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Design of Micromachined Patch Antenna with Performance Enhancement for Millimeter wave applications

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Abstract

This thesis presents the design and characterization of micromachined microstrip patch antenna for millimeter wave applications. The center frequency of the antenna is 60GHz. Since the frequency is high and the antenna size is small, the use of micromachining techniques is very convenient. There are three micromachining methods used to make improvements on the patch antenna performance by making modifications on the substrate to make its effective permittivity low. A conventional inset fed patch antenna with Gallium Arsenide GaAs is firstly designed and then different micromachining approaches have been applied to the initial design to investigate the effect on antenna parameters. The first method of micromachining is the bulk micromachining with its two types wet and dry etching, then the photolithography is applied to make the electromagnetic band gap (EBG) holes. An antenna structure combining the two micromachining techniques bulk and EBG micromachining has been investigated. Moreover, a micromachined patch antenna using the air as a substrate is presented in this thesis. A comparison has finally been carried out on the different designs of the micromachined antenna. Every design has its own improvements on the bandwidth and the gain in comparison to the conventional design. The programs used in this thesis are the CST microwave studio and the HFSS simulator to make simulations.

Acknowledgments

First of all I would like to thank my God (ALLAH) for giving me the knowledge, strength and patience to complete this work. I pray that He continues the same with rest of my life.

I would like to give special thanks to Dr. Talal F. Skaik for the help, guidance and attention that he produces throughout the course of this work. Without his guidance and useful feedback, this work could not have been realized.

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My wife and my lovely sons and daughter, thank you very much for all your patience.

Table of Contents

List of tables

List of Figures

Chapter 1

Introduction

1.1 Introduction

In this chapter, design and analysis of a micromachined micro strip patch antenna for the millimeter wave's applications are presented. Some definitions about the millimeter waves and their properties are given next.

1.1.1. Millimeter wave or EHF (Extremely high frequency)

Microwaves can be referred to the electromagnetic (EM) waves with frequencies ranging between 300 MHz and 300 GHz [1]. This range corresponds to the free space wavelengths varying from 1 m to 1 mm. The EM waves that travel in the millimeter wavelength range at frequencies between 30 GHz and 300 GHz are also known as millimeter waves as illustrated in figure 1.1 [2]. Millimeter wave communications have been studied since 1970's [2].

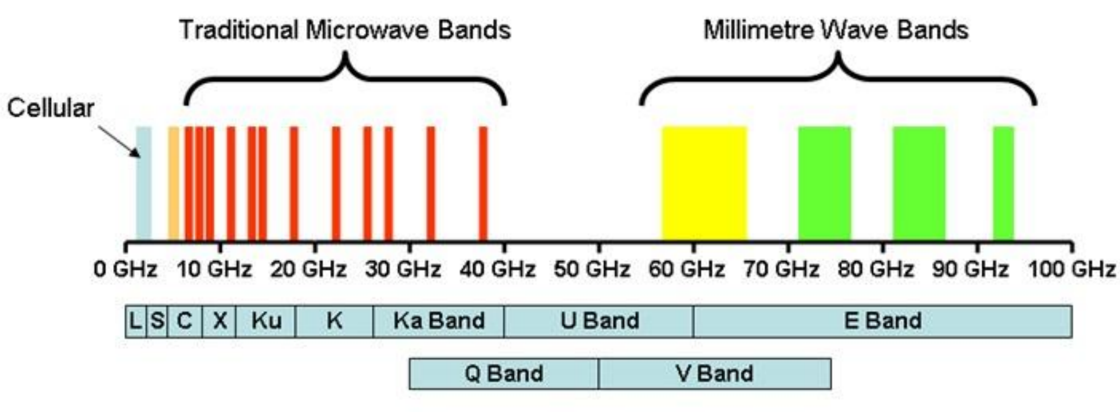

Figure 1.1: Electromagnetic (EM) waves bands

1.1.2. Properties of Millimeter waves.

Millimeter waves have some properties that are different from other microwaves and so it is used in application with specific demands, these properties and also the drawbacks will be illustrated bellow:

1.1.2.1.1 Large Bandwidth and Large data rate

One of the important advantages of the millimeter wave communication technology is the large amount of spectral bandwidth available. With such wide bandwidth available, millimeter wave wireless links can achieve capacities or data rate as high as 10 Gbps, which is more and more large compared with any lower frequency RF wireless technologies.

1.1.2.1.2 Narrow Beam So high density and low interference and security

Unlike microwave links, which cast very wide footprints, Millimeter wave links cast very narrow beams, as illustrated in Figure 1.2[4]. The narrow beams of millimeter wave links allow for deployment of multiple independent links so it gives security and lower the interference. For example, the beam width of a 70 GHz link is four times as narrow as that of an 18 GHz link, allowing higher density in the given area and this density is very useful for point-to-point connections. [4]

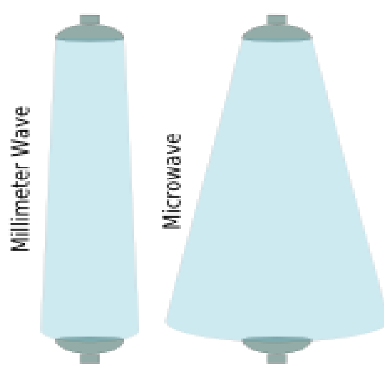

Figure 1.2: Millimeter wave& Microwave beam width

1.1.2.1.3 Licensed Spectrum with Low Cost Licensing

Unlike the microwave bands, in which licensing costs require significant investment, the cost of licensing millimeter waves is very low compared with microwaves [5].

1.1.2.1.4 Free Space Attenuation

One of the drawbacks of the millimeter waves is the free space attenuation which can be calculated using the following equation [1],

$$L_{dB}[attenuation] = 32.4 + 20\log f_{MHz} + 20\log d_{Km} \quad (1.1)$$

So from the equation we note that attenuation is high as the frequency is high and so the signal is attenuated in short distances, as an example, a 1 km path at 60 GHz has the same free space loss as a 100 km path at 600 MHz.

For this drawback the millimeter waves are widely used in the short rang applications as illustrated bellow.

1.1.3. Applications of millimeter waves

In the last few years, many applications have appeared for millimeter wave frequencies. Operating in the millimeter wavelength frequency range provides many benefits including the availability of a high bandwidth, small physical size of antenna and so very high data rate communications [4].

Frequencies ranging from 30 GHz up to 60 GHz are allocated for commercial applications in radar, satellite and mobile communications [5]. The 60 GHz with a 3-7 GHz bandwidth is open for wireless communication depending upon the country. This frequency band becomes of interest in the development of wireless indoor communication systems such as wireless local area networks (WLAN) and personal area networks (PAN), the millimeter wave band offers significant advantages in supplying enough bandwidth for the transmission of various multimedia contents. In particular, there has been an increasing requirement for the development of the V-band WLAN for commercial applications.

Smart transportation system is another application operating at millimeter wavelength see figure 1.2, Intelligent Transportation Systems (ITS) based on vehicle to vehicle and vehicle to roadside communications have been studied for many years in Europe, North America and Japan [5]. Short range radar (SRR) and long range radar (LRR) systems have been identified as significant technologies to improve road safety.

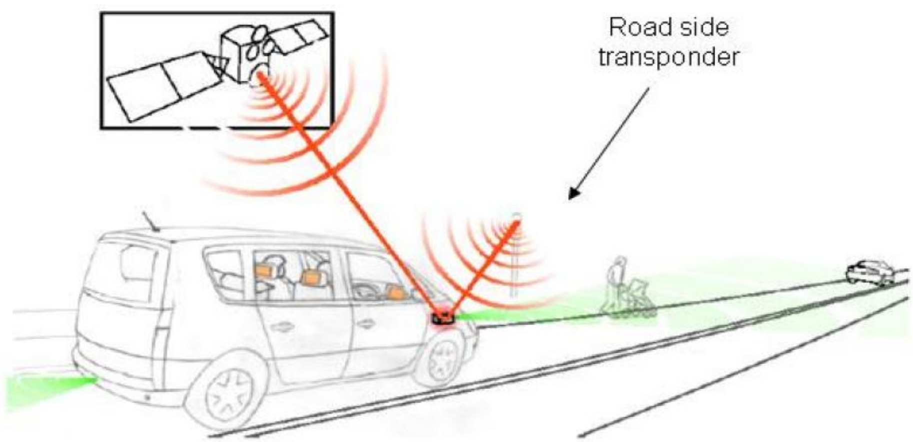

Figure 1.3: Intelligent Transportation Systems (ITS)

1.2 Introduction to the Patch antennas:

Microstrip patch antenna consists of a radiating patch on one side of a dielectric substrate which has a ground plane on the other side as shown in Figure 1.4.

The patch is generally made of conducting material such as copper or gold and can take any possible shape.

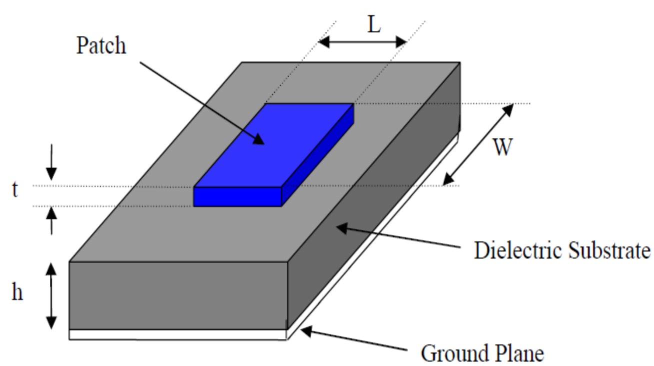

Figure 1.4: Microstrip patch antenna

Microstrip antennas are preferred for various applications because of their small size, low weight, and low manufacturing cost. But the requirements in designing this antenna which is the radiator element in the system are different from that of a closed circuit like transmitter and other components. So the losses of the antenna must be low enough to get an efficient radiator.

The best method for lower losses of the patch antenna is by designing the patch element of the antenna on a low dielectric constant substrate, on other words, the ideal microstrip antenna should have a substrate with low permittivity to get good performance. On the other hand using high permittivity substrates like silicon and gallium arsenide are in demand due to the rapid growth of IC technology and requirement of small size antennas for wireless communications. With such substrates it would be possible to integrate the antenna on a single chip with other circuit elements [6].

Such design i.e. on high permittivity substrates leads to increased surface wave losses and reducing bandwidth and so reducing the antenna efficiency.

From the above, the solution for lower losses can be achieved by reducing the substrate dielectric constant for the used substrate by one of the following four methods [7]:

1.2.1 Etching the antenna substrate:

This method is done by etching a portion of the substrate, this etch results in two separate regions of air and the substrate material, producing a mixed substrate region with low effective dielectric constant [7].

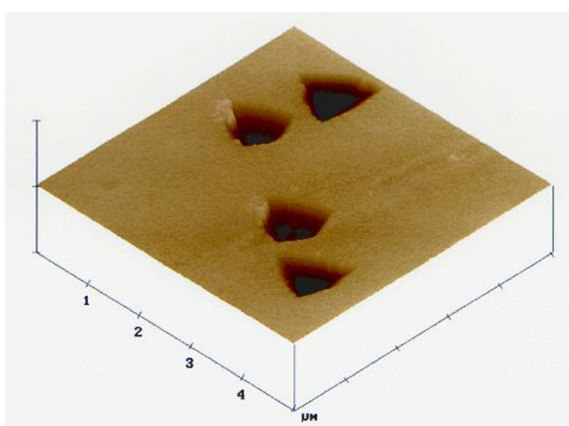

Figure 1.5: Etching the antenna substrate

1.2.2 Electromagnetic band gap (EBG):

Another possibility is to use an electromagnetic band gap (EBG) structure which can be achieved by making cylindrical holes in the substrate producing a mixed substrate region with low effective dielectric constant [8].

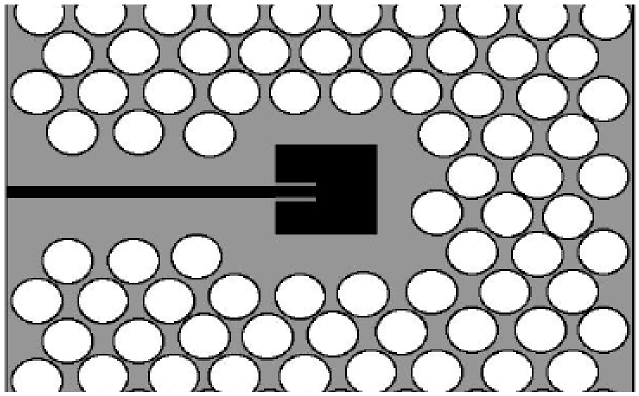

Figure 1.6: Electromagnetic band gap (EBG)

1.2.3 Elevating the antenna radiator:

It is achieved by elevating the radiator element above the substrate, this will help to reduce the substrate losses and improve the radiation efficiency [7].

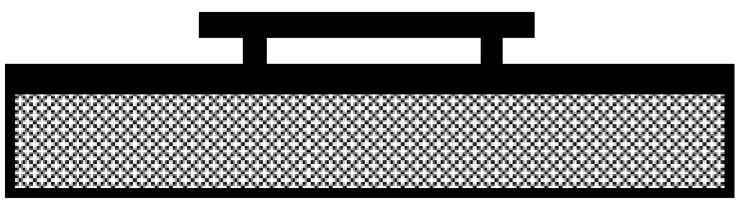

Figure 1.7: Elevating the antenna radiator

1.2.4 Using different substrates:

In this technique using different substrates, the radiator is formed on a substrate with low dielectric constant and the feed line on a substrate with high dielectric constant [8].

Because of the relatively small size of the antenna designed at the millimeter waves, these methods of the substrates modifications are done using micromachining techniques.

Figure 1.8: Using different substrates

1.3 Micromachining Fabrication Techniques

As the size of the antenna is very small when we deal with high frequency or with the millimeter waves, the modifications on the substrate are done by using one of the four methods in section 1.2.

The micromachining is a technique used in the fabrication process of the relatively small-size devices. Several types of micromachining are listed below:

1.3.1 Bulk Micromachining

The main process in bulk micromachining is the etching. There are two etching techniques; wet etching and dry etching [9]. The advantage of wet etching is that more than one wafer can be processed at a time. However, dry etching is preferred in achieving vertical walls [9].

1.3.2 Surface micromachining

Unlike Bulk micromachining, where a silicon substrate (wafer) is selectively etched to produce structures, surface micromachining builds microstructures by deposition and etching of different structural layers on top of the substrate [10]. The main advantage of this machining process is the ability to deal with extremely small size.

1.3.3 Membrane Technology

Membrane technology is commonly used in integrating micromachined transmission lines and antennas. In antenna design, the idea is to have a cavity underneath the radiator, thus reducing the effective permittivity of the substrate and consequently minimizing losses due to surface waves [10].

1.3.4 Photolithography technology

Photolithography (or "optical lithography") is a process used in microfabrication to selectively remove parts of a thin film or the bulk of a substrate. Or by other words the photolithography process is a process which uses light to make etching in the substrate by using a photo mask to make a geometric pattern which transfers this pattern to the substrate. A series of chemical treatments then are done in the substrate to finalize the etch shape [11].

1.4 Research objective:

In the previous sections, the properties of millimeter waves and their applications have been presented. Moreover, micromachining techniques have been generally illustrated to be applied to fabricate micromachined patch antennas for millimeter wave applications. The main objectives of this research are:

Study the millimeter waves and their properties and applications.

Design and analyze of the inset fed microstrip patch antenna for millimeter waves V-band around 60 GHz, using the CST 3D EM simulation software program.

Study micromachining techniques and understand fabrication process, and design an antenna that is compatible with the fabrication technique.

Study and apply some methods that improve the Patch antenna performance in Band Width and efficiency and Radiation Pattern by using the CST 3D EM simulation software program.

Apply new techniques to improve the antenna performance like combining two methods of the micromachining and investigate the results if there is an improvement or not.

1.5 Thesis overview:

The overall idea of the research work is introduced in Chapter 1 along with an introduction on the applications. An introduction on micromachining techniques has been presented, then the objectives of the research have been introduced. A brief introduction to each chapter is also given here.

Chapter 2 introduces a background on the antenna and its parameters, and explains the patch antenna in more details and its calculations and feeding mechanisms. The attenuation equations and the methods of reducing the substrate losses also will be introduced briefly in this chapter.

In chapter 3 various types of micromachining techniques will be introduced. Bulk micromachining, membrane and photolithography will be explained briefly in this chapter.

Chapter 4 introduces the simulations and the results of the antennas, explaining the improvements of the parameters after applying the techniques of the micromachining.

Chapter 5 introduces a conclusion of the thesis.

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Chapter 2

Antenna Theory and Background of Microstrip Patch Antennas

2.1 Introduction:

Before talking about microstrip antennas, it is necessary to provide some background information on antenna in general and its parameters also the types of the antenna. There are many antenna types - each with different geometry - but there are certain fundamental parameters which can be used to describe all of them.

This chapter presents the theory of antennas and the fundamental parameters used for evaluating antenna performance. The first part outlines what an antenna is and how it radiates. Also the fundamentals of antenna modeling equations or the Maxwell's equations will be presented. The radiation pattern of a given antenna and the far and near field of radiation regions will be determined. To help evaluate antenna performance, the fundamental antenna analysis parameters, such as return loss, impedance bandwidth, directivity, antenna efficiency, gain and polarization are discussed. The second part presents an introduction to the microstrip patch antenna and its shapes, then the feeding mechanisms which is used in this antenna and also the matching techniques of some of these feeding methods. The last section of this chapter talks about some models for the analysis of Microstrip patch antennas which are the transmission line model, cavity model, and full wave model or Method of Moments.

2.2 Antenna as general:

For any wireless system, the antenna element is very important in sending and receiving the signals or the electromagnetic energy because the antenna is interface between the system and the free space and it is sometimes referred to as the air interface [1]. In other words, antennas convert electromagnetic radiation into electric signal, or vice versa. A rather simpler definition of the antenna is that of a device for radiating or receiving radio waves.

Antennas are reciprocal devices. That means the properties of an antenna are identical in both the transmitting and receiving mode. For example, if a transmitting antenna radiates to certain directions, it can also receive from those directions - the same radiation pattern applies for both cases [2].

There are numerous types of antennas developed for many different applications and they can be classified based on four distinct groups as wire, aperture, reflector, and printed antennas, and they can be used as single element or arrays [3, 5].

Regardless of the type of the antenna, they are all based on the principle that electromagnetic radiation occurs due to accelerated or decelerated electric charges within a conducting material.

This can be explained with the help of Figure 2.1 which shows a voltage source connected to a two conductor transmission line [3]. When a sinusoidal voltage is connected to these two conductors, electric field E and magnetic field H are created. Due to the time varying electric and magnetic fields, electromagnetic waves are created and these travel between the conductors. As these waves approach open space, free space waves are formed.

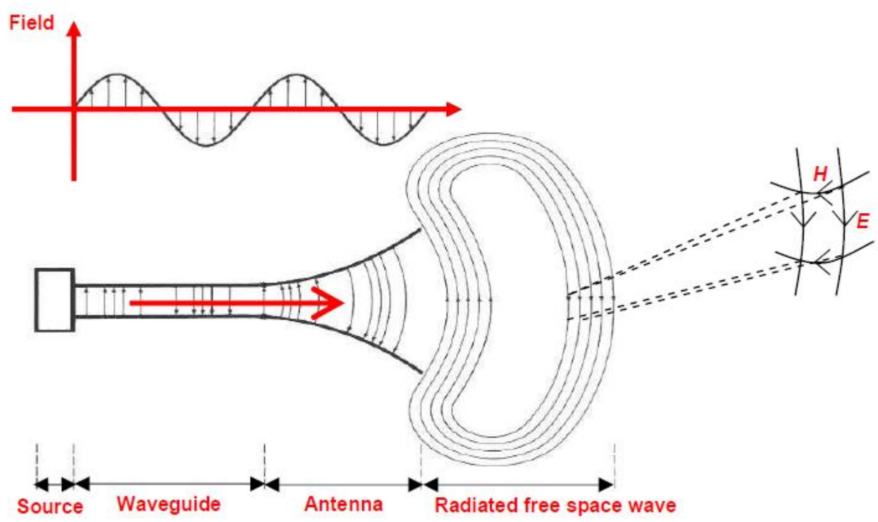


Figure 2.1: Antenna and electromagnetic waves generation.

2.3 Antenna modeling Equations

The basic equations which are used for antenna modeling are derived from Maxwell's equations. Maxwell's equations allow us to calculate the radiated fields from a known antenna current distribution. They also give a description of the behavior of the fields around the antenna geometry. Maxwell's equations can then be used to understand the fundamental principles of antennas. The equations are presented below [6-8].

$$\begin{aligned}
&\nabla \times \vec{E} = -j\omega\vec{B} - \vec{M} \rightarrow \textit{Faraday's Law} \\
&\nabla \times \vec{H} = j\omega\vec{D} + \vec{J} \rightarrow \textit{Ampere's Law} \\
&\nabla.\vec{D} = \rho_e \rightarrow \textit{Gauss' Laws for electric field} \\
&\nabla.\vec{B} = \rho_m \Rightarrow \text{Gauss' Laws for magnetic field}
\end{aligned} \tag{2.1}$$

Where $\vec{E}$ is the electric field intensity (V/m), $\vec{H}$ is the magnetic field intensity (A/m), $\vec{D}$ is the electric flux density (C/m^2), $\vec{B}$ is the magnetic flux density (Wb/m^3), $\vec{J}$ is the electric current density (A/m^2) and ρ_e is the electric charge density (C/m^3). The quantities of magnetic current density $\vec{M}$ and magnetic charge density ρ_m are non-physical and they are included in the symmetric forms of Maxwell's equation for mathematical convenience. From these Maxwell's equations and by following the derivation steps we can derive the electric and the magnetic fields.

But, with better computer simulation software like HFSS or CST, antenna modeling and evaluation is a much simpler, more convenient, and a more efficient procedure than in the manual derivation.

2.4 Antenna Radiation Field Regions

The space surrounding an antenna can be divided into three regions according to the properties of the radiated field. Figure 2.2 shows antenna radiation regions

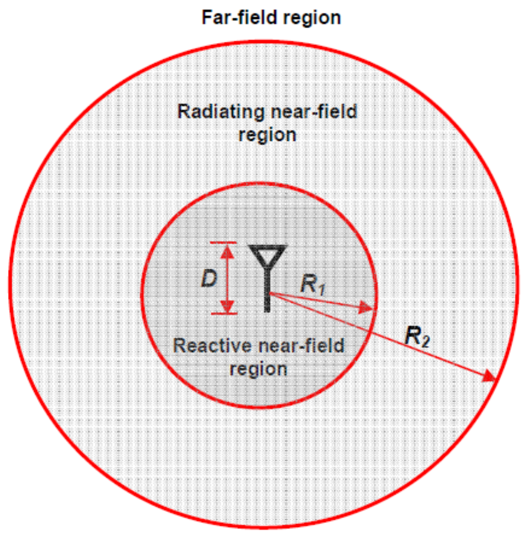


Figure 2.2: Typical boundaries for antenna radiation regions.

1) **Reactive Near-field Region:** This region is immediately surrounding the antenna. This region exists at $R < 0.62\sqrt{D^3/\lambda}$ from the antenna [3], where λ is the wavelength and D is the largest dimension of the antenna.

