequency. A plot of resonant length against the ratio $W_p/L_p$ is shown in the Figure 5.13.

![Figure 5.13](image1.png) ![Figure 5.14](image2.png)

Figure 5.13 Variation of resonant length for various width to length ratios
Figure 5.14 Variation of inset feed point for various width to length ratios

It is seen from the Figure 5.13 that with increasing the $W_p/L_p$ ratio, the resonant length decreases by a very small fraction. Similarly, when the $W_p/L_p$ ratio is increased, the location of the inset feed point from the edge is decreased and this is illustrated in Figure 5.14. From the Figure 5.14, it is seen that the inset feed point is decreased with a large factor for $W_p=2L_p$. The radiation pattern for $W_p=2L_p$ is

![Figure 5.15](image3.png) ![Figure 5.16](image4.png)

Figure 5.15 Radiation pattern for a microstrip patch with $W_p=2L_p$
Figure 5.16 E-field for a microstrip patch with $W_p=2L_p
shown in the Figure 5.15 and the distribution of E-field for Wp=2Lp is shown in the Figure 5.16. It is observed that when the patch width increased to double the patch length the location of inset feed approached to the radiating edge of the patch. The impedance at the radiating edge is higher as compared to the impedance of the microstrip feed line. The patch is still operated in the fundamental mode, but the other modes are being excited along the width of the patch (orthogonal to the fundamental mode).

It is also observed that the patch width has a minor effect on resonant frequency and on radiation properties of an antenna. However, a significant variation is observed for the -10dB bandwidth. The maximum -10dB bandwidth is observed for Wp=1.8Lp. The -10dB bandwidth tends to decrease if we increase the patch width above 1.8 times the patch length. To obtain the higher bandwidth, a width to length ratio between 1<Wp/Lp<2 can be used.

![Figure 5.17 Variation of Directivity for various width to length ratios](image)

A plot of directivity for various width to length ratios is shown in the Figure 5.17. It is seen that when the patch width is increased from Wp=Lp, the directivity is also increased. Maximum directivity is observed for a patch width of 1.6-1.8 times the patch length.
Chapter 6

Conclusions

In this thesis, three methods have been investigated for designing a microstrip patch antenna that include use of analytical models, numerical optimization and numerical variation of dimensions.

In Chapter 3, the boundary conditions, the mesh density and the port dimensions have been investigated for the given problem in order to get accuracy in the simulated results. The convergence in the simulated results of the numerical simulator is verified both by manual mesh settings and adaptive mesh refinement. However, it is decided to use the investigated manual mesh settings because adaptive mesh refinement takes much longer to simulate the same problem in specified number of passes.

In Chapter 4, a rectangular patch antenna has been designed and analysed. The transmission line model is applied to calculate the dimensions of the rectangular patch antenna by using the design specifications. In Chapter 4.1, it is observed that the dimensions of the rectangular patch obtained from analytical calculations proved to be good starting values quantitatively. The analytically calculated dimensions of the microstrip patch are numerically verified in CST Microwave Studio. In Chapter 4.2, the rectangular patch design is optimized at 70GHz with inset feed location by making use of the optimizer. During this optimization the patch width is kept 1.5 times the patch length.

The optimized patch dimensions are verified by parameter variation of these dimensions in equidistant steps around the found result of the optimizer. During the parameter variation, two out of these three dimensions are kept constant while the third is varied to observe the changes in the performance properties of the antenna. It is observed that the patch length, the patch width and the inset feed location are the major dimensions affecting the performance properties of the microstrip patch antenna. It is observed during the parameter variation that the patch length has major effect on resonant frequency and radiation properties of the antenna, while the patch width has smaller effects. It is also observed that the resonance frequency shifts in bigger steps with variation in patch length as compared to variation in patch width. It is observed that if the substrate height and the dielectric material are specified then there remain three parameters affecting the performance properties of the patch antenna i.e., the patch length, the patch width and the inset feed location. The parameter variation of dimensions is found to be most reliable among the investigated design methods but it is more complicated with many parameters.
Apart from using a width of 1.5 times the patch length, various width-to-length ratios have been used to observe the effect of variations in width on performance properties. There are occasions where a different ratio is required because of space limitations, or to change the input impedance. Starting with a patch width equal to its length, six designs of the microstrip patch antenna are optimized with feed location, up to a patch width equal to twice the patch length. In each case, it is seen that the patch length changed approximately 10µm with increasing width. It is seen that with increasing width, the inset feed location moves towards edge. When the patch width becomes double the patch length, it resulted in a degradation of the radiation properties. The antenna gain, directivity, and realized gain are decreased. The patch is still operated in the fundamental mode, but the other modes are being excited along the width of the patch (orthogonal to the fundamental mode).