2) **Radiating Near-field (Fresnel) Region:** This region lies between the reactive near-field region and the far field region. The boundary for this region is $0.62\sqrt{D^3/\lambda} \le R_2 \le 2D^2/\lambda$

3) **Radiating Far-field (Fraunhofer) Region:** This region is the farthest away from the antenna, the inner boundary is taken to be at $R > 2D^2/\lambda$ distance and the outer boundary is ideally at infinity [3]. This region is the important in this thesis.

2.5 Antenna parameters:

To describe the performance of an antenna, definitions of various parameters are necessary. The most fundamental antenna parameters are described below.

2.5.1 Antenna Radiation Pattern

An antenna radiation pattern is a distribution of a quantity that characterizes the electromagnetic field generated by the antenna as function of position [3]. The radiation pattern can be a mathematical function or a graphical representation (2-D or 3-D) in the far-field region. The E-plane is the plane containing the electric field vector and the direction of maximum radiation, and the H-plane is the plane containing the magnetic field vector and the direction of maximum radiation [3, 8]. See figure 2.3.

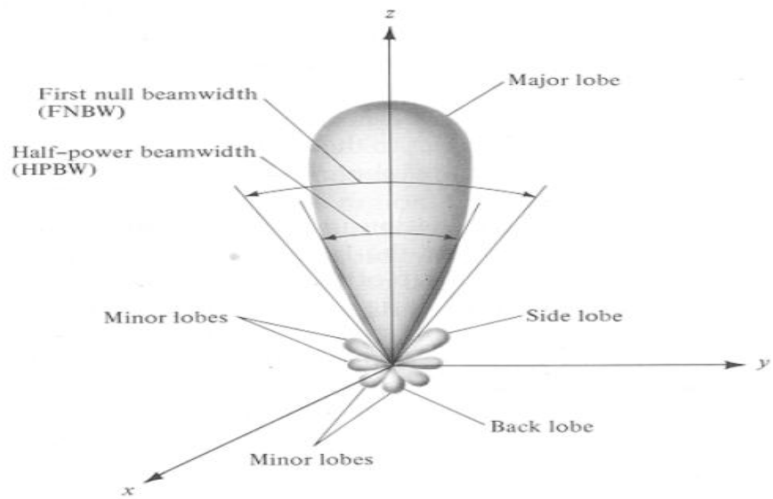


Figure 2.3: Radiation Pattern of antenna

Radiation patterns of antennas can be classified based on the pattern shape into isotropic, omnidirectional or directional patterns [3, 12]. The isotropic antenna radiates equally in all directions. The antenna radiates and receives equally in a given plane is called an omnidirectional antenna, and it is also called a non-directional antenna because it does not favor any particular direction in this plane. The directional antennas focus the energy more in a particular direction than in others [12].

2.5.2 Directivity

Directivity can be defined as the ability of an antenna to focus energy in a particular direction when transmitting. Or, equivalently, to receive energy better from a particular direction when receiving. It is a function of direction [3, 11, 12]. A comparison between an isotropic antenna and a practical antenna pattern fed with the same source is used to calculate the directivity.
Directivity is a dimensionless quantity and it is generally expressed in dB. An antenna that has a narrow main lobe would have better directivity than one which has a broad main lobe.

2.5.3 Input Impedance

As the electromagnetic wave travel through the different parts of the antenna system, from the source (device) to the feed line to the antenna and finally to the free space, they may caused differences in impedance at each interface. Because of this difference in impedances some fraction of the wave's energy will reflect back to the source forming a standing wave in the feed line. Another definition of the input impedance is the ratio of the appropriate components of the electric to magnetic fields [12].

The frequency response of an antenna at its port is defined as input impedance (Z_{in}). The input impedance is the ratio between the voltage and currents at the antenna port. Input impedance is a complex quantity that varies with frequency as $Z_{in}(f) = R_{in}(f) + jX_{in}(f)$, where f is the frequency.

2.5.4 Voltage Standing Wave Ratio (VSWR)

In order for the antenna to operate efficiently, maximum transfer of power must take place between the transmitter and the antenna. Maximum power transfer can take place only when the impedance of the antenna (Z_A) is matched to that of the transmitter (Z_g).

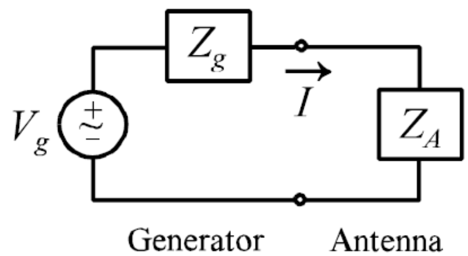


Figure 2.4: Impedance of Generator and Antenna

The maximum power can be transferred only if the impedance of the transmitter is a complex conjugate of the impedance of the antenna or $Z_A = Z_g{}^*$ [11], where $Z_A = R_A + jX_A, Z_g = R_g + jX_g$. see figure 2.7

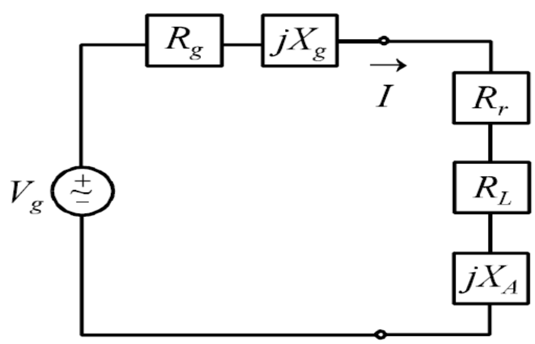


Figure 2.5: Impedance matching

Z_A is the antenna impedance.

R_A is the antenna resistance.

X_A is the antenna reactance.

R_A of the impedance of an antenna can be divided into radiation and loss resistances.

$R_A = R_r + R_L$ Where R_r is the radiation resistance, R_L is the loss resistance.

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

$$VSWR = \frac{1+|\Gamma|}{1-|\Gamma|} \quad , \quad \Gamma = \frac{V_r}{V_i} = \frac{Z_A - Z_g}{Z_A + Z_g} \tag{2.2}$$

Where Γ is called the reflection coefficient, V_r is the amplitude of the reflected wave V_i is the amplitude of the incident wave.

The VSWR is basically a measure of the impedance mismatch between the transmitter and the antenna. The higher the VSWR, the greater is the mismatch. The minimum VSWR which corresponds to a perfect match is unity [3]. A practical antenna design should have an input impedance of either 50 Ω or 75 Ω since most radio equipment is built for this impedance.

2.5.5 Return Loss (RL)

The Return Loss (RL) is a parameter which indicates the amount of power that is "lost" to the load and does not return as a reflection. As explained in the preceding section, waves are reflected leading to the formation of standing waves, when the transmitter and antenna impedance do not match. Hence the RL is a parameter similar to the VSWR to indicate how well the matching between the transmitter and antenna has taken place. The RL is given by [3]

$$RL = -20\log_{10}|\Gamma| \qquad \text{(dB)} \tag{2.3}$$

For perfect matching between the transmitter and the antenna, $\Gamma = 0$ and $RL = \infty$ which means no power would be reflected back, whereas a $\Gamma = 1$ has a RL = 0 dB, which implies that all incident power is reflected. For practical applications, a VSWR of 2 is acceptable, since this corresponds to a RL of -9.54 dB.

2.5.6 Antenna Efficiency

When an antenna is driven by a voltage source (generator), the total power radiated by the antenna will not be the total power available from the generator. The loss factors which affect the antenna efficiency can be identified by considering the common example of a generator connected to a transmitting antenna via a transmission line as shown in figure 2.4.

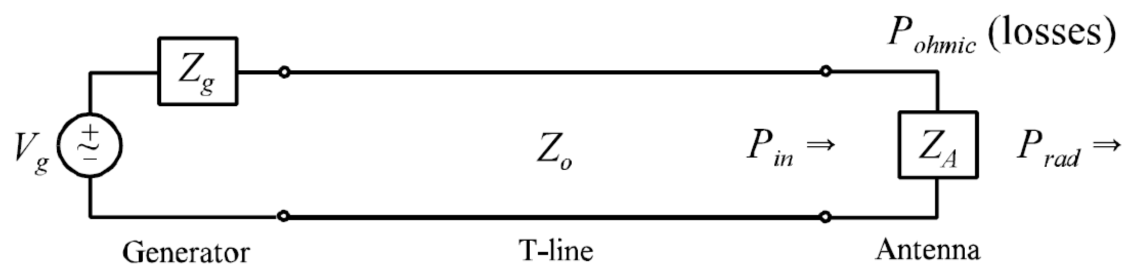


Figure 2.6: Transmitting antenna via a transmission line

Z_g is the source impedance

Z_A is the antenna impedance

Z_o is the transmission line characteristic impedance

P_{in} is the total power delivered to the antenna terminals

P_{ohmic} is the antenna ohmic (I^2R) losses [conduction loss + dielectric loss]

P_{rad} is the total power radiated by the antenna

The total power delivered to the antenna terminals is less than that available from the generator given the effects of mismatch at the source/t-line connection, losses in the t-line, and mismatch at the t-line/antenna connection. The total power delivered to the antenna terminals must equal that lost to I^2R (ohmic) losses plus that radiated by the antenna.

$$P_{in} = P_{ohmic} + P_{rad} \quad (2.4)$$

The antenna efficiency is a parameter which takes into account the amount of losses at the terminals of the antenna and within the structure of the antenna. These losses are given as: Reflections because of mismatch between the transmitter and the antenna and Losses due to conduction and dielectric materials.

Hence the total antenna efficiency can be written as:

$$e_t = e_r.e_c.e_d \quad (2.4)$$

Where e_t = total antenna efficiency = $(1-\left|\Gamma^2\right|)$, e_r = reflection (mismatch) efficiency, e_c = conduction efficiency, e_d = dielectric efficiency. Since e_c and e_d are difficult to separate, they are lumped together to form the e_{cd} efficiency which is given as:

$$e_{cd} = e_c . e_d = \frac{R_r}{R_r + R_L} \tag{2.5}$$

e_{cd} is called as the antenna radiation efficiency and is defined as the ratio of the power delivered to the radiation resistance R_r, to the power delivered to $R_r + R_L$.

2.5.7 Antenna Gain

Antenna gain is a parameter which is closely related to the directivity of the antenna. We know that the directivity is how much an antenna concentrates energy in one direction in preference to radiation in other directions. Hence, if the antenna is 100% efficient, then the directivity would be equal to the antenna gain and the antenna would be an isotropic radiator.

Since all antennas will radiate more in some direction that in others, therefore the gain is the amount of power that can be achieved in one direction at the expense of the power lost in the others. The gain is always related to the main lobe and is specified in the direction of maximum radiation unless indicated [3]. It is given as:

$$G(\theta,\phi) = e_{cd} . D(\theta,\phi) \qquad dBi \tag{2.6}$$

2.5.8 Polarization

Polarization of a radiated wave is defined as “the property of an electromagnetic wave describing the time varying direction and relative magnitude of the electric field vector” [3]. The polarization of an antenna refers to the polarization of the electric field vector of the radiated wave. In other words, the position and direction of the electric field with reference to the earth’s surface or ground determines the wave polarization. The most common types of polarization include the linear (horizontal or vertical) and circular (right hand polarization or the left hand polarization).

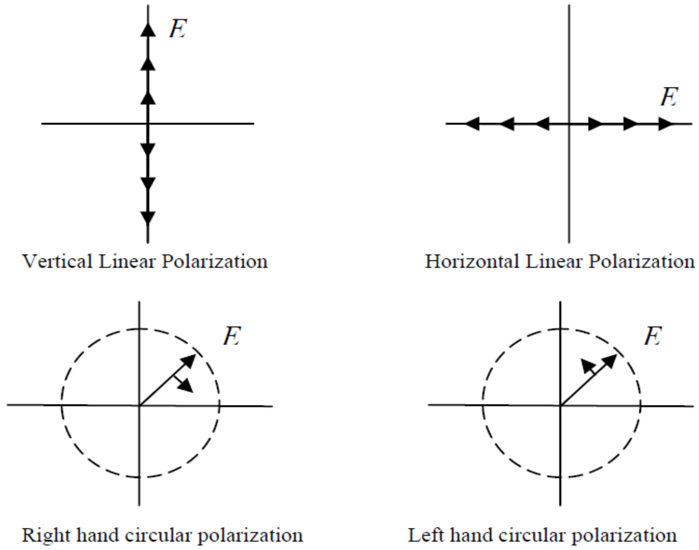


Figure 2.7: Commonly used polarization schemes

2.5.9 Bandwidth

The bandwidth of an antenna is defined as "the range of usable frequencies within which the performance of the antenna, with respect to some characteristic, conforms to a specified standard." [3]On other words, the bandwidth can be the range of frequencies on either side of the center frequency where the antenna characteristics like input impedance, radiation pattern, beamwidth, polarization, gain, are close to those values which have been obtained at the center frequency. The bandwidth of a broadband antenna can be defined as the ratio of the upper to lower frequencies of acceptable operation. The bandwidth of a narrowband antenna can be defined as the percentage of the frequency difference over the center frequency [3]. According to [3] these definitions can be written in terms of equations as follows:

$$BW_{broadband} = \frac{f_H}{f_L} \quad , \quad BW_{narrowband(\%)} = \left[\frac{f_H - f_L}{f_C}\right].100 \tag{2.7}$$

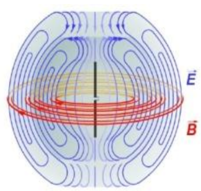
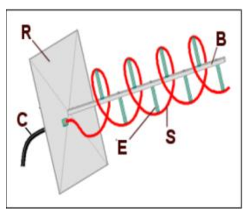
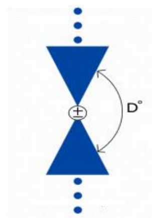
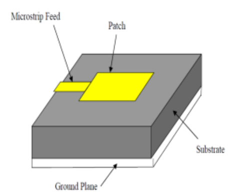
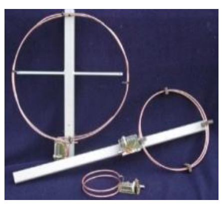
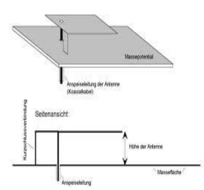
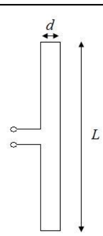
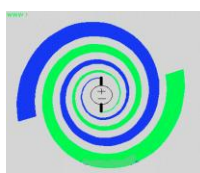
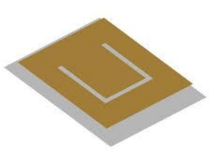
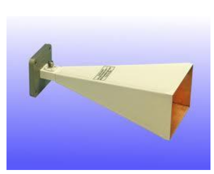
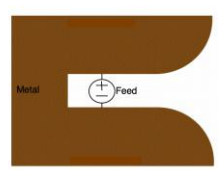
Where f_H = upper frequency , f_L =lower frequency , f_C = center frequency

2.6 Antenna types:

Antennas can be classified in several ways. One way is the frequency band of operation. The other is by physical structure. Most simple of antennas are nondirectional antennas like basic dipoles or monopoles. The complex types are directional antennas which consist of arrays of elements, such as Log periodic and Yagi [3].

In table 2.1, some of the antenna types are introduced with figures.

Table2.1: Antenna types

Wire Antennas	Travelling Wave	Log-Periodic	Microstrip Ant.	Reflector Ant.
Dipole Antenna 	Helical Antennas 	Bow Tie 	Microstrip 	Corner Reflector 
Loop Antenna 	Yagi-Uda Ant. 	Log-Periodic 	PIFA Antenna 	Reflector Ant. 
Folded dipole 	Spiral Antennas 			
Aperture Antennas	Slot Ant. 	Horn Ant. 	Vivaldi Ant. 	Slotted Waveguide 

Figures in table 2.1 are in [4].

2.7 Microstrip Patch Antenna

2.7.1 Introduction

Microstrip patch antenna consists of a radiating patch on one side of a dielectric substrate which has a ground plane on the other side as shown in Figure 2.7.

The patch is generally made of conducting material such as copper or gold and can take any possible shape.

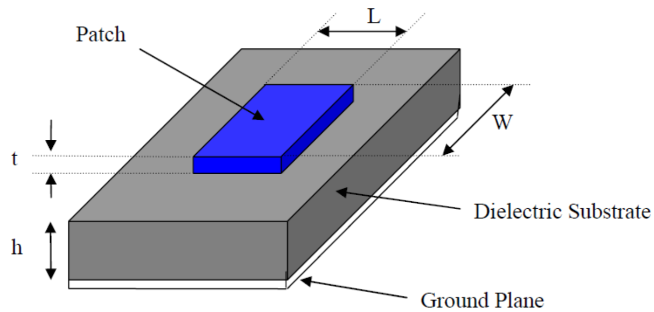


Figure 2.8 Structure of a Microstrip Patch Antenna

In order to simplify analysis and performance prediction, the patch is generally square, rectangular, circular, triangular, and elliptical or some other common shape as shown in Figure 2.8.

For a rectangular patch, the length L of the patch is usually $0.3333\lambda < L < 0.5\lambda$, where λ is the free-space wavelength. The patch is selected to be very thin such that $t \ll \lambda$ (where t is the patch thickness). The height h of the dielectric substrate is usually $0.003\lambda \leq h \leq 0.05\lambda$. The dielectric constant of the substrate ε_r is typically in the range $2.2 \leq \varepsilon_r \leq 12$ [12].

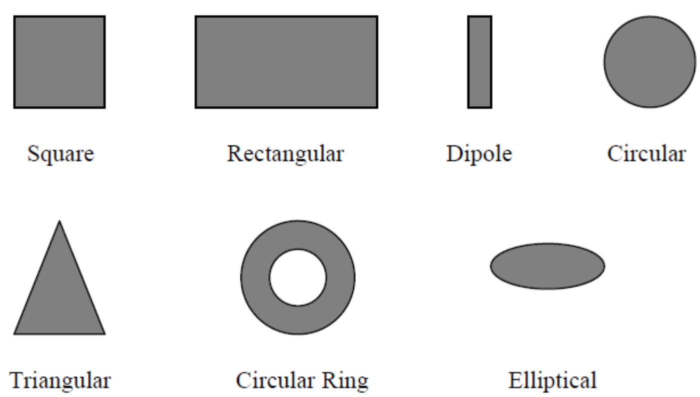


Figure 2.8: Common shapes of microstrip patch elements

Microstrip patch antennas radiate because of the fringing fields between the patch edge and the ground plane. For good antenna performance, a thick dielectric substrate having a low dielectric constant so this provides better efficiency, larger bandwidth and better radiation [12]. However, such a configuration leads to a larger antenna size.

In order to design a compact Microstrip patch antenna, higher dielectric constants must be used which are less efficient and result in narrower bandwidth. Hence a compromise must be reached between antenna dimensions and antenna performance.

2.7.2 Advantages and Disadvantages

Microstrip patch antennas are increasing in need for use in wireless applications due to their low-profile structure. Therefore they are extremely compatible for embedded antennas in handheld wireless devices such as cellular phones, pagers etc... The communication antennas on missiles need to be thin and conformal and are often Microstrip patch antennas. Another area where they have been used successfully is in satellite communication. Advantages and disadvantages of the patch antenna are discussed in [13]. Some of these are shown below:

1. Light weight and low volume.
2. Low fabrication cost, hence can be manufactured in large quantities.
3. Supports both, linear as well as circular polarization.
4. Can be easily integrated with microwave integrated circuits (MICs).
5. Capable of dual and triple frequency operations.

Microstrip patch antennas suffer from a number of disadvantages as compared to conventional antennas. Some of their major disadvantages are shown below:

1. Narrow bandwidth
2. Low efficiency
3. Low Gain

2.7.3 Feed Techniques

Microstrip patch antennas can be fed by a variety of methods. These methods can be classified into two categories contacting and non-contacting. In the contacting method, the RF power is fed directly to the radiating patch using a connecting element such as a microstrip line. In the non-contacting scheme, electromagnetic field coupling is done to transfer power between the microstrip line and the radiating patch [13]. The four most popular feed techniques used are the microstrip line, coaxial probe (both contacting schemes), aperture coupling and proximity coupling (both non-contacting schemes).

2.7.3.1 Microstrip Line Feed

In this type of feed technique, a conducting strip is connected directly to the edge of the microstrip patch as shown in Figure 2.9. The conducting strip is smaller in width as compared to the patch and this kind of feed arrangement has the advantage that the feed can be etched on the same substrate to provide a planar structure [3].

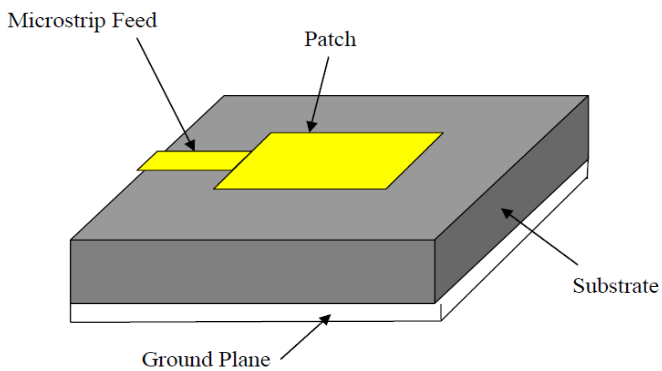


Figure 2.9: Microstrip Line Feed

2.7.3.2 Coaxial Feed

The Coaxial feed or probe feed is a very common technique used for feeding Microstrip patch antennas. As seen from Figure 2.10, the inner conductor of the coaxial connector extends through the dielectric and is soldered to the radiating patch, while the outer conductor is connected to the ground plane [3].

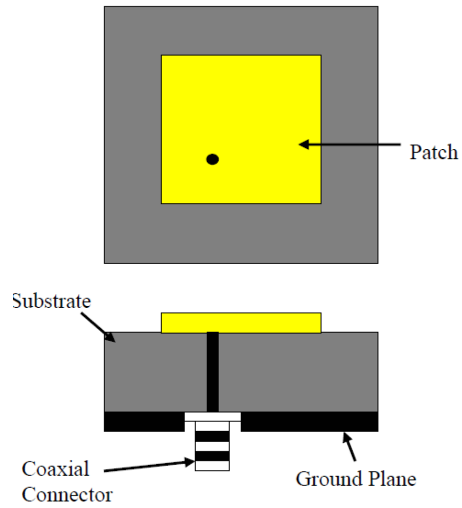


Figure 2.10: Probe fed Rectangular Microstrip Patch Antenna

The main advantage of this type of feeding scheme is that the feed can be placed at any desired location inside the patch in order to match with its input impedance. This feed method is easy to fabricate. However, its major disadvantage is that it provides narrow bandwidth and is difficult to model since a hole has to be drilled in the substrate and the connector stay outside the ground plane, thus not making it completely planar for thick substrates.

2.7.3.3 Aperture Coupled Feed

In this type of feed technique, the radiating patch and the microstrip feed line are separated by the ground plane as shown in Figure 2.11. Coupling between the patch and the feed line is made through a slot or an aperture in the ground plane [3].

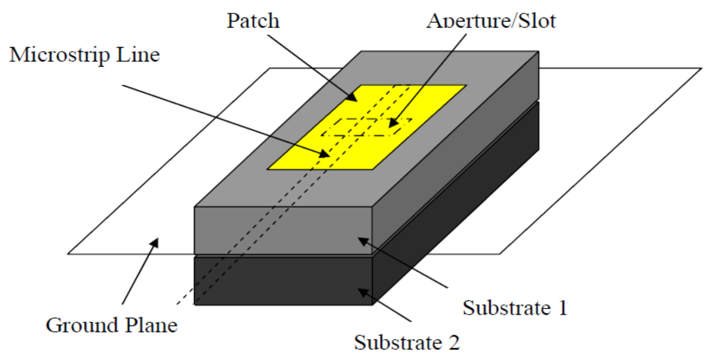


Figure 2.11: Aperture-coupled feed

The coupling aperture is usually centered under the patch. The amount of coupling from the feed line to the patch is determined by the shape, size and location of the aperture. Since the ground plane separates the patch and the feed line, spurious radiation is minimized. Generally, a high dielectric material is used for the bottom substrate and a thick, low dielectric constant material is used for the top substrate to optimize radiation from the patch [12]. The major disadvantage of this feed technique is that it is difficult to fabricate due to multiple layers, which also increases the antenna thickness. This feeding scheme also provides narrow bandwidth.

2.7.3.4 Proximity Coupled Feed

This type of feed technique is also called as the electromagnetic coupling scheme. As shown in Figure 2.12, two dielectric substrates are used such that the feed line is between the two substrates and the radiating patch is on top of the upper substrate. The main advantage of this feed technique is that it eliminates spurious feed radiation and provides very high bandwidth (as high as 13%) [13], due to overall increase in the thickness of the microstrip patch antenna. This scheme also provides choices between two different dielectric media, one for the patch and one for the feed line to optimize the individual performances.

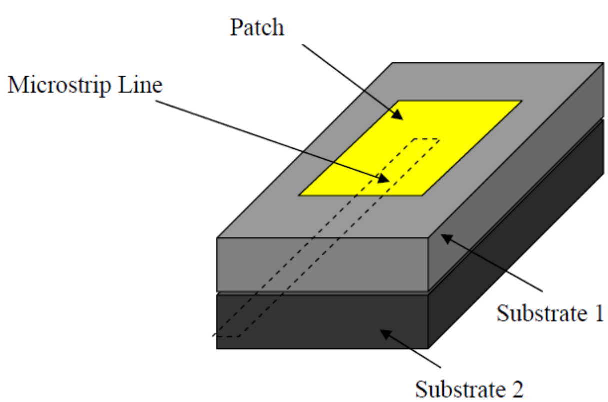


Figure 2.12: Proximity-coupled Feed

Matching can be achieved by controlling the length of the feed line and the width-to-line ratio of the patch. The major disadvantage of this feed scheme is that it is difficult to fabricate because of the two dielectric layers which need proper alignment. Also, there is an increase in the overall thickness of the antenna.

2.7.4 Methods of Analysis

The Microstrip Patch Antenna generally has a two-dimensional radiating patch on a thin dielectric substrate and therefore may be categorized as a two-dimensional planar component for analysis purposes. The analysis methods for Microstrip Patch Antennas can be broadly divided into two groups.

In the first group, the methods are based on equivalent magnetic current distribution around the patch edges (similar to slot antennas). There are two popular analytical techniques:

1. The transmission line model
2. The cavity model

In the second group, the methods are based on the electric current distribution on the patch conductor and the ground plane (similar to dipole antennas, used in conjunction with full-wave simulation/numerical analysis methods). Some of the numerical methods for analyzing Microstrip Patch Antenna are listed as follows:

1. The method of moments (MoM);
2. The finite-element method (FEM);
3. The spectral domain technique (SDT);
4. The finite-difference time domain (FDTD) method.

This section briefly describes these methods.

2.7.4.1 Transmission Line Model

The transmission line model is very simple and helpful in understanding the basic performance of a Microstrip Patch Antenna. The microstrip radiator element is viewed as a transmission line resonator with no transverse field variations (the field only varies along the length), see figure 2.13, the radiation occurs mainly from the fringing fields at the open circuited ends. The patch is represented by two slots that are spaced by the length of the resonator. This model was originally developed for rectangular patches but has been extended for generalized patch shapes. Many variations of this method have been used to analyze the Microstrip Patch Antenna [9, 15–19].

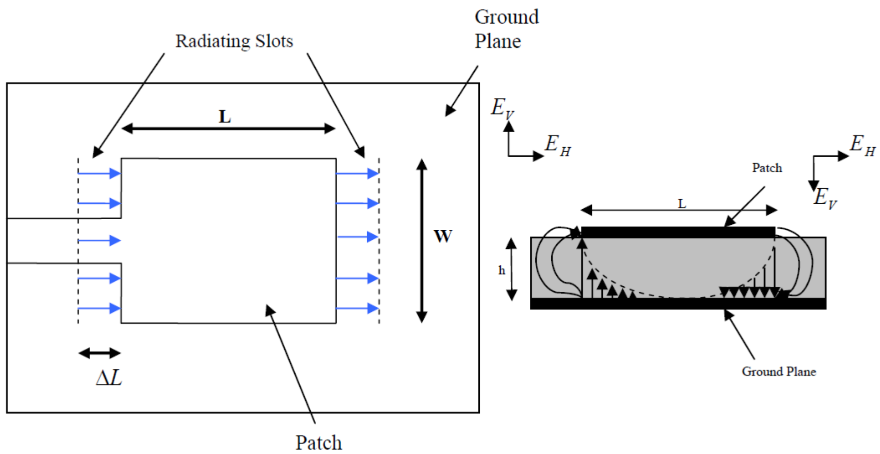


Figure 2.16 Top and side View of Antenna

Although the transmission line model is easy to use, all types of configurations cannot be analyzed using this model since it does not take care of variation of field in the orthogonal direction to the direction of propagation.

2.7.4.2 Cavity Model

In the cavity model, the region between the patch and the ground plane is treated as a cavity that is surrounded by magnetic walls around the periphery and by electric walls from the top and bottom sides. Since thin substrates are used, the field inside the cavity is uniform along the thickness of the substrate [18–22]. The fields underneath the patch for regular shapes such as rectangular, circular, triangular, and sectoral shapes can be expressed as a summation of the various resonant modes of the two-dimensional resonator. The fringing fields around the periphery are taken care of by extending the patch boundary outward so that the effective dimensions are larger than the physical dimensions of the patch. The effect of the radiation from the antenna and the conductor loss are accounted for by adding these losses to the loss tangent of the dielectric substrate. The far field and radiated power are computed from the equivalent magnetic current around the periphery. An alternate way of incorporating the radiation effect in the cavity model is by introducing an impedance boundary condition at the walls of the cavity. The fringing fields and the radiated power are not included inside the cavity but are localized at the edges of the cavity. However, the solution for the far field, with admittance walls is difficult to evaluate [9].

2.7.4.3 MoM

In the MoM, the surface currents are used to model the microstrip patch, and volume polarization currents in the dielectric slab are used to model the fields in the dielectric slab. An integral equation is formulated for the unknown currents on the microstrip patches and the feed lines and their images in the ground plane [26]. The integral equations are transformed into algebraic equations that can be easily solved using a computer. This method takes into account the fringing fields outside the physical boundary of the two-dimensional patch, thus providing a more exact solution.

2.7.4.4 SDT

In the SDT, a two-dimensional Fourier transform along the two orthogonal directions of the patch in the plane of substrate is employed. Boundary conditions are applied in Fourier transform plane. The current distribution on the conducting patch is expanded in terms of chosen basis functions, and the resulting matrix equation is solved to evaluate the electric current distribution on the conducting patch and the equivalent magnetic current distribution on the surrounding substrate surface. The various parameters of the antennas are then evaluated [26].

2.7.4.5 FDTD Method

The FDTD method is well-suited for Microstrip Patch Antennas, as it can conveniently model numerous structural inhomogenities encountered in these configurations [10]. It can also predict the response of the Microstrip Patch Antenna over the wide Band Width with a single simulation. In this technique, spatial as well as time grid for the electric and magnetic fields are generated over which the solution is required.

2.7.4.6 Finite Element Method (FEM)

The Finite Element Method (FEM) as a method of solution is introduced in this thesis because the two programs HFSS and CST are depend on it in there solution method. The FEM, unlike the MoM, is suitable for volumetric configurations. In this method, the region of interest is divided into any number of finite surfaces or volume elements depending upon the planar or volumetric structures to be analyzed [26]. These discretized units, generally referred to as finite elements, can be any well-defined geometrical shapes such as triangular elements for planar configurations and tetrahedral and prismatic elements for three-dimensional configurations, which are suitable even for curved geometry. It involves the integration of certain basic functions over the entire conducting patch, which is divided into a number of subsections. The problem of solving wave equations with inhomogeneous boundary conditions is tackled by decomposing it into two boundary value problems, one with Laplace's equation with an inhomogeneous boundary and the other corresponding to an inhomogeneous wave equation with a homogeneous boundary condition [10].

Since antenna deals with electromagnetic waves, Maxwell's equations are to be considered and the start point for obtaining the vector wave equations and the other parameters and steps for solution as illustrated below.

$$\begin{aligned} &\nabla\times B = -jwB \quad , \quad \nabla\times H = J_S + \sigma E + jwD \\ &\text{Where} \quad D = \varepsilon_r^{'}\varepsilon_o E \quad , \quad B = \mu_r\mu_o H \end{aligned} \tag{2.8}$$

In the above equations, H is the magnetic field intensity, E is the electric field intensity and ω is the operating frequency. Also, ε_0 and μ_0 is the permittivity and permeability of free space, whereas, ε_r and μ_r are the relative permittivity and relative permeability respectively. The vector wave equation for E and H is given by

$$\begin{aligned} &\nabla\times\left(\frac{1}{\mu_r}\nabla\times E\right) - k_o^2\varepsilon_r E = -jk_o\eta_o J_S \\ &\nabla\times\left(\frac{1}{\varepsilon_r}\nabla\times H\right) - k_o^2\mu_r H = \nabla\times\left(\frac{1}{\varepsilon_r}J_S\right) \end{aligned} \tag{2.9}$$

Where J_S is the current source,

$$\varepsilon_r = \varepsilon_r^{'} - j\frac{\sigma}{w\varepsilon_o} \quad , \quad k_o = w\sqrt{\varepsilon_o \mu_o} \ ,$$

Let us consider the dimensions of the substrate such that the height of substrate h is very small in comparison to the wavelength λ within the dielectric. Thus, the field variation along the height is considered as constant due to very small substrate height. Since, the electric field is normal to the surface of the patch, hence, only transverse magnetic (TM) mode is considered. Hence the electric field will be normal to the surface of the ground plane. The top and bottom walls of the patch are perfectly electric conducting layers and the four side walls will be perfectly conducting magnetic walls. Let ε_r is the dielectric constant of the substrate and is smaller than the edges of the patch. The homogenous wave equation for the vector potential A_x is given by

$$\nabla^2 A_x + k^2 A_x = 0 \tag{2.10}$$

The solution for this equation using the separation of variables is given as

$$\begin{aligned} A_x = &\left[A_1 \cos(k_x x) + B_1 \sin(k_x x)\right] \cdot \left[A_2 \cos(k_y y) + B_2 \sin(k_y y)\right] \\ &\cdot \left[A_3 \cos(k_z z) + B_3 \sin(k_z z)\right] \end{aligned} \tag{2.11}$$

Where k_x, k_y and k_z are the wave numbers along the x, y and z direction respectively. These can be determined using boundary conditions. The electric and magnetic field related to the vector potential A_x is given by

$$\begin{aligned} &E_x = -j\frac{1}{w\mu\varepsilon}\left(\frac{\partial^2}{\partial x^2} + k^2\right)A_x \quad , \quad E_x = -j\frac{1}{w\mu\varepsilon}\cdot\frac{\partial^2 A_x}{\partial x \partial y} \\ &E_z = -j\frac{1}{w\mu\varepsilon}\cdot\frac{\partial^2 A_x}{\partial x \partial z} \quad , H_x = 0, H_y = \frac{1}{\mu}\cdot\frac{\partial A_x}{\partial z}, H_z = -\frac{1}{\mu}\cdot\frac{\partial A_x}{\partial y} \end{aligned} \tag{2.12}$$

Another important parameter for finite element analysis is the scattering parameter and this can be extracted using reflection coefficient S_{11} from the calculated electric field [20]. Thus the input impedance can be calculated as

$$Z = Z_o \frac{1+S_{11}}{1-S_{11}} \tag{2.13}$$

Where Z_0 is the characteristic or the matching impedance.

2.7.4.7.1 Parametric Study

Some important antenna parameters can be calculated by the transmission line method [7] and is explained as below.

1. **Patch Width**

Numerically, the width of the microstrip patch can be calculated using the equation as [23]

$$W = \frac{c}{2 f_0 \sqrt{\frac{(\varepsilon_r + 1)}{2}}} \tag{2.14}$$

Where c is the velocity of light in free space, f_0 is the resonant frequency and ε_r is the dielectric constant of the substrate.

2. **Patch Length**

The length of the patch can be calculated only if the effective dielectric constant is known [25], and the effective dielectric constant can be calculated as

$$\varepsilon_{reff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left[1 + 12\frac{h}{W}\right]^{-\frac{1}{2}} \tag{2.15}$$

Where ε_{reff} is the effective dielectric constant, ε_r is the dielectric constant of substrate, h is the height of dielectric substrate and w is the width of the patch. The dimensions of the patch is extended on each end by a distance ΔL and is calculated by

$$\Delta L = 0.412h \frac{(\varepsilon_{reff} + 0.3)(\frac{W}{h} + 0.264)}{(\varepsilon_{reff} - 0.258)(\frac{W}{h} + 0.8)} \tag{2.16}$$

The actual length L of the patch is given as

$$L = \frac{\lambda_o}{2} = 2\Delta L \tag{2.17}$$

3. Input Impedance

The input impedance can be obtained by the equation [21]

$$X_f = \frac{L}{\sqrt[2]{\varepsilon_{reff}}} \tag{2.18}$$

Where X_f is the desired input impedance of the coaxial cable and ε_{reff} is the effective dielectric constant. Similarly, the admittance can be found using the equation

$$Y_f = \frac{w}{2} \tag{2.19}$$

3.4. Ground Dimensions

For practical design, it is necessary to have some finite ground plane. For optimum design of small patch antenna, it is required that the ground plane should be greater than the patch dimensions by approximately six times the substrate thickness all around the fringe [25]. Hence, the ground plane dimensions would be given as

$$\begin{aligned} L_g &= 6h + l \\ W_g &= 6h + w \end{aligned} \tag{2.20}$$

3.5. Return Losses

Return losses depend upon the scattering parameters and for N = 1, S-matrix consists of a single term S_{11} known as reflection coefficient [26]. The magnitude of S_{11} can be expressed in decibels and the return losses can be estimated as

$$RL = 20\log_{10}|S_{11}|dB \tag{2.21}$$

The reflection coefficient is given by

$$S = \frac{Z_L - Z_S}{Z_L + Z_S} \tag{2.22}$$

Where Z_S is the impedance toward the source and Z_L is the impedance toward the load. The following equation can be used to calculate the input impedance of rectangular microstrip antenna.

$$Z = \frac{R}{1 + Q^2\left[\frac{f}{f_o} - \frac{f_o}{f}\right]^2} + j\left[X_L - \frac{RQ\left[\frac{f}{f_o} - \frac{f_o}{f}\right]}{1 + Q^2\left[\frac{f}{f_o} - \frac{f_o}{f}\right]^2}\right] \qquad (2.23)$$

Where R is the resistance of the resonant parallel RLC circuit, f_0 is the resonant frequency, and Q is the quality factor associated with system losses including radiation, the loss due to heating in the conducting elements and the ground plane, and the loss due to heating within the dielectric medium [26].

3.6. Quality Factor

The quality factor is given as,

$$Q = \frac{c\sqrt{\varepsilon_{reff}}}{4hf_o} - \frac{\varepsilon_{reff}\,\Delta L}{h} \qquad (2.24)$$

where c is the velocity of light in free space, E_{reff} is the effective dielectric constant, f_0 is the resonant frequency and h is the height if the patch. The above quoted physical parameter equations for antenna design is used to set the input parameters of the microstrip patch antenna [26].

2.7.5 Matching techniques:

Matching technique is a technique used to reduce the reflected waves when there is difference in impedances between the feed line and the antenna. For the patch antenna there are two types of matching inset fed and feed with a Quarter-Wavelength Transmission Line

2.7.5.1 Inset feed

Since the current is low at the ends of a half-wave patch and increases in magnitude toward the center, the input impedance (Z=V/I) could be reduced if the patch was fed closer to the center[13].

$$Z_{in}(R) = \cos^2\left(\frac{\pi R}{L}\right) Z_{in}(0) \qquad (2.12)$$

In the above equation, $Z_{in}(0)$ is the input impedance if the patch was fed at the end. Hence, by feeding the patch antenna as shown in figure 2.18, the input impedance can be decreased. As an example, if R=L/4, then $\cos(\pi.{}^{R}\!/_{L}) = \cos({}^{\pi}\!/_{4})$, so that $[\cos(\pi/4)]^2 = 1/2$ Hence, a (1/8)-wavelength inset would decrease the input impedance by 50%. This method can be used to tune the input impedance to the desired value.

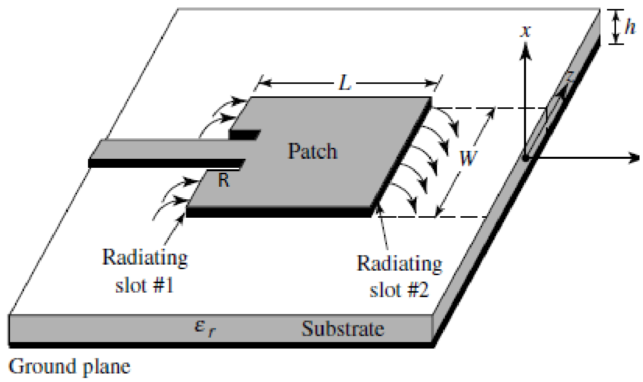


Figure 2.18: Patch Antenna with an Inset Feed

2.7.5.2 Feeding with a Quarter-Wavelength Transmission Line

The microstrip antenna can also be matched to a transmission line of characteristic impedance Z_o by using a quarter-wavelength transmission line of characteristic impedance Z_1 as shown in Figure 2.19

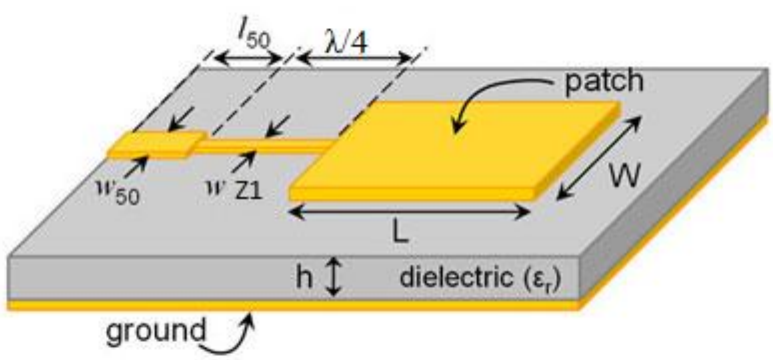


Figure 2.19: Patch antenna with a quarter-wavelength matching section.

The goal is to match the input impedance (Z_{in}) to the transmission line (Z_o). If the impedance of the antenna is Z_A, then the input impedance viewed from the beginning of the quarter-wavelength line becomes [13]

$$Z_{in} = Z_o = Z_1^2 / Z_A \tag{2.13}$$

2.8 Summary

In this chapter an introduction and background of the antenna is introduced, the Maxwell's equations and the radiation pattern of antenna and the far and near field regions are also presented in this chapter. The antenna parameters such as return loss, input impedance, bandwidth, directivity, antenna efficiency, gain and polarization are discussed. An introduction to the microstrip patch antenna and its shapes, then the feeding mechanisms which is used in this antenna and also the matching techniques of some of these feeding methods are also introduced in this chapter. The last section of this chapter talked about the transmission line model and the analysis of the microstrip patch antennas.

References

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Chapter 3
Micromachining technology

3.1 Introduction:

Working on the millimeter waves or high frequency ranges of about 60 GHz leads to deal with micro devices because of the Inverse relationship between the frequency and the size of the antenna as mentioned in chapter 2. This challenge in the small devices leads us to study a technique called micromachining.

This chapter introduces an overview of micromachining, and how micromachining techniques are used to make the cavity or the gap on the substrate. There are many types of micromachining processes and this chapter introduces some of them.

Firstly the bulk micromachining and its two types wet and dry etching will be discussed, then the surface micromachining and the difference between it and the bulk micromachining is disused. Membrane technology, another micromachining technique used in transmission lines and antennas is also discussed. Other types of micromachining which are more accurate and can deal with extremely small size are the photolithography and LIGA technology.

3.2 Micromachining overview:

Dealing with extremely small size which about nanometers devices obliges us to study a technique called micromachining.

The micromachining is a process of fabrication with different types used to deal with very small size devices. For the patch antenna proposed in this thesis, micromachining process is used to make etch or gab in the substrate of the antenna to make the modifications wanted as discussed in the chapters 1 and 2.

There are many types of micromachining fabrication process and every type of them has its advantages and disadvantages. The micromachining process may be classified into bulk micromachining or surface micromachining. The bulk micromachining which aim to etch in the substrate is classified into dry etching and wet etching. Also there are other techniques of the micromachining process like photolithography, membrane micromachining, liga and so on. Those techniques are presented throughout this chapter.

3.3 Bulk Micromachining

Bulk micromachining is a process that defines structures by selectively removing or etching into a substrate, or by another definition Bulk micromanufacturing technique involves creating 3-D components by removing materials from thick substrates (silicon or other materials) using primarily etching method [1]. From the two definitions we note that the main process in bulk micromachining is the etching, see figure 3.1

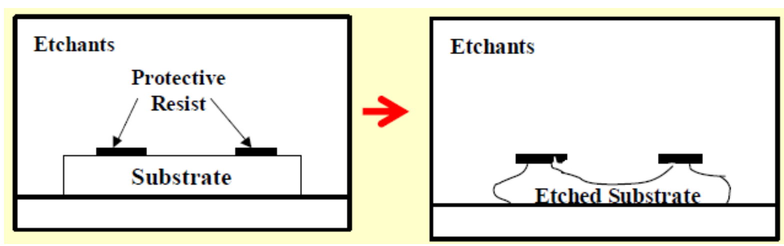

Figure 3.1: the substrate etching overview

By looking at figure 3.1, we note that the etching process is done in the substrate which is silicon for example, and to make the shape wanted the protective resist or the mask is used to prevent the etching under this mask.

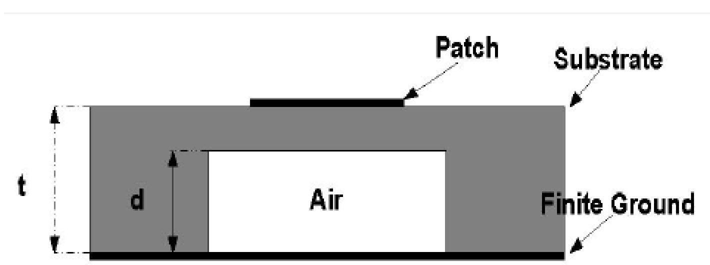

Figure 3.2: the bulk micromachining affect in the substrate

Note: the bulk micromachining makes a cavity in the substrate of the antenna, so the substrate seems as a mix of two materials the air and the substrate material.