A solution falling between 1<Wp/Lp<2 can be selected depending on -10dB bandwidth of input matching and maximum achieved directivity, antenna gain, and realized gain. From Chapter 5.7, it is concluded that a patch width of 1.8 times the patch length can be selected since the highest 10dB bandwidth is achieved. Also, the directivity, antenna gain, and realized gains are highest in that case.

Finally, the optimum dimensions of a single rectangular patch antenna at 70GHz have been investigated. The performance properties are analyzed for the optimized dimensions. In future, the same procedure could be applied to design other planar antennas operating at other frequency levels. For example, the same procedure could be applied to applications of E-band frequency levels at 71-76GHz and 81-86GHz. The designed patch element could be part of an array.
References


Appendix-A

Manual calculations for calculation of the dimensions of rectangular patch antenna.
The dimensions of the patch are calculated by using equations 2-6 - 2-9.

\[ \lambda_o = \frac{v_o}{f_r} = \frac{3 \times 10^8}{70 \times 10^9} = 4286 \mu m \]

\[ k_o = \frac{2\pi}{\lambda_o} = \frac{2\pi}{4286} = 1.466 \times 10^{-3} \]

\[ W = \frac{v_o}{2f_r} \sqrt{\frac{2}{\varepsilon_r + 1}} \]

\[ W = \frac{3 \times 10^8}{2 \times 70 \times 10^9} \sqrt{\frac{2}{3.16 + 1}} = 1486 \mu m \]

Effective dielectric constant is calculated by using (2-6)

\[ \varepsilon_{\text{eff}} = \frac{3.16 + 1}{2} + \frac{3.16 - 1}{2} \left[ 1 + \frac{100}{1486} \right]^{-1/2} \]

\[ = 2.88 \]

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

\[ \frac{\Delta L}{100} = 0.412 \left( \frac{2.88 + 0.3}{2.88 - 0.258} \left( \frac{1486}{100} + 0.264 \right) \right) \]

\[ \Delta L = 48.3 \mu m \]

The length of the patch is calculated by using (2-8).

\[ L = \frac{3 \times 10^8}{2 \times 70 \times 10^9 \sqrt{2.88}} - 2(48.3) \]

\[ L = (1.26269 \times 10^{-3}) - 96.6 \mu m \]

\[ L = 1166 \mu m \]

The equations through (2-11 – 2-16) are used to calculate the position of inset feed point. The conductance is calculated by using (2-13).
\[ G_1 = \frac{1}{120\pi^2} \int_0^\pi \left( \frac{\sin \left( \frac{k_o W}{2} \cos \theta \right)}{\cos \theta} \right)^2 \sin^3 \theta d\theta \]

Equating the values, we get.

\[ G_1 = \frac{1}{120\pi^2} \int_0^\pi \left( \frac{0.001466 * 1486 \cos \theta}{2 \cos \theta} \right)^2 \sin^3 \theta d\theta \]

*Mathematica* 5.2 is used to calculate the conductance and the programme is given in Appendix-B.

\[ G_1 = 0.001236 \text{ Siemens} \]

Mutual conductance is calculated by using (2-14).

\[ G_{12} = \frac{1}{120\pi^2} \int_0^\pi \left( \frac{\sin \left( \frac{0.001466 * 1486 \cos \theta}{2 \cos \theta} \right)}{J_o (0.001466 * 1486 \sin \theta) \sin^3 \theta} \right) d\theta \]

Matlab programme is used to calculate the value of mutual conductance. The programme is given in Appendix-B.

\[ G_{12} = 6 \times 10^{-4} \]

Input resistance at the radiating edge of the patch is calculated by using (2-15).

\[ R_{in} = Z_{in} = \frac{1}{2(0.001236 + 6 \times 10^{-4})} \]

\[ R_{in} = 273 \Omega \]

Here the input impedance at the radiating edge is 273\( \Omega \) while we are using 50\( \Omega \); the inset feed point for 50\( \Omega \) is calculated by using (2-16). Rewriting equation (2-16) as

\[ d = \cos^{-1} \left( \frac{\left( \frac{Z_o}{R_{in}} \right) * \frac{L}{\pi} }{\sqrt{273}} \right) \]

\[ d = \cos^{-1} \left( \frac{50}{\sqrt{273}} \right) * \frac{1166}{\pi} \]

\[ d = 418 \mu m \]
Appendix-B

Programming codes for calculating patch dimensions.

*Mathematica 5.2 programme to calculate conductance for inset feed point.*

In[14]:=
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\(a = \((1/((120 \ \pi ^2)))\) \((\((\sin[k*W*\cos[\theta]/2]/\cos[\theta])\)^2)\)*\((\sin[\theta]^3)\))\)

Out[14]=
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