So by looking at figure 3.2 the effective dielectric constant become as follow [2]:

$$\varepsilon_{reff} = \frac{(\varepsilon_{air} + \varepsilon_{material}).t}{(d(\varepsilon_{material} - \varepsilon_{air}) + t.\varepsilon_{air})} \tag{3.1}$$

There are two etching techniques; wet etching and dry etching [1].

3.3.1 Wet etching:

Wet etching use liquid to make a chemical reaction with the substrate material and then make the etching shape, the etching process is not ideal, and the etching shape is done as the reaction take place. Another problem is the deep of the reaction between the liquid and the substrate material, from this problem there exist an etching stop circuit [2], as shown in figure 3.3.

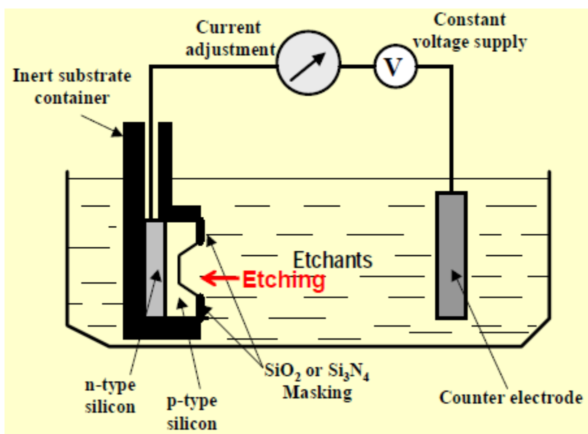

Figure 3.3: Wet etching stop circuit

3.3.2 Dry etching:

Dry etching is a process used to make the etching on the substrate by one of the following methods [2]:

- Ion etching, see figure 3.4.
- Plasma etching.
- Reactive ion etching or Deep reactive ion etching (DRIE).

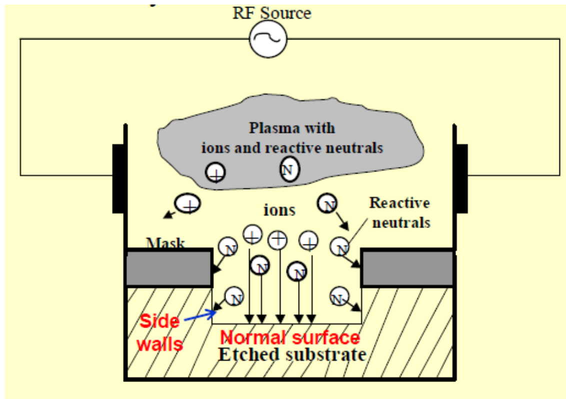

Figure 3.4: Dry etching method

The challenge in the etching process is classified in two notes:

1. The dry etching process makes deep etching in the substrate as demand in the design, so it is preferred when deep etching is wanted.
2. The ability to make the etch shape ideal as possible θ=0, see figure 3.5, and this shape is preferred to be done by the dry etching [3].

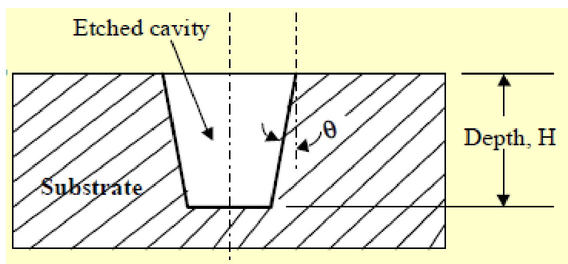

Figure3.5: The slope angle of the etching

3.4 Surface Micromachining

Surface micromachining builds microstructures by deposition and etching different structural layers on the top of the substrate, in other words, the surface micromachining depend on adding layers then make etching then finally remove layer like in figure 3.6 [5].

The steps of this technique are in the notes below [5]:

- Deposit a layer of PSG (Phosphosilicate glass) as in A.

- Cover the PSG layer with Mask 1 (made of Si_3N_4) for subsequent etching away the PSG as in B and C.
- Produce a Mask 2 (Si_3N_4) with opening of the size of the beam length and width.
- Cover this Mask on top of the PSG layer as in D.
- Deposit polysilicon over the masked region as in E.
- Remove the sacrificial PSG by etching as in F.

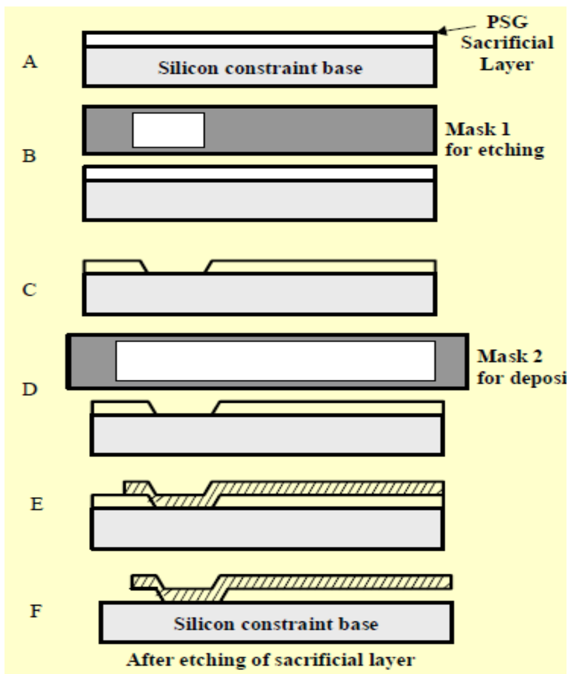

Figure 3.6: Surface micromachining

3.5 Membrane Technology

Membrane technology in micromachining gained attention due to its ability to deal with small size components and without complexity in steps see figure 3.7 [4]. The etch step discussed earlier is very useful in fabricating membranes. Membrane technology is commonly used in integrating micromachined transmission lines and antennas. In antenna design, the idea is to have a cavity underneath the radiator, thus reducing the effective permittivity of the substrate and also minimizing losses.

The manufacturing process is depicted in Figure 3.7.

The process in Figure 3.7 starts with a 2 mm layer of SiO2 deposited on the silicon substrate before it was metalized by 3 mm thick Cr and Au on both sides as shown Figure 3.7 (a). Then, the Au layer on the front side was patterned to realize the patch antenna as shown in Figure 3.7 (b). The back side was patterned as an open window for the bulk micromachining etching process as shown in Figure 3.7 (c). Wet etching is applied to remove the silicon substrate underneath the circuit area to obtain a thin layer membrane as depicted in Figure 3.7 (d). Finally, the Cr layer was patterned as shown in Figure 3.7 (e) [3].

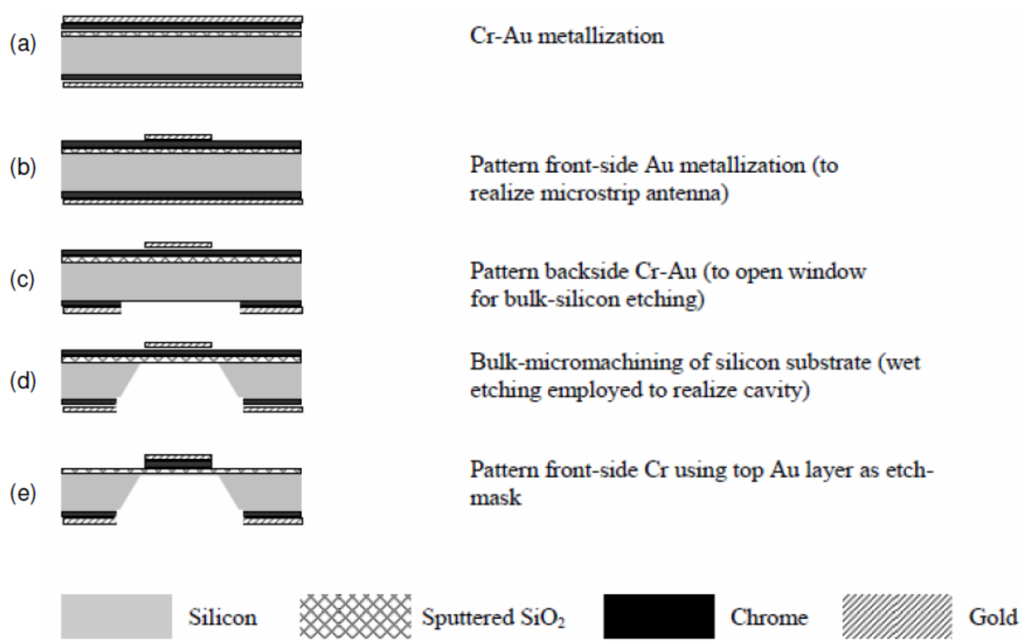

Figure 3.7: The manufacturing process of membrane micromachining

3.6 Photolithography technology

Photolithography (or "optical lithography") is a process used in microfabrication to selectively remove parts of a thin film or the bulk of a substrate. Or by other words the photolithography process is a process which uses light to make etching in the substrate by using a photo mask to make a geometric pattern which transfers this pattern to the substrate see figure 3.8 [6]. A series of chemical treatments are then done in the substrate to finalize the etch shape [6].

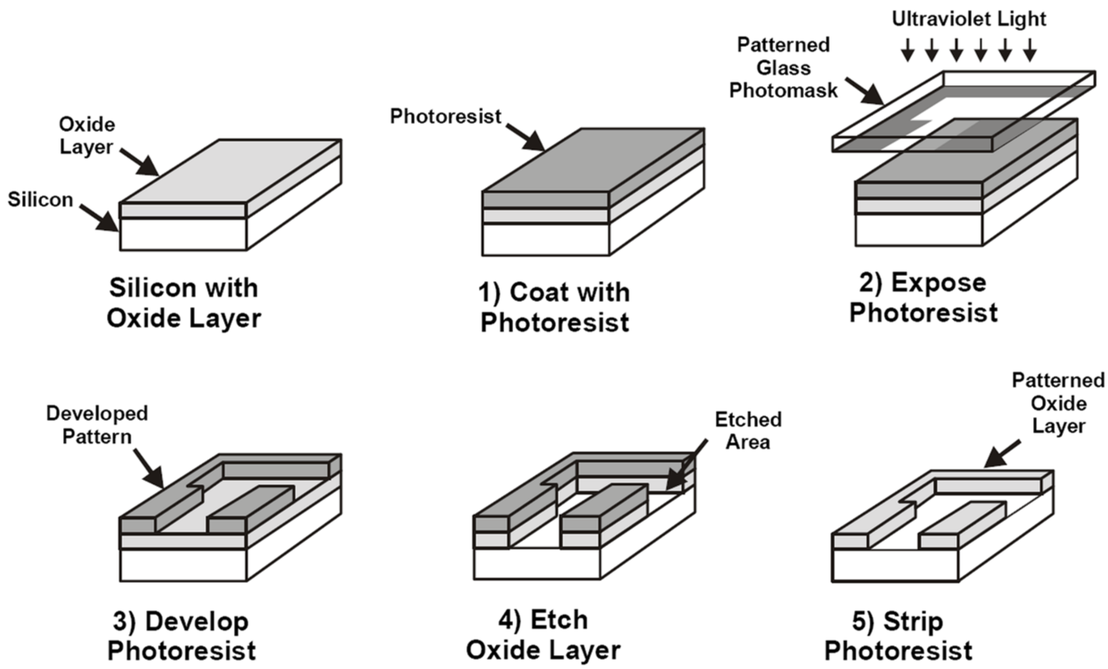

Figure 3.8: Photolithography process

Firstly, the substrate is covered by an oxide layer then with a photoresist layer as shown in figure 3.8, and then a mask is used to cover the photoresist layer. The Ultraviolet light then go through the mask to make the shape wanted as shown in figure 3.8, finally the mask and the photoresist layers are removed and the result is the shape wanted as shown in figure 3.8.

3.6.1 Advantages of this technique:

The Photolithography can etch a pattern into an integrated circuit with a single beam of ultraviolet light and does not require any additional materials. This allows photolithography to be highly efficient and cost-effective while producing extremely small size in a substrate. Also, photolithography controls the exact size and shape of the entire substrate [6].

3.7 LIGA Technology

LIGA is a German acronym for **Li**thographie, **G**alvanoformung, **A**bformung or (Lithography, Electroplating, Molding) describes a fabrication technology [7]. In other words LIGA is a type of the photolithography fabrication process which uses the X-ray instead of the Ultraviolet Light. The same process discussed in section 3.8 is applied in LIGA but with the use of X-ray [7].

3.8 Electromagnetic band gap (EBG):

The electromagnetic band gap (EBG) is a technique of micromachining techniques used to make a structure of cylindrical holes in the substrate producing a mixed of the substrate material and the air to achieve a low effective dielectric constant, see figure 3.9 [8].

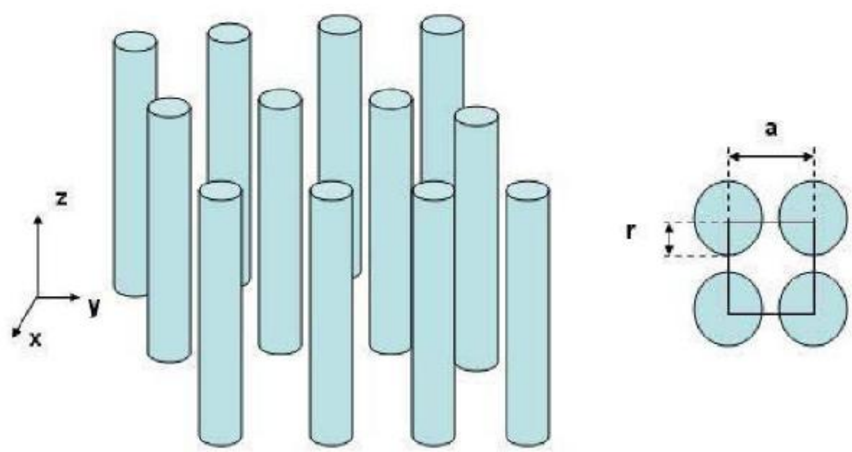

Figure 3.9: electromagnetic band gap (EBG)

These cylindrical holes are drilled in the substrate with Particular order to achieve the best performance. The ratio of radius of air cylinders (r) to the lattice constant (a) is taken as 0.45. The ratio (a/λ) where λ is the wavelength is taken as 0.5 [8].

3.9 Summary

An overview of micromachining and how micromachining techniques are used to make the cavity or the gap on the substrate is introduced in this chapter. There are many types of micromachining processes and this chapter introduced some of them.

The bulk micromachining and its two types wet and dry etching are also discussed, the surface micromachining and the membrane technology are also discussed in this chapter. The last part of this chapter discussed other types of micromachining which are more accurate and can deal with extremely small size which are the photolithography and LIGA technology.

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Chapter 4

Design of Micromachined Patch Antenna for Millimeter wave applications

4.1 Introduction:

This chapter introduces the design part of the micromachined antenna. The simulation is done by CST microwave studio program and also some parts of the simulations were done by HFSS program.

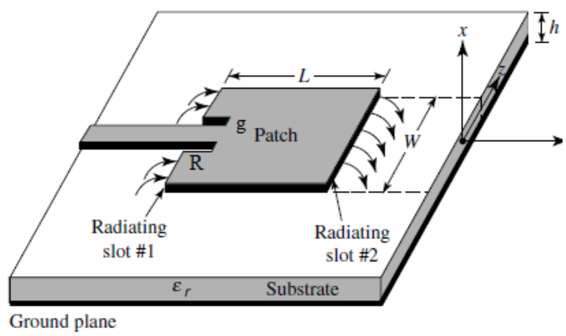
The main goal of this thesis as introduced in chapter 1 is to design a micromachined patch antenna for millimeter wave applications. To achieve this goal, the following steps have been followed:

- Make numerical solution by equations of the inset-fed antenna to find the initial dimensions used in the CST program.
- Design a rectangular patch antenna with inset feeding by CST program and compare the results with others.
- Apply the first type of micromachining which is the bulk micromachining with its two type's wet and dry etching. The results are then compared with above.
- Apply the second type of micromachining used to make modification in the substrate which is the electromagnetic band gap (EBG) as in chapter 3, and also the results will be compared.
- Apply the two techniques above: bulk micromachining and EBG on the same antenna and see the results, and compare them with the main antenna.
- Apply a new design of the antenna with the substrate material is the air only. Two designs are considered for this, the first is without supporting lines and the second is with supporting lines.
- Make comparisons between all the designs applied in this chapter and see the best design.

4.2 Inset fed antenna design for 60 GHz frequency.

After studding the Transmission Line Model and inset feed matching in sections 2.6.4 and 2.6.5 in chapter 2, and using the equations 2.8-2.13, the following table gives the results and the numerical parameters used to design an antenna for 60GHz frequency. Some of the results were obtained using HFSS antenna design toolkit like the feed length and width and the inset distance and gab.

Table 4.1: Inset Fed Patch antenna dimensions

<table>
<tr><td>Width of patch</td><td>0.98mm</td><td rowspan="6">
</td></tr>
<tr><td>Length of patch</td><td>0.62mm</td></tr>
<tr><td>Thinness of substrate</td><td>0.27mm</td></tr>
<tr><td>Width of substrate</td><td>3.1mm</td></tr>
<tr><td>Length of substrate</td><td>2.22mm</td></tr>
<tr><td>Inset distance R</td><td>0.228mm</td></tr>
<tr><td>Inset Gab g</td><td>0.108mm</td><td>Frequency 60GHz</td></tr>
<tr><td>Feed Width</td><td>0.217mm</td><td>Substrate material Gallium Arsenide GaAs, ε_r = 12.9</td></tr>
<tr><td>Feed Length</td><td>0.745mm</td><td>Characteristic impedance 50 ohms</td></tr>
</table>

4.2.1 Simulations by CST program:

Firstly, the inset fed antenna for 60GHz has been designed without modifications in the substrate.

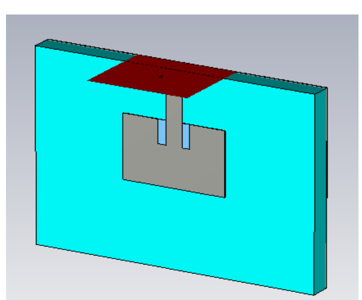


Figure 4.1: Inset feed patch antenna

4.2.2 S-Parameters

The results are shown in figure 4.2. The bandwidth of the normal inset fed patch antenna is 2.5GHz. The FBW is 4.1% and the S-parameter magnitude at 60 GHz is -41.6 dB.

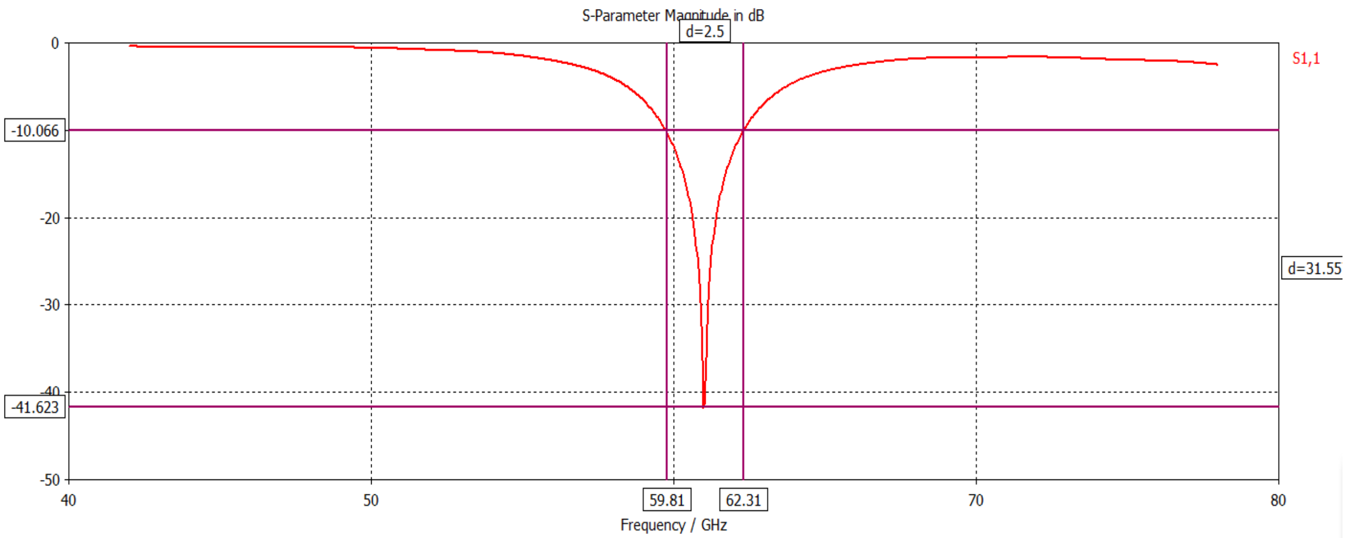


Figure 4.2: $S_{11}$of inset fed

4.2.3 Input Impedance and current distribution

The real part of the input impedance shown in figure 4.3 is around 60 ohm at frequency 60.6 GHz and the Imaginary part as shown in figure 4.4.

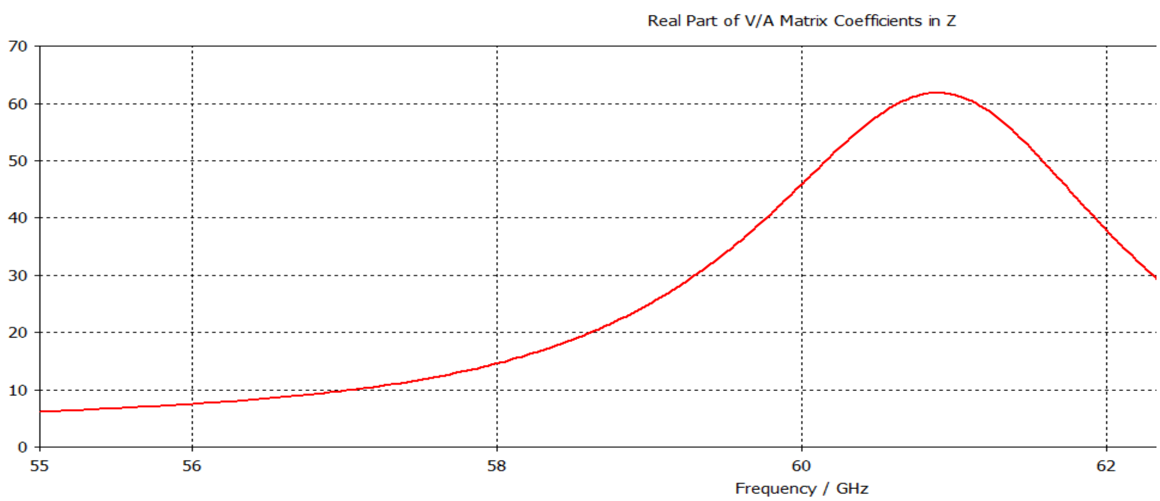


Figure 4.3: Real Part of input impedance

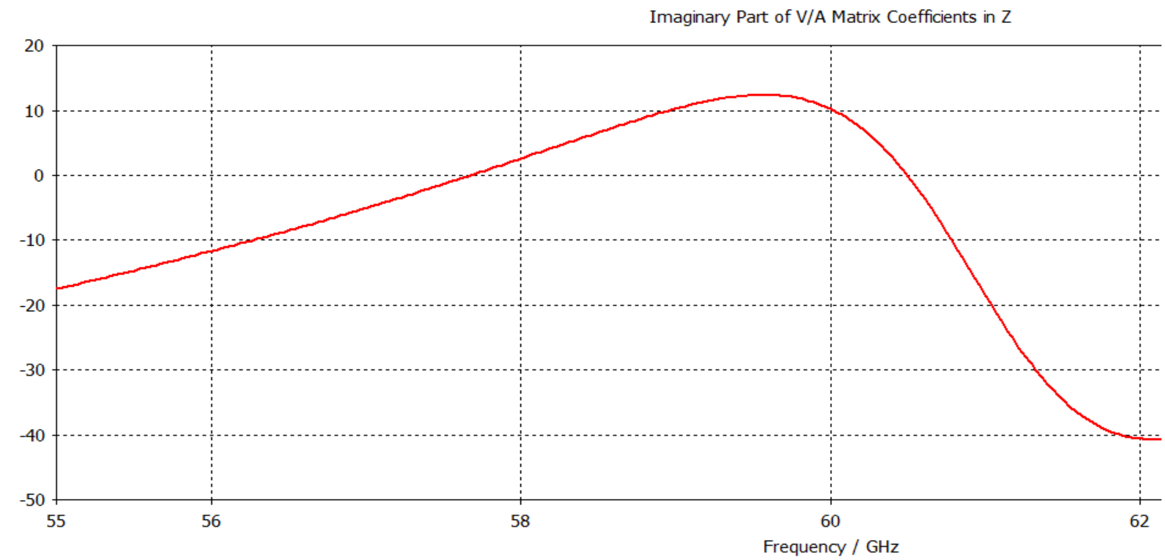


Figure 4.4: Imaginary part of input impedance

The current distribution of the inset fed patch antenna is shown in figure 4.5

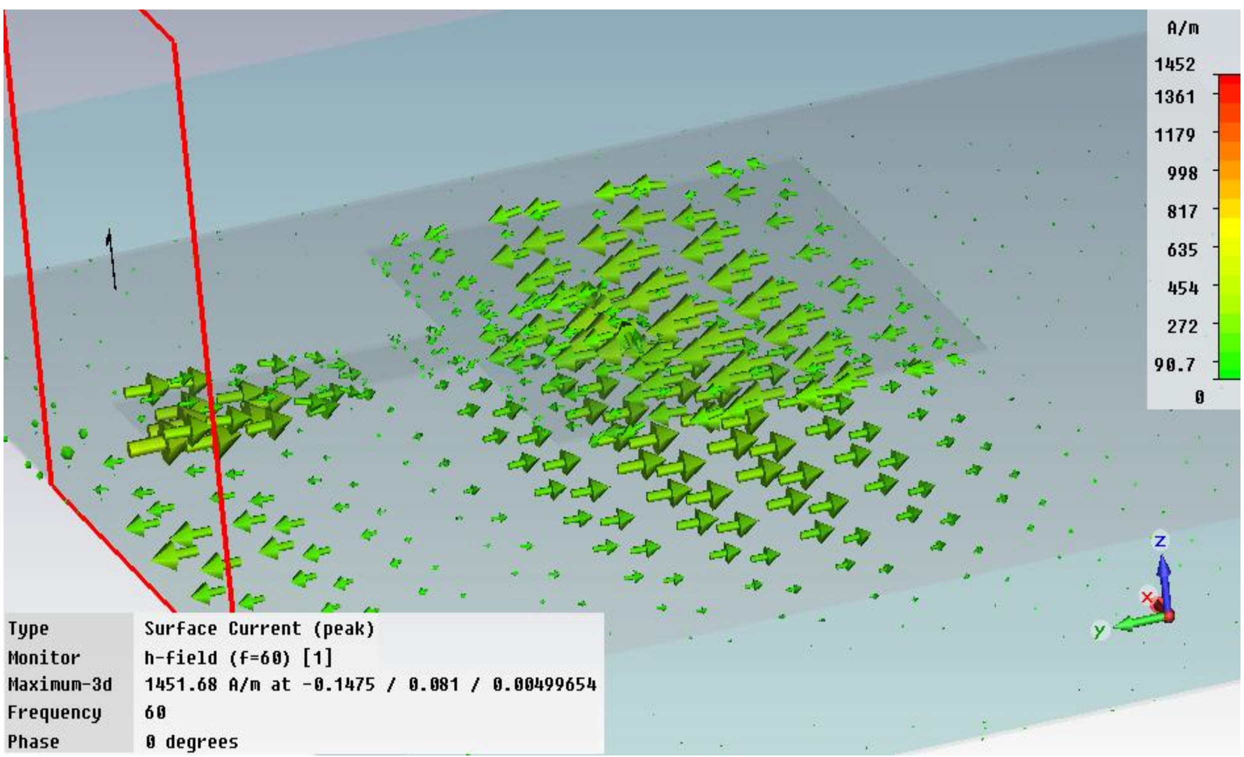


Figure 4.5: Current distribution

4.2.4 Gain and Radiation fields:

The gain of the normal inset fed patch antenna is 3.82 dB at the centre frequency as shown in figure 4.6, and the radiation pattern is also shown in this figure.

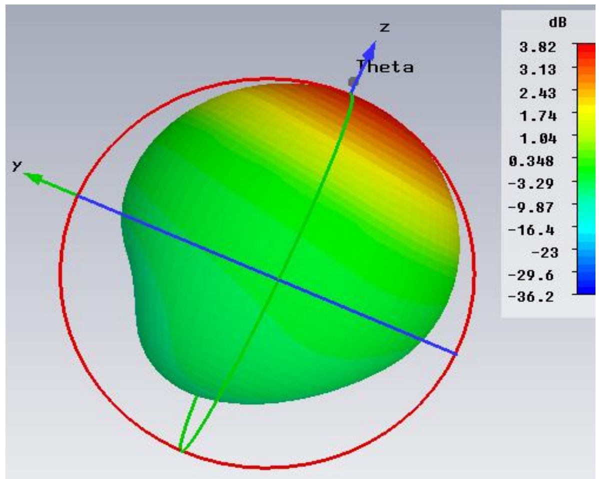


Figure 4.6: Gain & Radiation fields

4.3 Bulk Micromachining Wet & Dry etching in the substrate:

4.3.1 Dry etching:

In dry etching the cavity is made in the substrate with vertical walls like in figure 4.7.

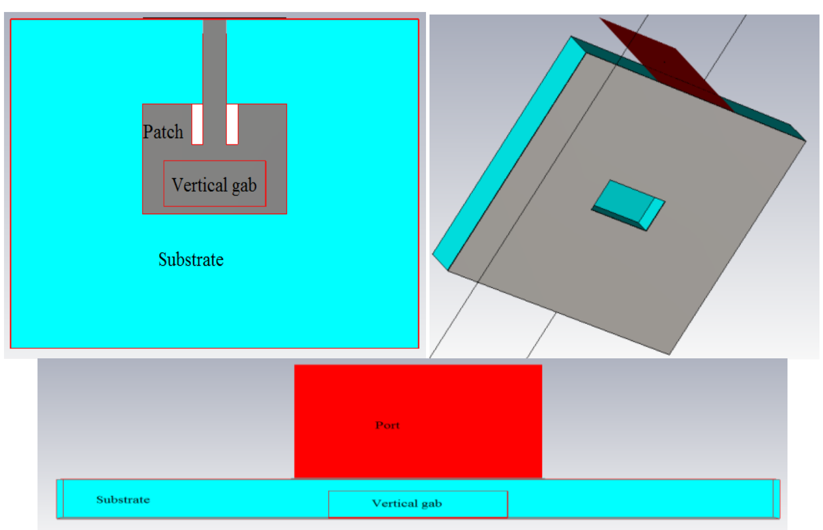


Figure 4.7: inset feed patch with dry etching-vertical walls.

4.3.1.1 S-Parameters

The results are shown in figure 4.8. The bandwidth is from 58.829 to 61.551GHz, and hence the bandwidth of inset fed patch antenna with dry etching is 2.72GHz. The FBW is 4.53% and the S-parameter magnitude at 60 GHz is -34.47dB.

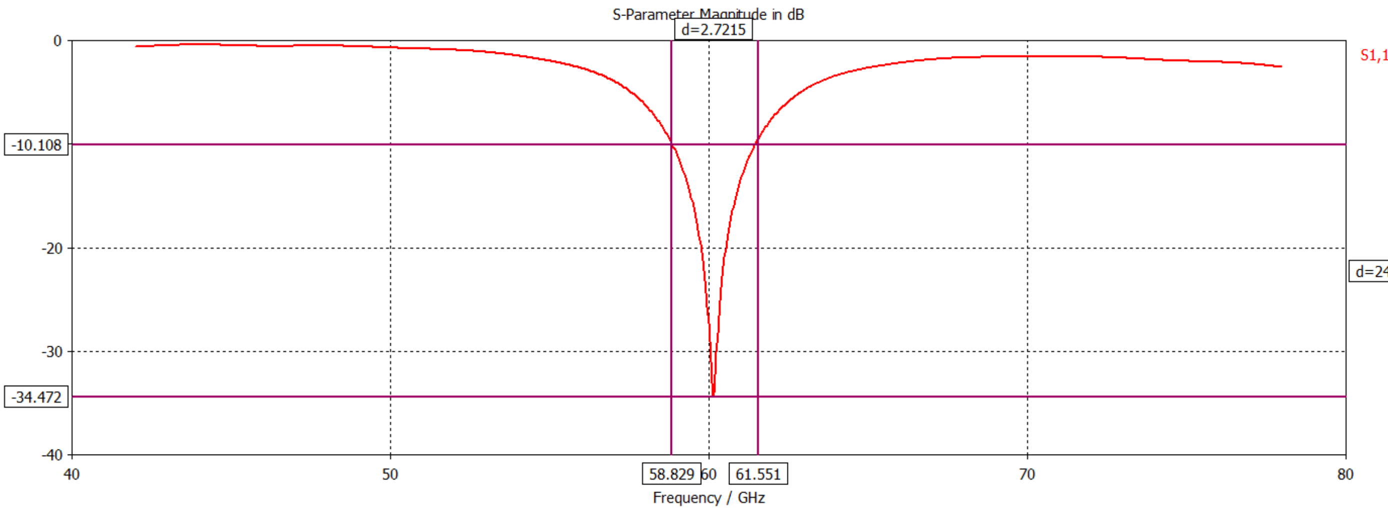


Figure 4.8: S_{11} of the inset fed antenna with dry etching

4.3.1.2 Input Impedance and current distribution

The real part of the input impedance shown in figure 4.9 is around 55 ohm at frequency 60 GHz and the Imaginary part as shown in figure 4.10.

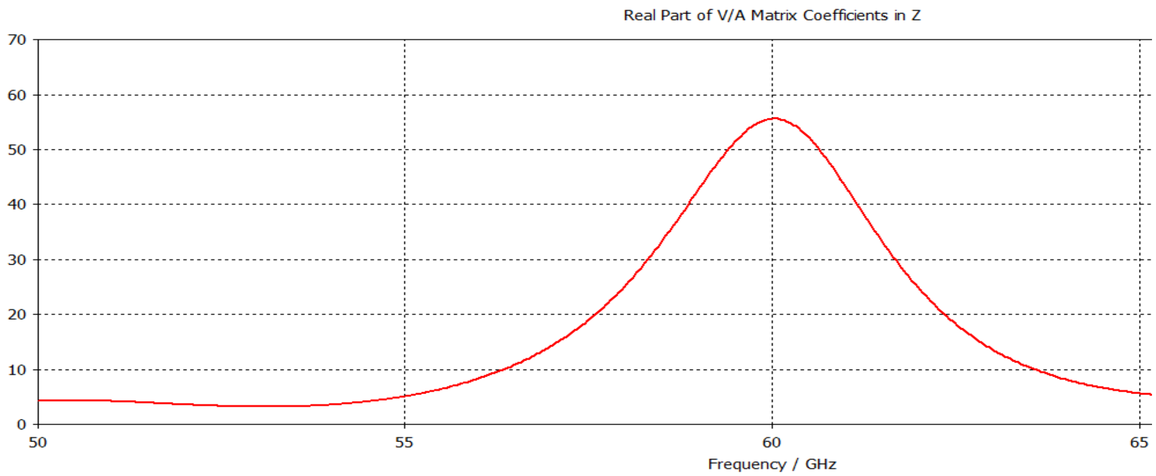


Figure 4.9: Real Part of input impedance

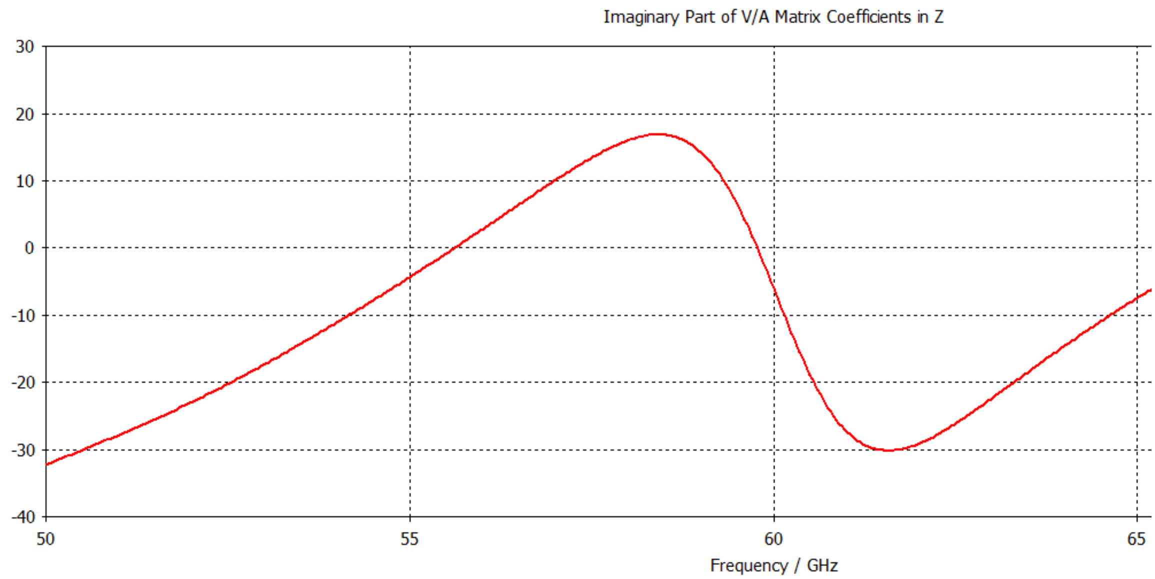


Figure 4.10: Imaginary part of input impedance

The current distribution of the inset fed patch antenna with bulk micromachining dry etching is shown in figure 4.11

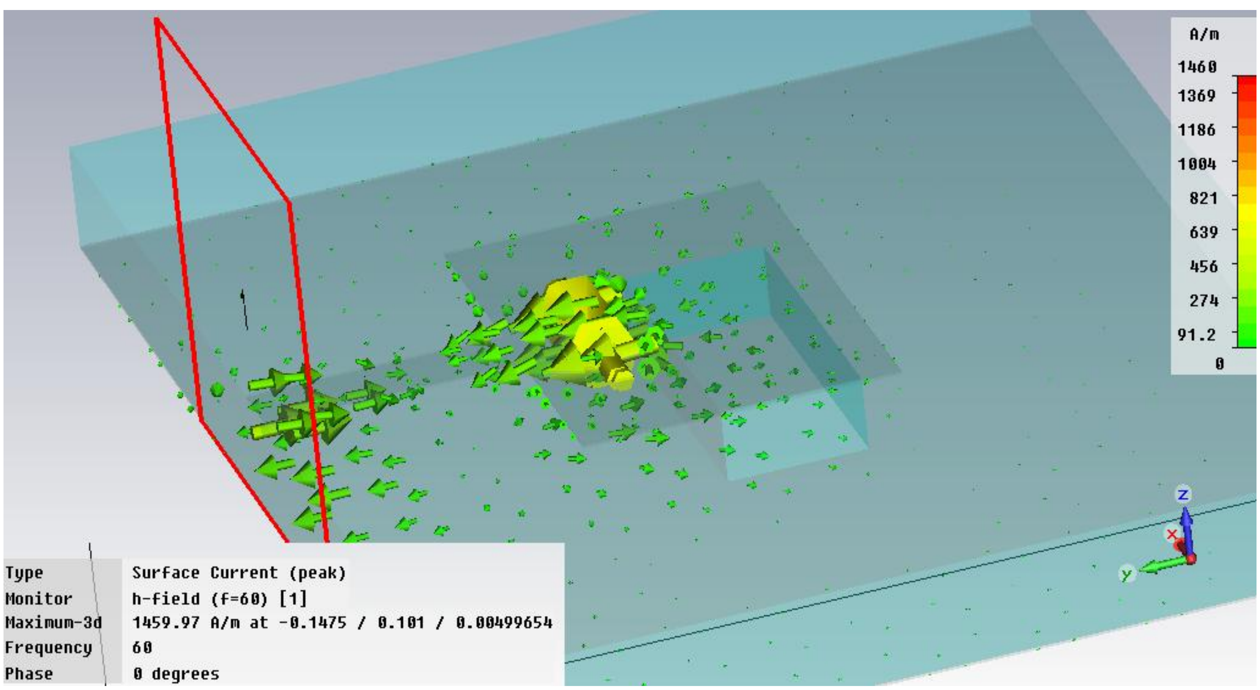


Figure 4.11: Current distribution

4.3.1.3 Gain and Radiation fields:

There is a small improvement in the gain from 3.82dB to 3.83dB as shown in figure 4.12 and no improvements in the radiation pattern as compared with figure.4.6.

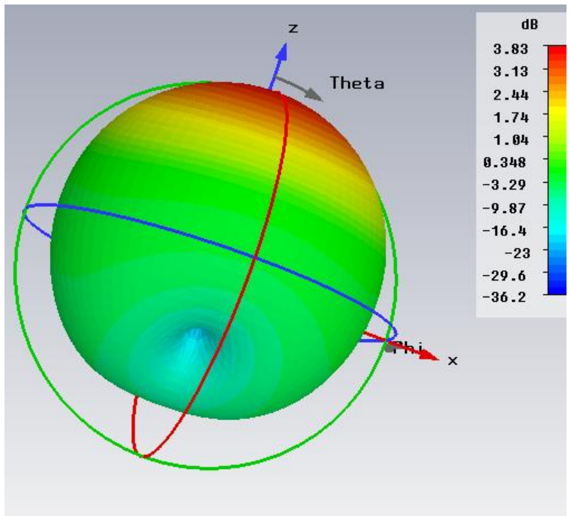


Figure4.12: Gain & Radiation fields

4.3.2 Wet etching:

In wet etching the walls of the cavity do not seem to be ideal or vertical, they are with slope nearly 54.4^{o}. This is considered in the design. The simulation of this structure is done using HFSS program.

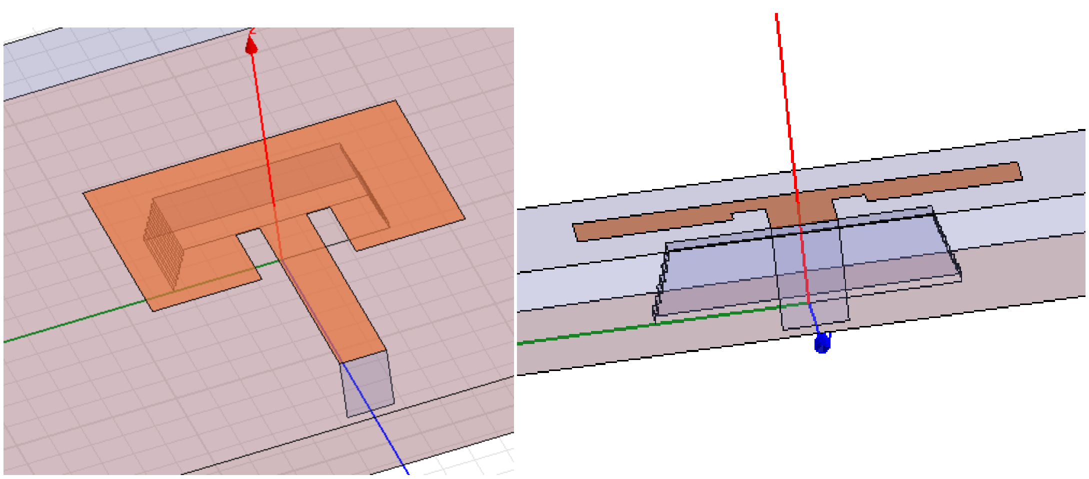


Figure 4.13: Wet etching with slope 54.4^{o} by HFSS program.

4.3.2.1 S- Parameters

In this type there is no improvement in the bandwidth. The achieved bandwidth here is 2.2 GHz.

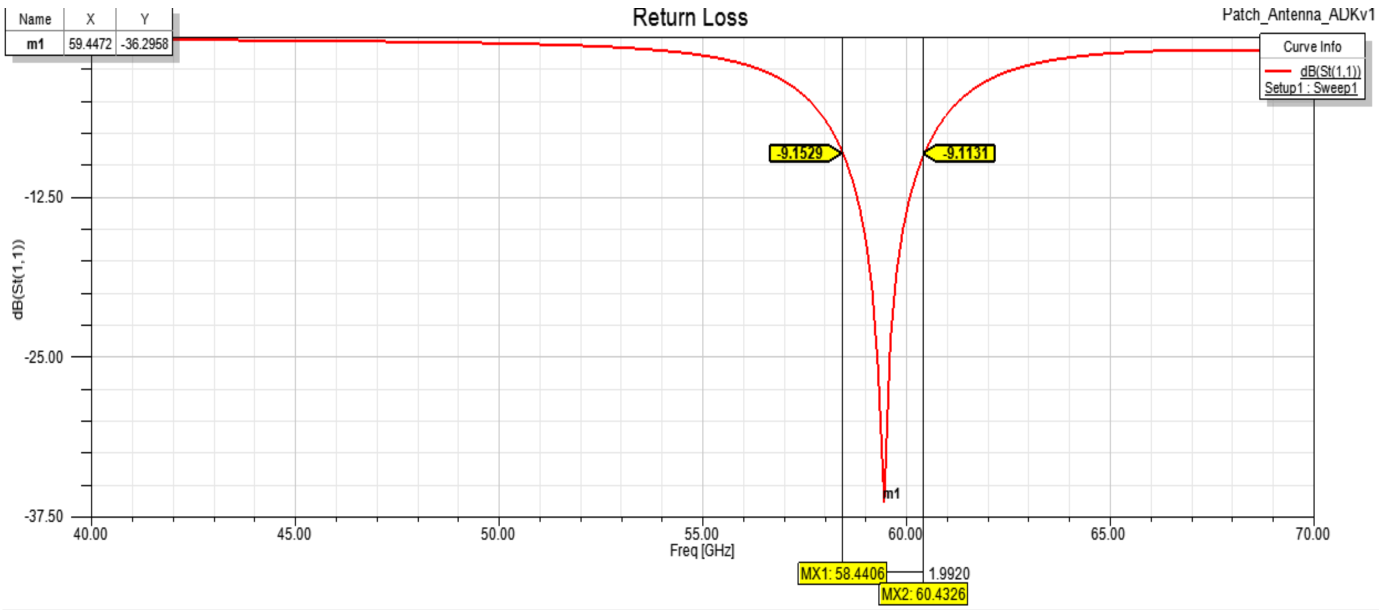


Figure 4.14: S_{11} of wet etching micromachining

4.3.2.2 Input Impedance and current distribution

The real part of the input impedance shown in figure 4.15 is around 50 ohm at frequency 60 GHz and the Imaginary part as shown in figure 4.16.

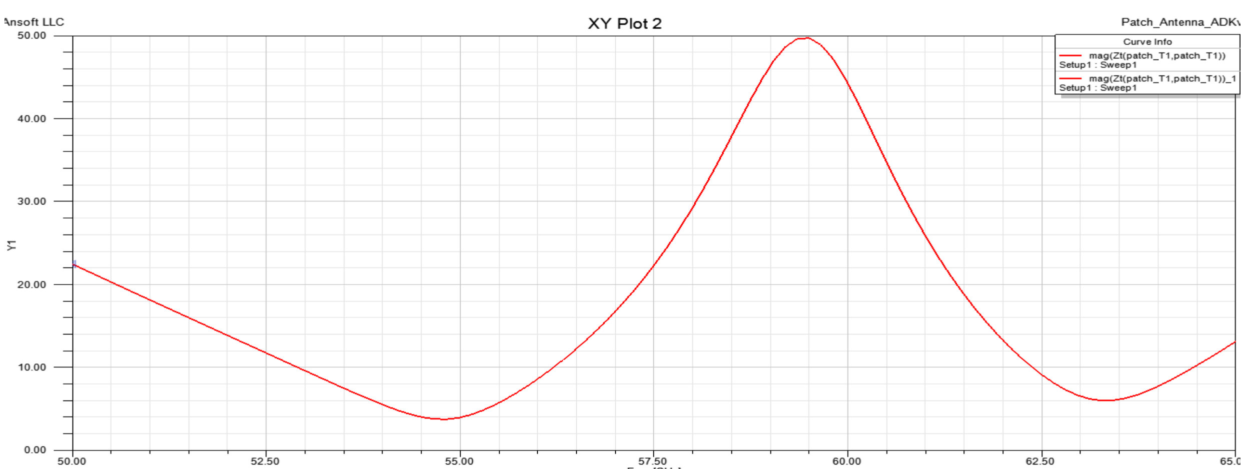


Figure 4.15: Real Part of input impedance

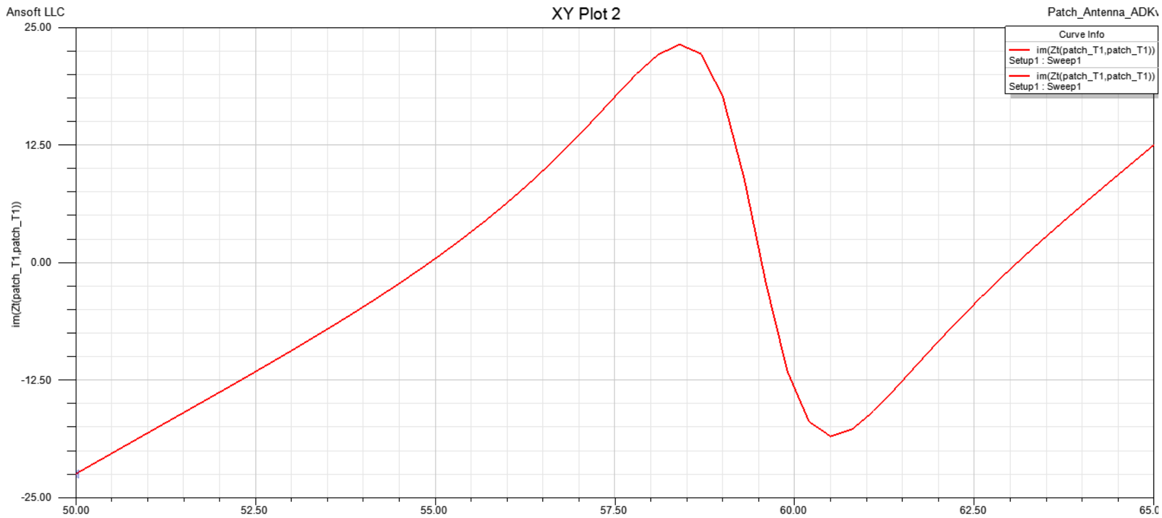


Figure 4.16: Imaginary Part of input impedance

4.3.2.3 The Gain and Radiation fields:

The improvement in this type of micromachining is in the gain. It is about 6.05 dB as shown in Figure 4.17.

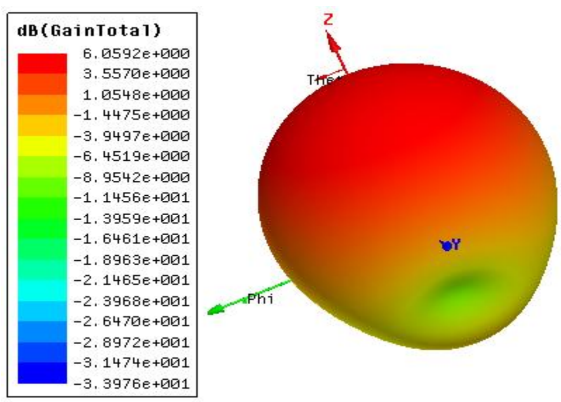


Figure 4.17: Gain and Radiation fields

4.4 Photolithography electromagnetic band gap (EBG):

By looking at section 3.8 in chapter 3, the structure of the holes or the EBG arranged in the substrate with specific dimensions, the two dimensions wanted in the design are the lattice constant which is the spacing between the holes and the radius of every hole. To calculate the two dimensions the wavelength and the velocity are wanted.

$$\lambda = \frac{u}{f}, u = \frac{c}{\sqrt{\varepsilon_r}} \quad (4.1)$$

From equation 4.1 we find the wavelength for our design and then calculate the radius and the lactic constant of the design.

The velocity $u = 3 * \frac{10^8}{\sqrt{10.003}}$, then the wavelength is $\lambda = \frac{94.85*10^6}{60*10^9} = 1.58\text{mm}$

Then form section 3.8, $a/\lambda = 0.5$, $r/a = 0.45$, so the (lattice constant) a = 0.00158*0.5 = 0.37mm, the (radius) r = 0.37*0.45 = 0.144mm.

4.4.1 The CST design:

From the calculations above, the radius of the cylindrical holes is 0.144mm and the distance between the holes is 0.32. The holes are arranged as an equilateral triangle, see Figure 4.18. The holes shown in the figure are after optimizing the structure using CST.

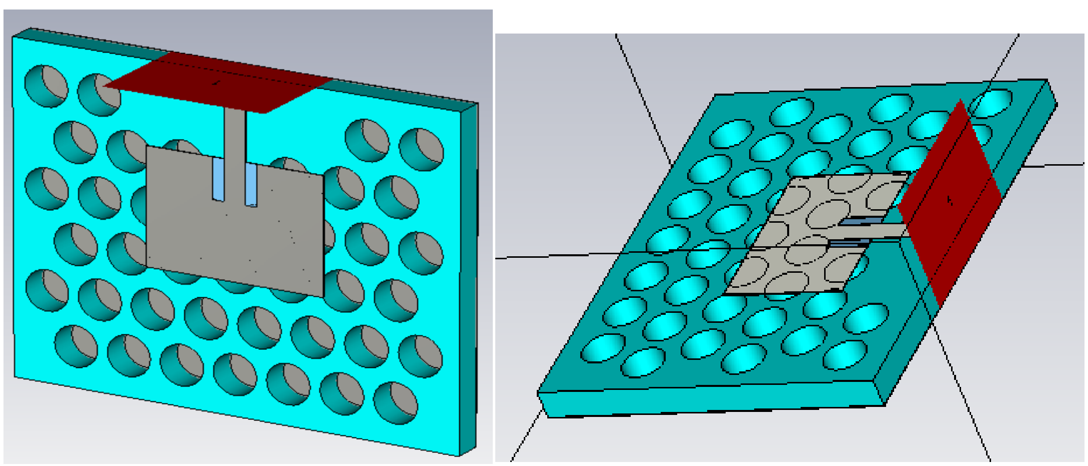


Figure 4.18: Electromagnetic band gap structure

4.4.1.1 S-parameter:

Figure 4.19 shows an improvement in the matching at the centre frequency which around -50dB, but there is no improvement in the bandwidth.

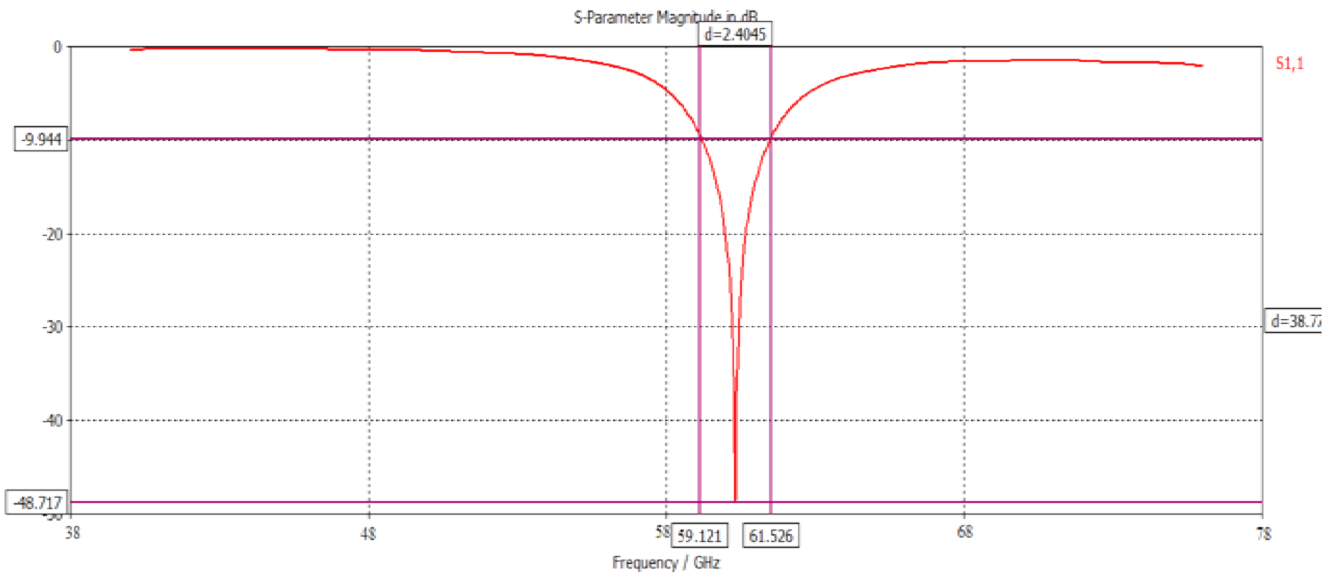


Figure 4.19: S_{11} of the Electromagnetic band gap holes.

4.4.1.2 Input Impedance and Current distribution

The real part of the input impedance shown in figure 4.20 is around 60 ohm at frequency 60 GHz and the Imaginary part as shown in figure 4.21.

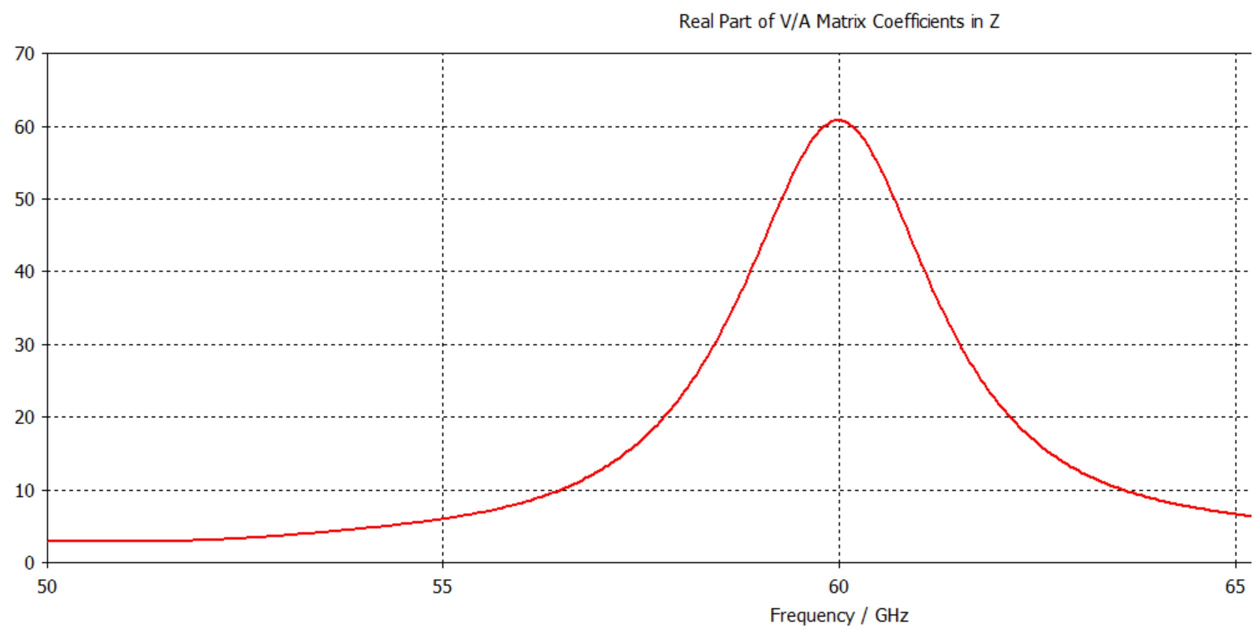


Figure 4.20: Real Part of input impedance

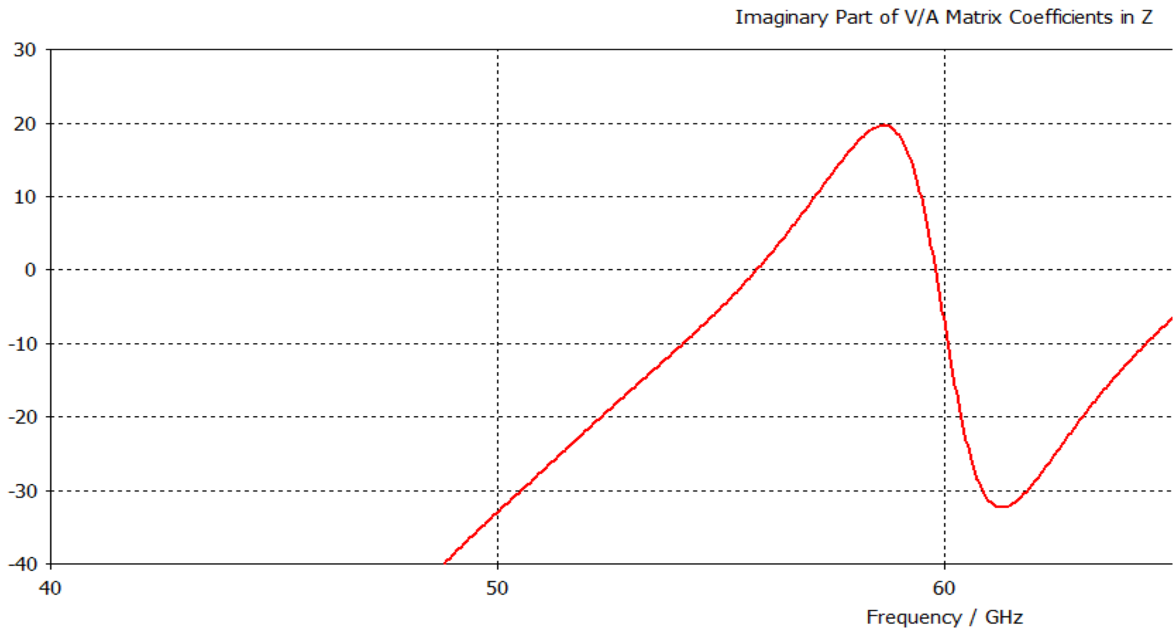


Figure 4.21: Imaginary part of input impedance

The current distribution of the inset fed patch antenna with photolithography EBG holes is shown in figure 4.22

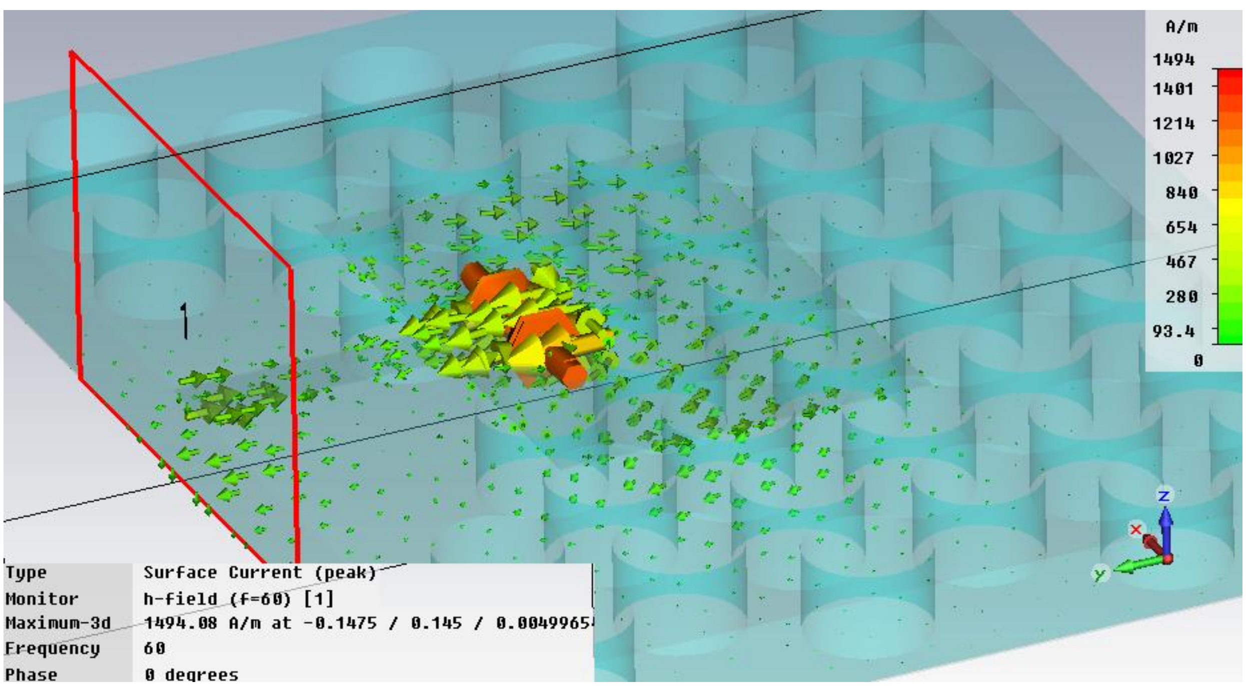


Figure 4.22: Current distribution

4.4.1.3 Gain and Radiation fields:

The EBG holes make improvements in the gain of the antenna. The gain is 4.72 dB as shown in Figure 4.23.

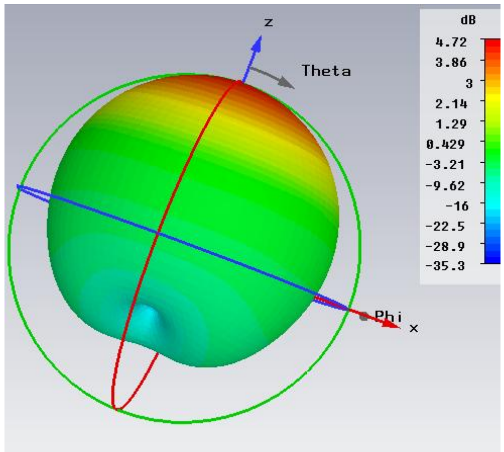


Figure 4.23: Gain and Radiation fields of EBG

4.5 Wet etching and EBG

When the wet etching is done in the substrate, the effective dielectric constant is changed as in section 3.3 and this result is then applied in the EBG calculations to make the final design.

Equation 4.2 is used to calculate the effective dielectric constant which is

$$\varepsilon_{reff} = \frac{(\varepsilon_{air} + \varepsilon_{material}).t}{(d(\varepsilon_{material} - \varepsilon_{air}) + t.\varepsilon_{air})} \tag{4.2}$$

With $\varepsilon_{air} = 1, \varepsilon_{material-GaAs} = 12.9, t = 0.27mm, d = 0.2mm - optmized, So \rightarrow \varepsilon_{reff} = 1.41$

Then by Appling the equations in section 4.4, the wavelength is 4.21mm because of the modifications in the substrate, and consequently the radius is 0.105mm and the lattice constant is 0.25mm.

4.5.1 Design by CST program:

The design in this section is by making a combination between the two techniques, the EBG and the Wet etching as shown in figure 4.24.

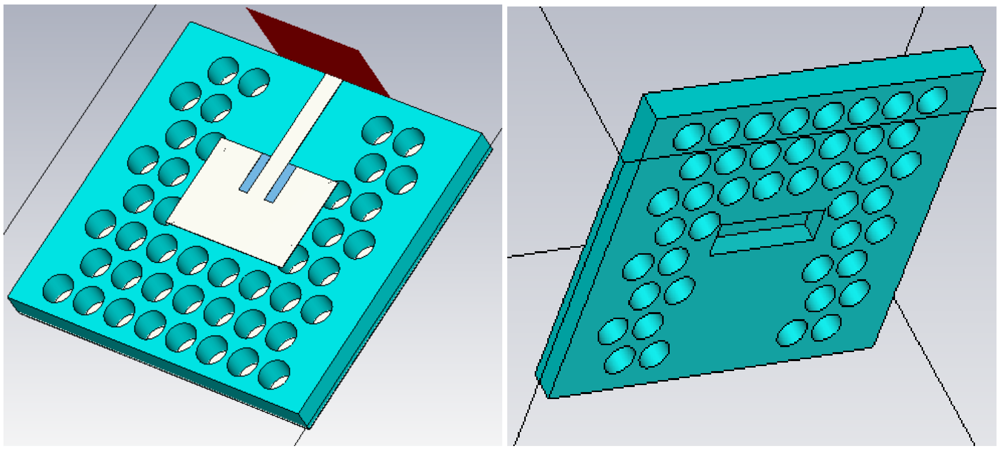


Figure 4.24: Structure with combination of EBG and Wet etching

4.5.1.1 S-Parameter

In combining the cylindrical holes and wet etching in one structure, the result depicted in figure 4.25 shows that the bandwidth is the best which is about 2.6GHz, giving a 4.3% fractional bandwidth.

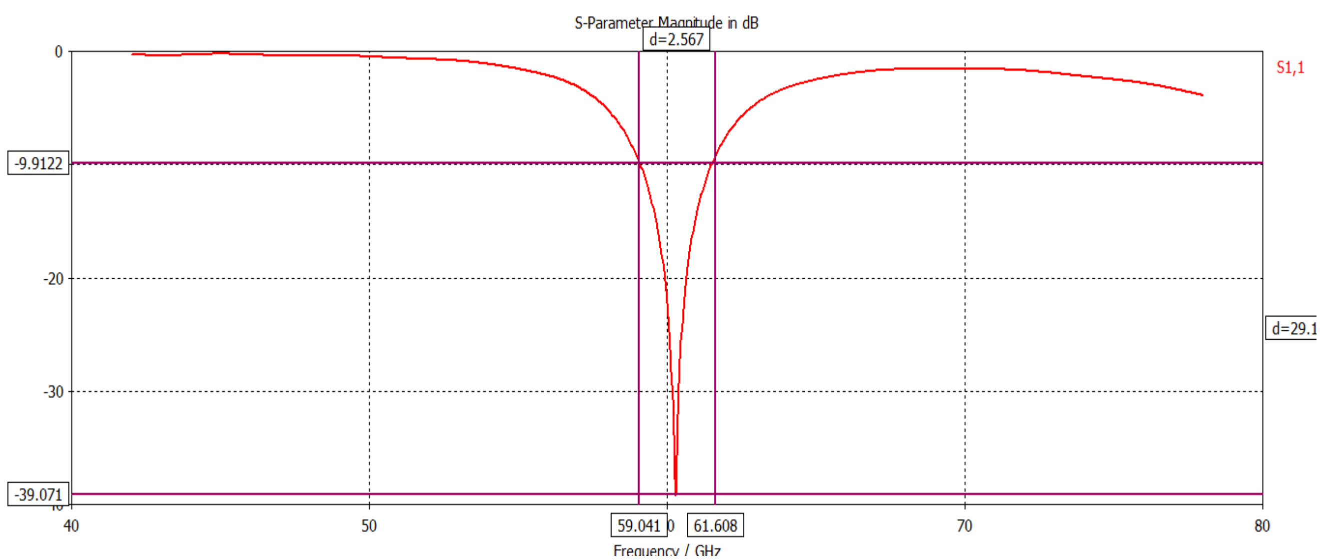


Figure 4.25: S_{11} of the combination design.

4.5.1.2 Input Impedance and Current distribution

The real part of the input impedance shown in figure 4.26 is around 65 ohm at frequency 61 GHz and the Imaginary part as shown in figure 4.27.

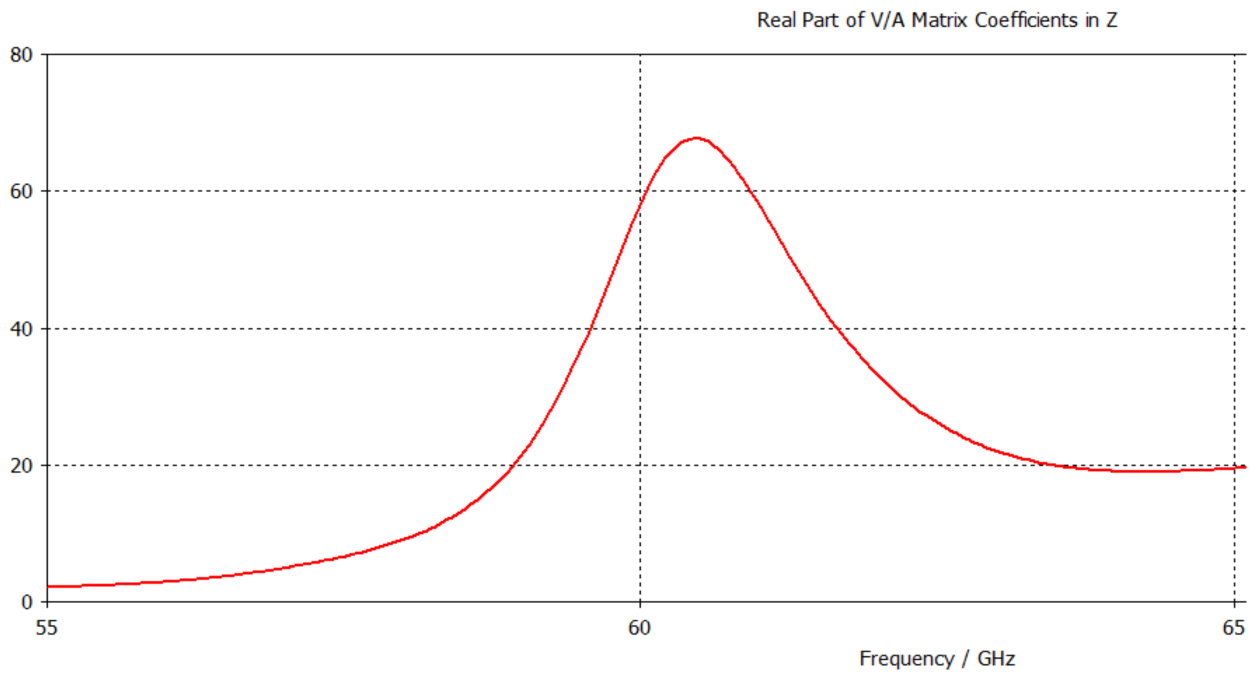


Figure 4.26: Real Part of input impedance

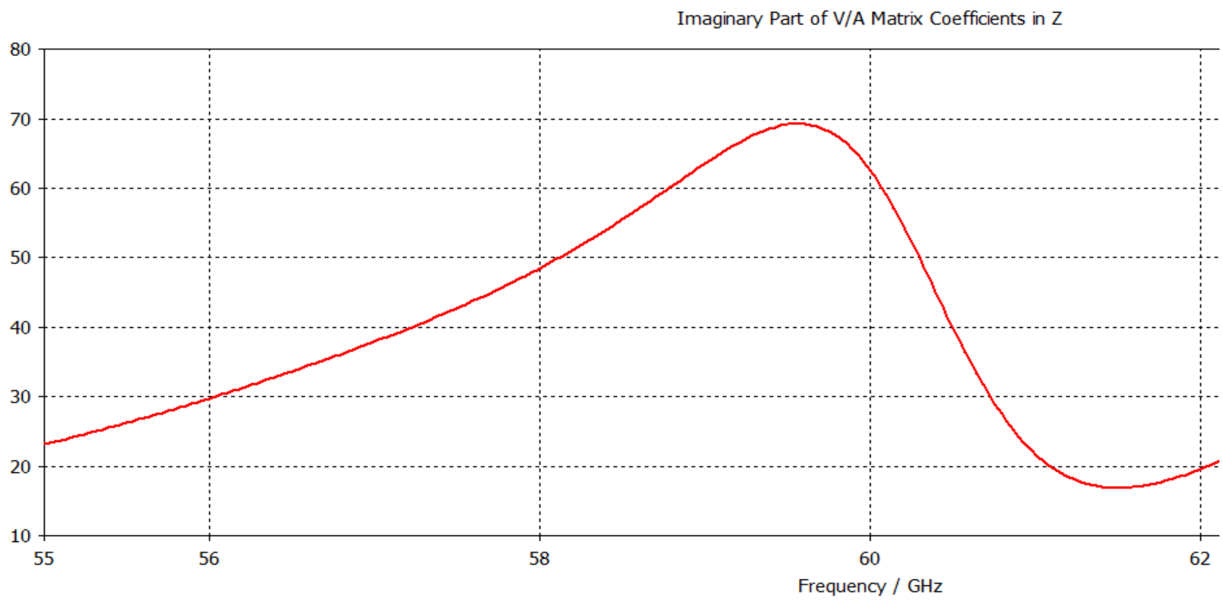


Figure 4.27: Imaginary part of input impedance

The current distribution of the inset fed patch antenna with combination of EBG technique and wet etching is shown in figure 4.28

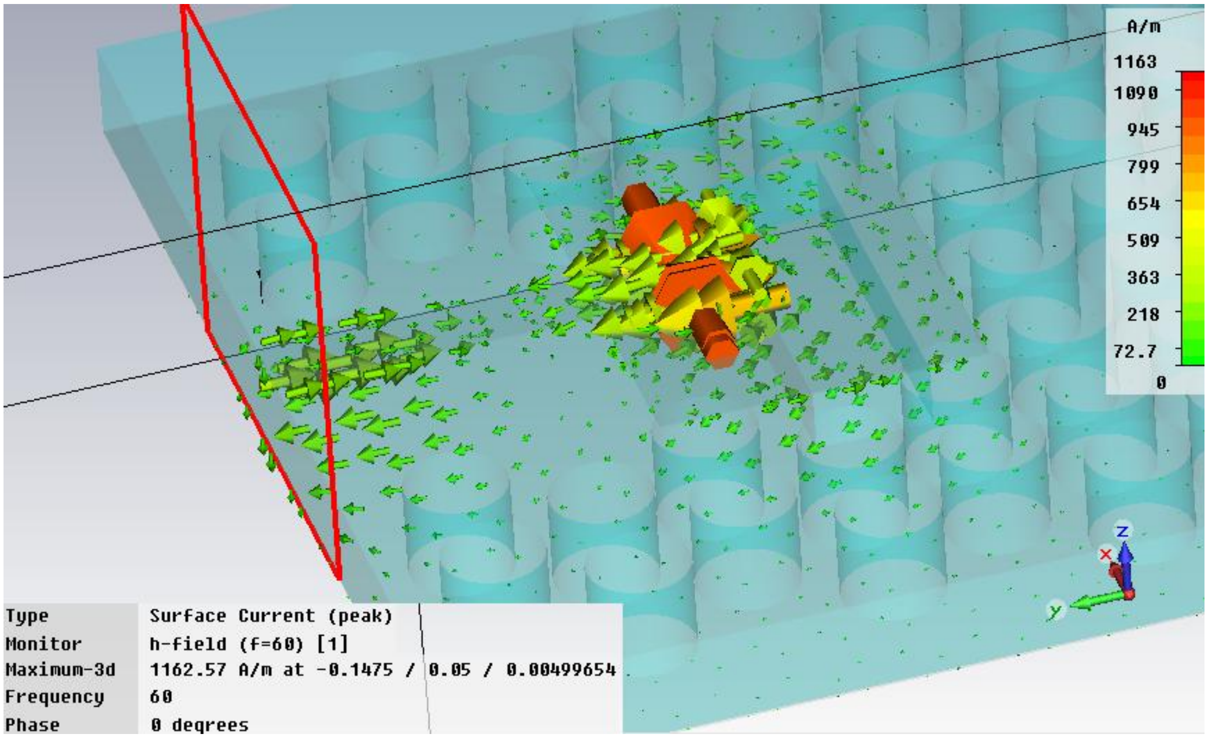


Figure 4.28: Current distribution

4.5.1.3 The Gain and Radiation fields:

The combination gives better gain as shown in figure 4.14.

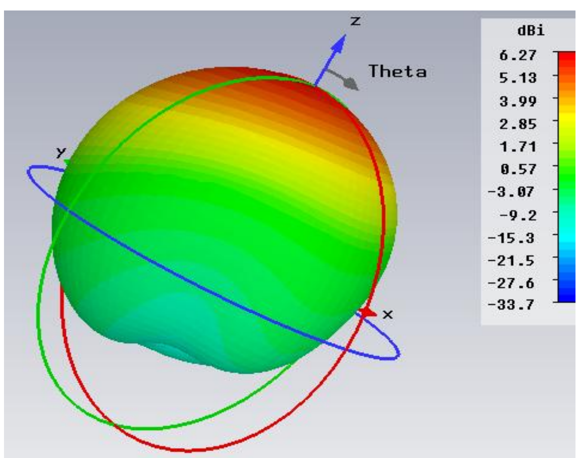


Figure 4.29: The gain of the combination design

4.6 Micromachined Patch Antenna design using photolithography:

For the previous designs of the micromachining patch antenna, the modifications in the substrate material are done to decrease the dielectric constant of it. The obtained results are good as shown in sections 4.2-4.5. The improvements were achieved because of the combination between the substrate material and the air. But to complete the idea of the micromachining which make better bandwidth and gain, the use of the air as a substrate is the next design.

4.6.1 Micromachined patch antenna with air substrate.

Using the same dimensions with some modifications optimized in the design as shown in figure 4.16 [1]. Five layers each with thickness equal to the patch thick form the structure of the antenna. The port is connected directly by the positive connector to the patch element and the negative is connected to the ground plane with the five layers as shown in the figure 4.16. The air is the separation medium between the two connectors the patch and ground plane.

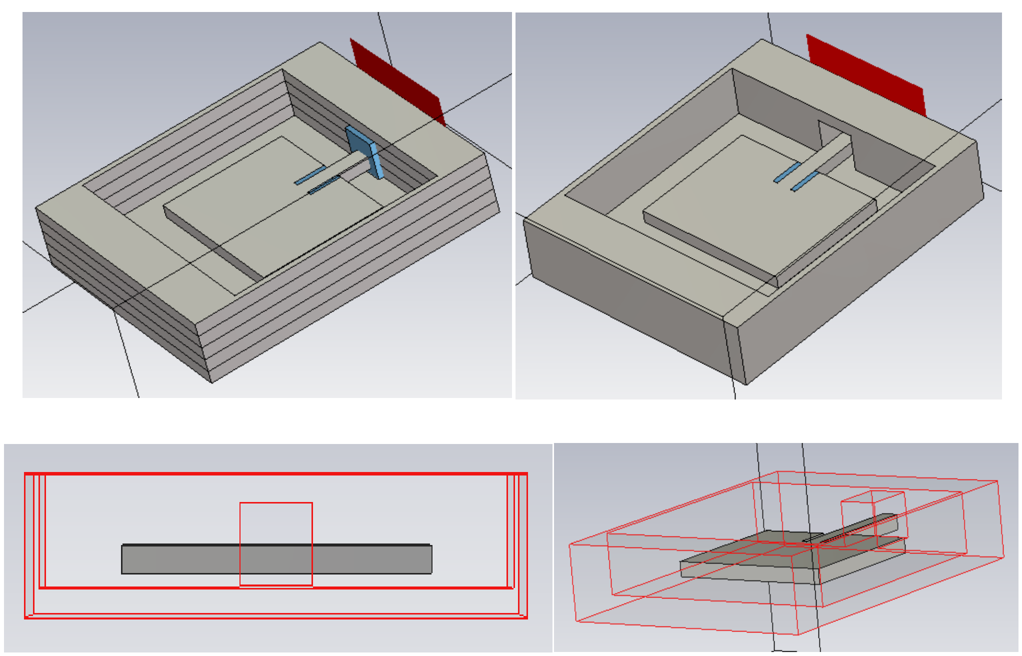


Figure 4.30: Micromachining patch antenna with air substrate.

4.6.1.1 S-Parameter

For figure 4.17, the bandwidth achieved by the micromachined air substrate patch antenna is 2.95GHz which is about 5% fractional bandwidth. This value of the bandwidth is very good value compared with the previous values.

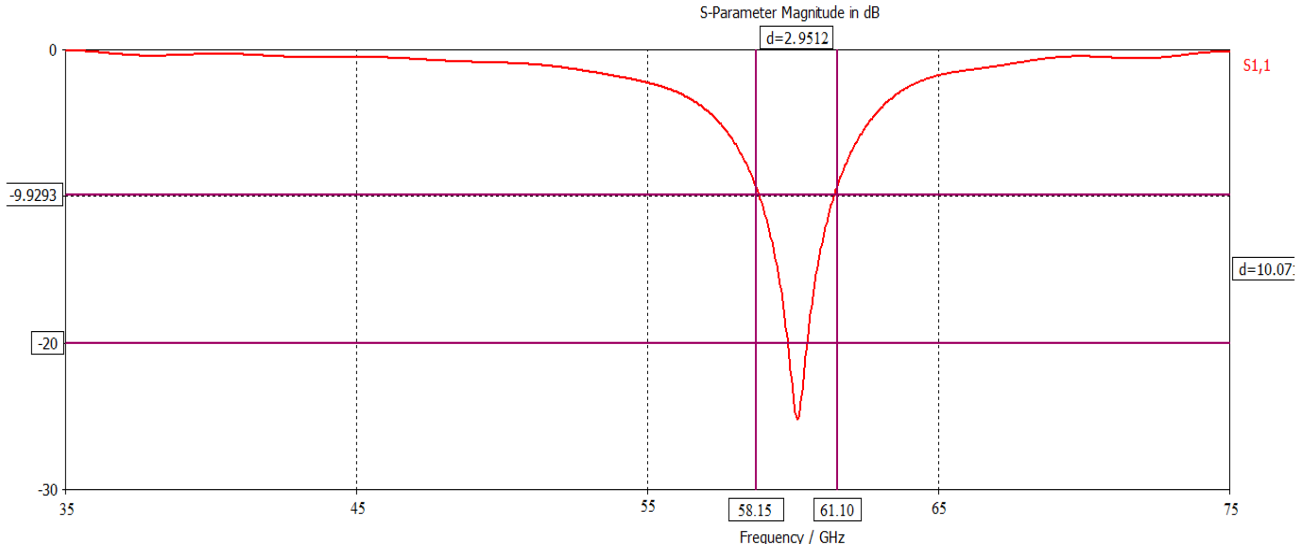


Figure 4.31: S_{11} of the air substrate micromachined patch antenna

4.6.1.2 Input Impedance and Current distribution

The real part of the input impedance shown in figure 4.32 is around 45 ohm at frequency 60 GHz and the Imaginary part as shown in figure 4.33.

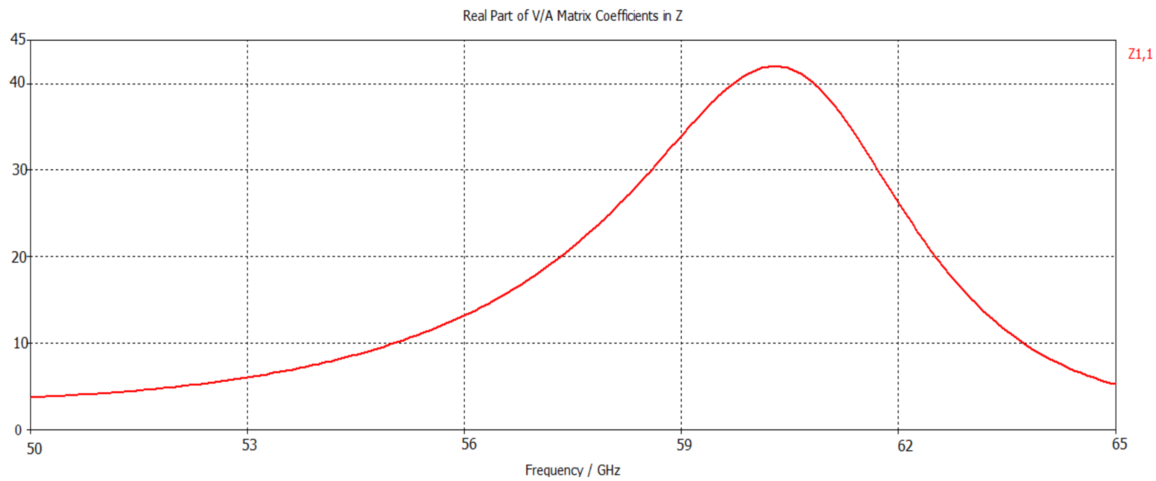


Figure 4.32: Real part of input impedance

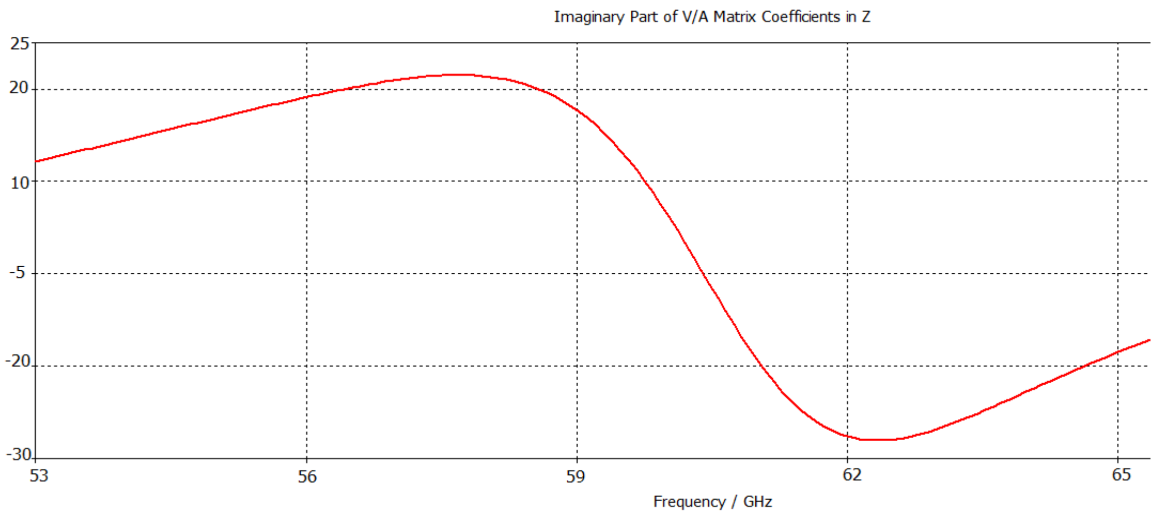


Figure 4.33: Imaginary part of input impedance

The current distribution of the Micromachined inset fed patch antenna with air substrate is shown in figure 4.34

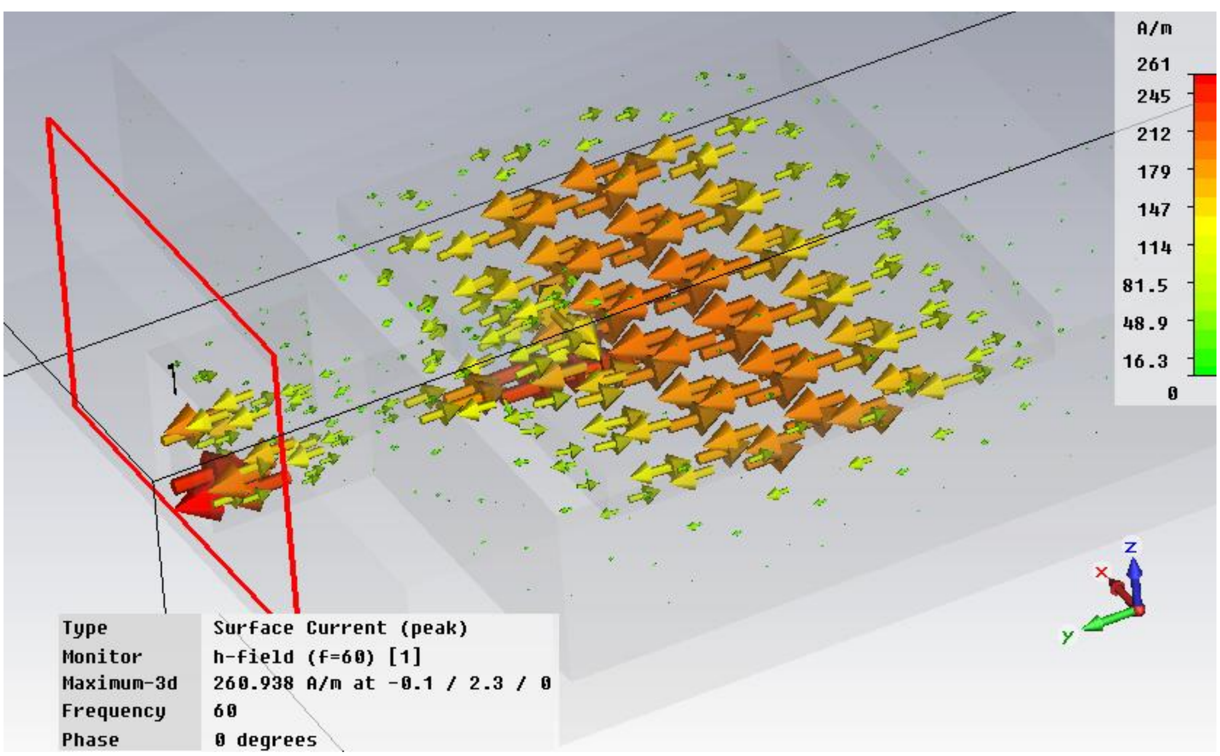


Figure 4.34: Current distribution

4.6.1.3 The Gain and Radiation fields:

As shown in figure 4.35, the gain achieved by this type of antennas is very good value which is about 9.2dB.

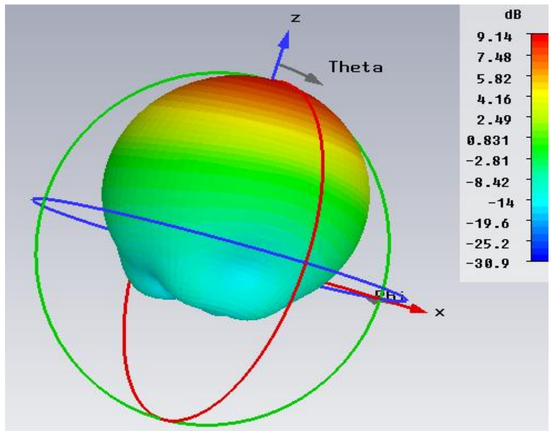


Figure 4.35: The gain of the air substrate micromachined patch antenna

4.6.2 Micromachined patch antenna with supporting lines.

For the antenna shown in figure 4.36, the patch element is suspended and this causes the patch element to be not stable and weak because the weight is centered on the feeding section. The solution of this problem is to make tow supporting lines between the patch and the layers as shown in figure 4.36 [1].

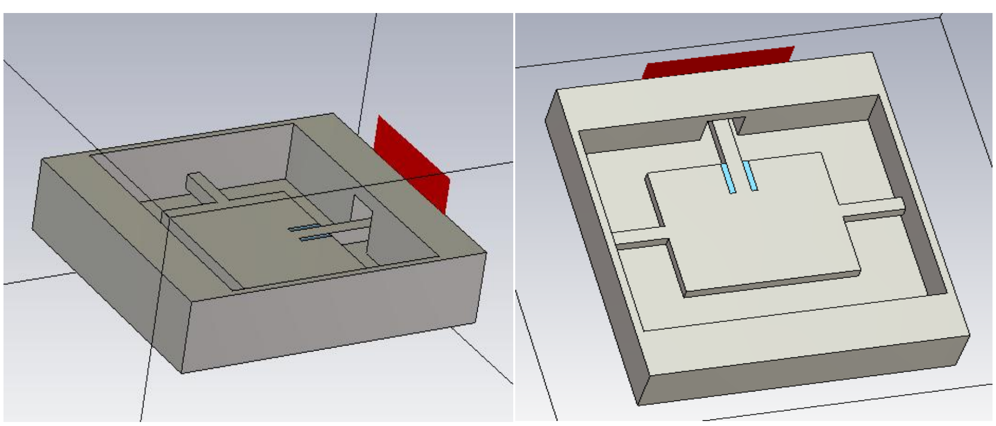


Figure 4.36: Micromachined Patch antenna with supporting lines

4.6.2.1 S-Parameter

From figure 4.19, the micromachined patch antenna with supporting lines make some modifications in the bandwidth by lowering the fractional bandwidth to 4.7% or 2.83GHz bandwidth, also the matching decreased by 3dB.

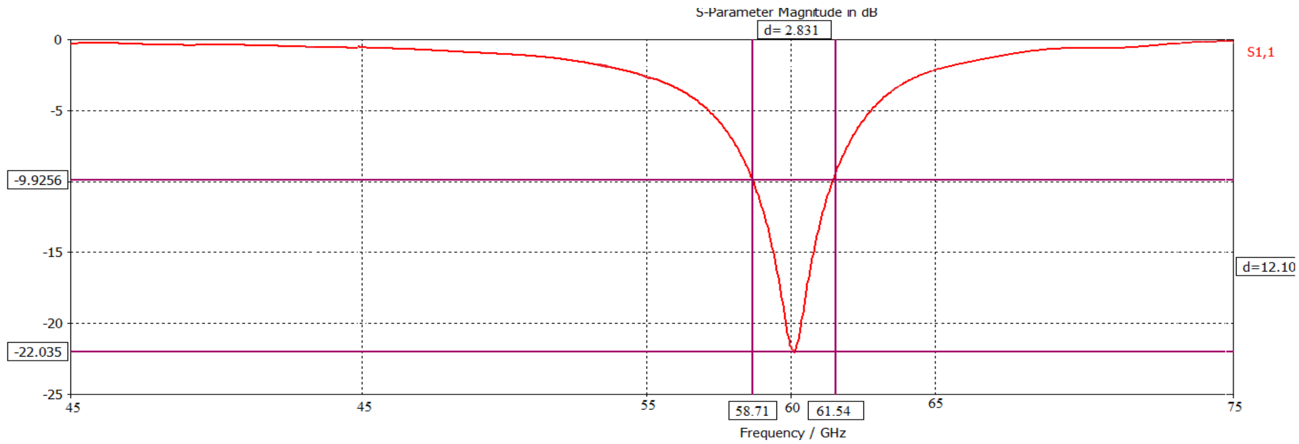


Figure 4.37: S_{11} of the micromachined patch antenna with supporting lines

4.6.2.2 Input Impedance and Current distribution

The real part of the input impedance shown in figure 4.38 is around 60 ohm at frequency 60 GHz and the Imaginary part as shown in figure 4.39.

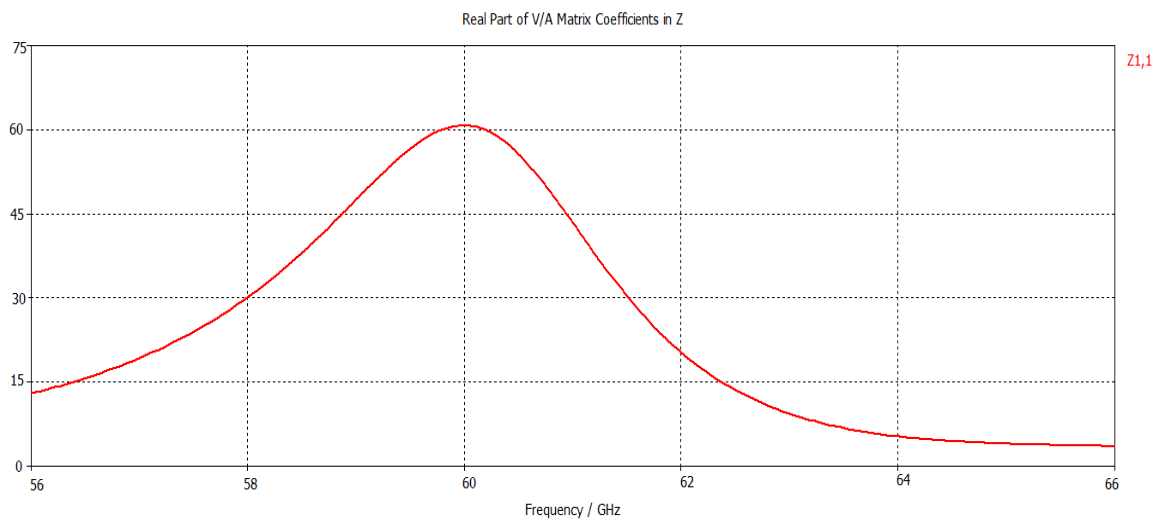


Figure 4.38: Imaginary part of input impedance

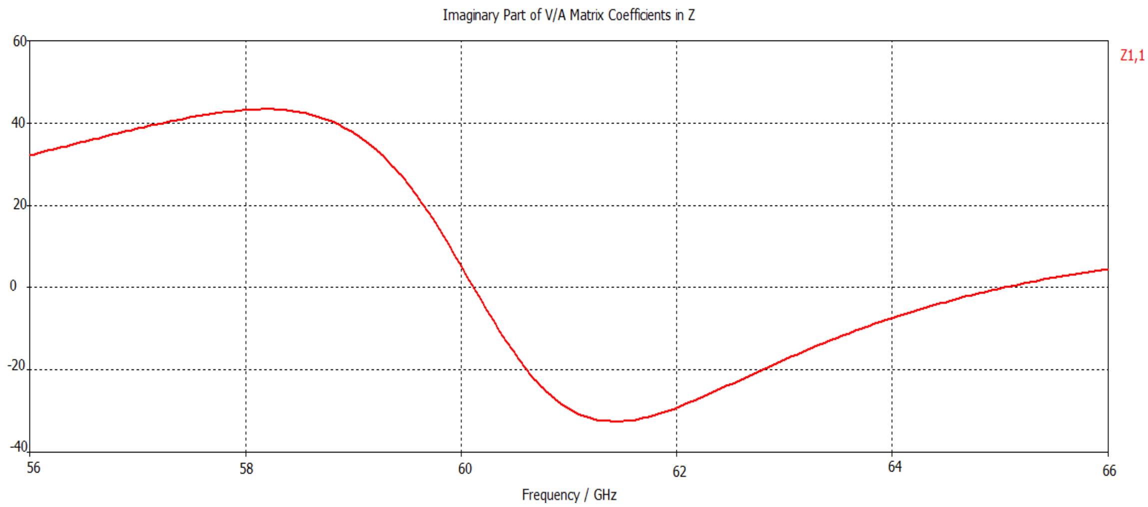


Figure 4.39: Imaginary part of input impedance

The current distribution of the Micromachined inset fed patch antenna with air substrate with supporting lines is shown in figure 4.40

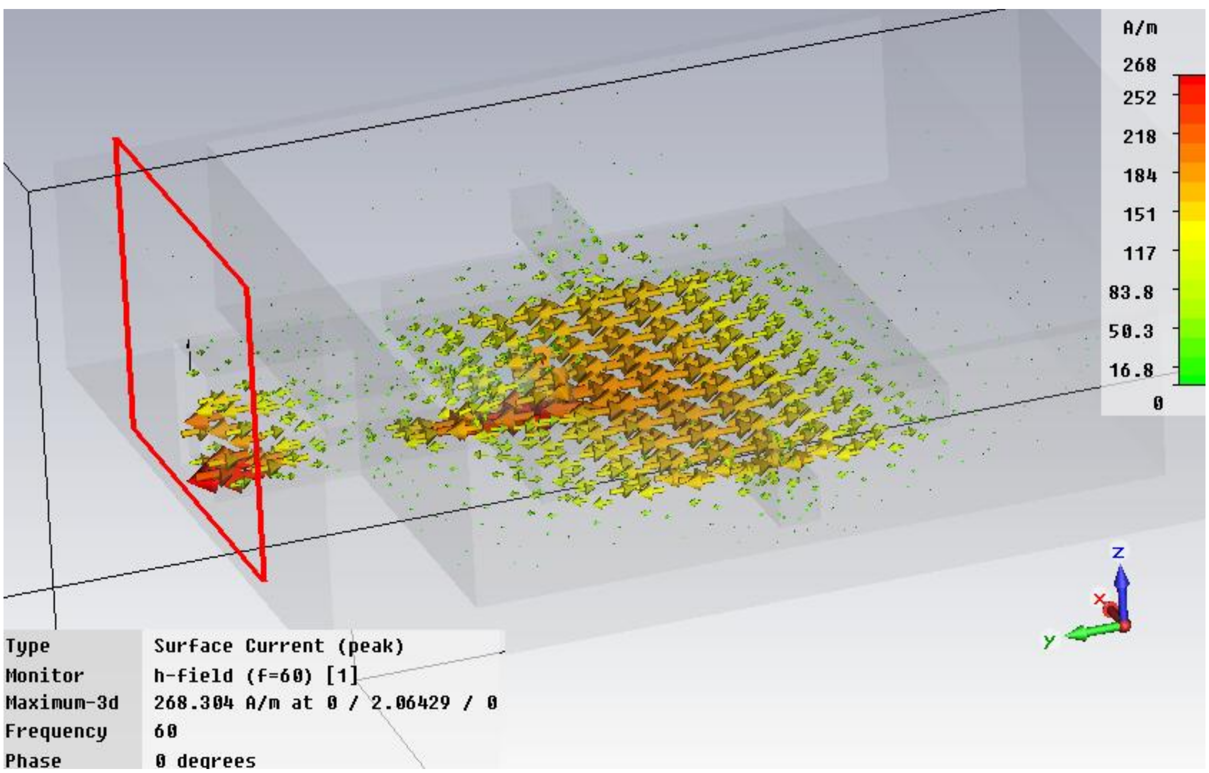


Figure 3.40: Current distribution

4.6.2.2 The Gain and Radiation fields:

The gain decreased by 0.1dB because of the supporting lines, see figure 4.41.

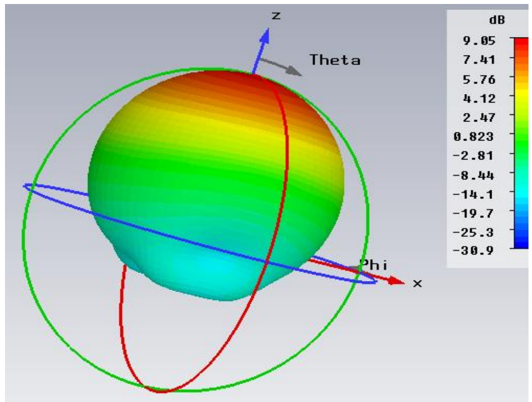
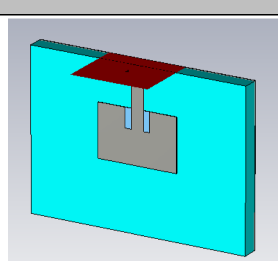
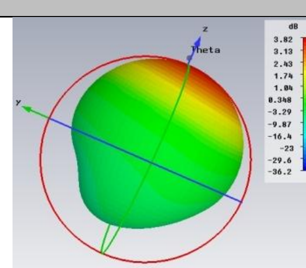


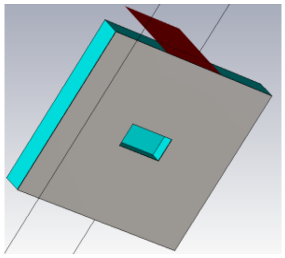
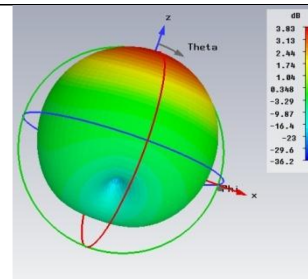
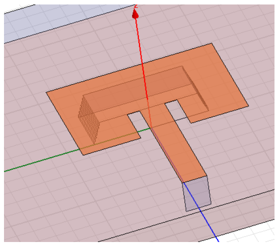
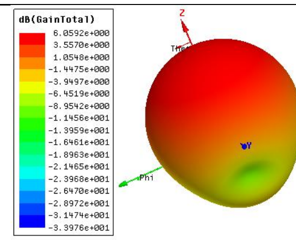
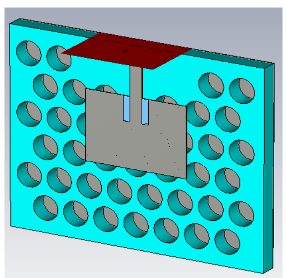
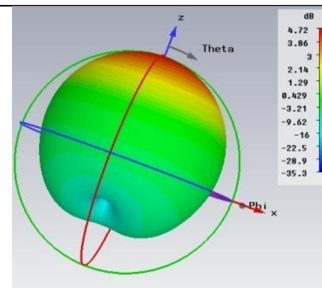
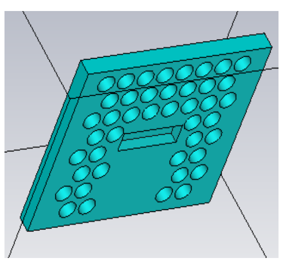
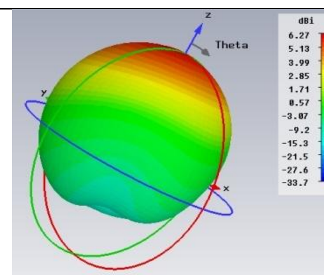
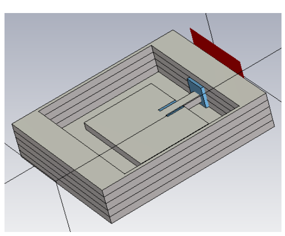
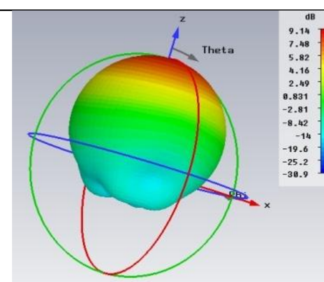
Figure 4.41: the Gain of the micromachined patch antenna with supporting lines

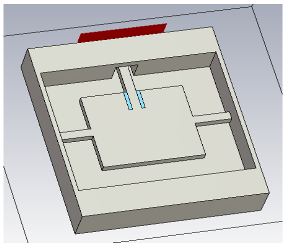
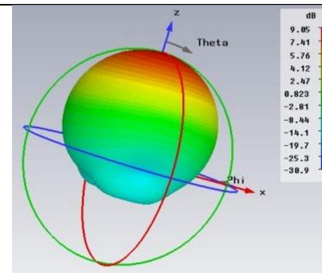
4.7 Comparison between the simulations in the above sections:

This section summarizes the antenna with substrate modifications by micromachining, and also the micromachined design of the antenna with air substrate. The following table describes the results as comparisons between different designs.

Table 4.2: Comparisons between the different types of antenna

Micromachining	Design Figure	Band Width, Gain, Matching	Gain	Comparison with Normal
Normal		B.W= 2.5 GHz F.B.W= 4.1% Matching = -40dB Gain= 3.81dB		-------

Dry etching		B.W= 2.72GHz F.B.W= 4.5% Matching = -34dB Gain= 3.83dB		BW.↑ Gain.↑ Matching.↓
Wet etching		B.W= 2GHz F.B.W= 3.3% Matching= -28dB Gain= 6.05dB		BW.↓ Gain.↑↑ Matching.↓
EBG		B.W= 2.43GHz F.B.W= 4% Matching = -50dB Gain= 4.72dB		BW.↓ Gain.↑ Matching.↑
EBG & Wet etching		B.W= 2.6GHz F.B.W= 4.5% Matching= -40dB Gain= 6.27dB		BW.↑ Gain.↑ Matching…
Air substrate		B.W= 2.96GHz F.B.W= 5% Matching= -25dB Gain= 9.14dB		BW.↑↑ Gain.↑↑ Matching.↓

Air substrate with supporting lines		B.W= 2.84GHz F.B.W= 4.7% Matching= -23dB Gain= 9.05dB		BW. ↑↑ Gain. ↑↑ Matching. ↓

↑ Increase, ↓ Decrease

For table 4.2, the best performance achieved by combining the two types of micromachining which are the wet etching and the EBG or by combining the bulk and photolithography micromachining, this combination of the two techniques make an improvement in the gain with 2.47dB and 100MHz bandwidth larger than the normal inset fed patch antenna as shown in table 4.2. The use of the air substrate patch antenna makes gain improvement of 5.33dB and bandwidth improvement of 460MHz. The final design with supporting lines causes very small effects on the gain and the bandwidth as shown in table 4.2.

4.8 Summary

In this chapter the design part of micromachined patch antenna for millimeter wave applications is introduced. The first of all is the design of the normal inset fed patch antenna with 60GHz centre frequency, and the results are 3.81dB gain and 2.5GHz. The first modification done is the use of bulk micromachining with its two types dry and wet etching. The dry etching which makes vertical walls makes an improvement in the bandwidth with 220MHz larger than the normal inset fed patch antenna. The other type of bulk micromachining which is wet etching makes an improvement in the gain with 2.24dB larger than the normal antenna. The EBG photolithography micromachining is designed also and it makes improvement in the matching at the center frequency. Structure combining the wet etching and the EBG micromachining is designed, the improvements achieved are increase of 100MHz in bandwidth and increase of 2.47dB in gain. The final design done is by making the substrate to be the pure air The best improvements are achieved by this design with 5.33dB gain increase and 460MHz bandwidth increase too. For practical purposes, supporting lines have been added to the latest design to fix the patch element and this design causes very small modifications in the results.

References:

[1] N. A. Murad, "Micromachined Millimeter Wave Circuits," PhD thesis in the University of Birmingham, pp. 92-99, May 2011.

[2] CST 3D electromagnetic simulation software.

[3] HFSS 3D electromagnetic simulation Program.

[4] Ansoft HFSS antenna design tool kit.

Chapter 5

Conclusion and Future work

5.1 Conclusion:

The work presented in this thesis focused on the design of micromachined inset fed patch antenna for using it in millimeter wave applications. At millimeter waves, the size of any antenna design is relatively small, as the relation between the frequency and the antenna size is inversely proportional. For this reason the study of the micromachining techniques becomes very important. Micromachining is used to deal with the patch antenna by making modifications in the substrate materials when its size is very small, so in this thesis the different types of micromachining techniques are presented and introduced. The use of this technique in the design of inset fed patch antenna or by other words the use of the modifications in the substrate by using micromachining techniques aims to two goals; the first is to get better bandwidth than the conventional inset fed design, and the second is to get better gain in the same antenna.

Firstly, the patch antenna with inset fed matching is designed by using equations and HFSS toolkit to obtain initial design then the antenna was optimized by CST-microwave studio program. This conventional design gives bandwidth of about 2.4GHz with 3dB gain.

When the first type of micromachining which is the dry etching is applied to the conventional design, the bandwidth improved to 2.7GHz but the gain did not improve.

For the second type of the bulk micromachining which is wet etching, HFSS program is used for the design. The gain improved to 6dB and there were no improvements in the bandwidth.

The other type of micromachining used in the design is the EBG holes that are made by photolithography. For this type, there was improvement in the matching at the center frequency with -20dB less than the previous types of micromachining.

The combination of the two techniques the wet etching and the EBG photolithography is applied to the antenna. The improvements made from this combination were an increase of 100MHzin bandwidth, an increase of 2.47dBin gain and -10dBin matching. These improvements make the combination design effective.

The last design is done by making the substrate to be the pure air. The improvements achieved by this design are 5.33dBincrease in gain and also 460MHzincrease in bandwidth. However, this design makes the patch element not stable, so the practical design is made by using supporting lines to fix the patch element, this design caused very small modifications in the results or by other words the bandwidth achieved by the final design is 2.84GHz with 4.7% fractional bandwidth and the gain is 9.05dB and the matching is -23dB at the center frequency.

5.2 Future work:

Although the research for this thesis has been extensive, there are still several unexplored areas of research that can be suggested for future work such as:

- Study more shapes of the microstrip patch antenna like elliptical and triangular shapes, the use of these different shapes will give different improvements and modifications in bandwidth, radiation pattern and gain.
- In this thesis, the micromachining patch antenna has been studied for the millimeter wave applications, the future may be in care with other applications in other wave bands. So the researchers may concentrate in high frequency applications larger than the millimeter wave like the terahertz application -300GHz-. Also there are many applications in other frequencies in the millimeter waves.
- In this thesis, the material used in the substrate is the Gallium Arsenide-GaAs, the researchers can make designs by using other materials with different dielectric constant like silicon.
- Study more micromachining processes and use it in the design.
- Fabricate and test all the designed antennas to validate the results.