DESIGN AND ANALYSIS OF MASSIVE MIMO ANTENNA FOR 2.4GHZ ISM BAND AND WLAN APPLICATIONS

PROJECT REPORT

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ABSTRACT

MIMO system is well known technique to enhance the performance of wireless communication system. The antenna design is the one of the major concerns in MIMO antenna technology. In order to create a MIMO antenna system on a wireless device, two or more antenna elements could be placed in a very small place. Thus the mutual coupling including radiation pattern coupling between closely spaced antenna elements cause a decrease in MIMO antenna performance. It means that we must consider not only the antenna size but also suitable antenna array method to design the MIMO system. Effective MIMO antenna system requires multiple antennas receiving uncorrelated signal.

In this project compact antenna have been designed and implemented in a MIMO system for WLAN applications. By using antenna array we can place a hundred number of antenna for improving antenna performance. Massive MIMO play a major in wireless communication. This brings huge improvements in throughput, energy efficiency. The designed antennas are double-sided printed microstrip patch antenna. The antenna is designed over the operating frequency is 2.4GHZ using the substrate material as FR4 which has the dielectric constant of 4.3(ε_r). The designed antenna can be used for ISM (industrial, scientific and medical) band and WLAN applications. The designed antennas have low profile, low cost, easy fabrication and good isolation. The antenna is designed by using Ansoft HFSSV13 simulation software and designed antenna provides return loss less then -10dB.Simulation result of various MIMO configurations are presented and discussed.

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LIST OF ABBREVATIONS

MIMO	Multiple Input Multiple Output
ISM BAND	Industrial, Scientific & Medical Band
WLAN	Wireless LAN
RL	Return Loss
HPBW	Half Power Beam Width
LTE	Long Term Evolution
HFSS	High Frequency Structural Simulator
MOM	Method Of Moment
FEM	Finite Element Method
SISO	Single Input Single Output
SIMO	Single Input Multi Output

CHAPTER 1

MIMO ANTENNA

1.1 INTRODUCTION

Multiple-Input and Multiple-Output or **MIMO** is the use of multiple antennas at both the transmitter and receiver to improve communication performance. It is one of several forms of smart antenna technology. MIMO technology has attracted attention in wireless communications, because it offers significant increases in data throughput and link range without additional bandwidth or increased transmit power. It achieves this goal by spreading the same total transmit power over the antennas to achieve an array gain that improves the spectral efficiency (more bits per second per hertz of bandwidth) or to achieve a diversity gain that improves the link reliability (reduced fading. MIMO technology has attracted attention in wireless communications, because it offers significant increases in data throughput and link range without additional bandwidth or increased transmit power. MIMO is an important part of modern wireless communication standards such as IEEE 802.11n (Wi-Fi), 4G, WiMAX. The basic aim of MIMO antenna design is to minimize the correlation between the multiple signals as in to achieve compactness in MIMO systems. In this paper, a simple and compact antenna is designed that shows acceptable return loss for 2.4GHZ ISM band frequency.

1.1.1 THE NEED FOR MULTIPLE ANTENNA

This chapter describes the development and testing of antenna elements for use in a Multiple input-multiple-output (MIMO) application. MIMO wireless systems have antenna arrays at both the transmitter and receiver terminals. This project focuses on the terminal Massive MIMO antenna array design. The requirements of the antenna element at the terminal are as yet not well-defined but will include (for commercial reasons) low antenna profile, low volume, light weight and low cost while maintaining good electrical properties such as return loss and isolation (<-10dB). The radio environment on electrically small platforms is changing rapidly. Until recently one radio was used in isolation and was usually connected to only one antenna. The situation today is very different: there is usually more than one radio used at once for example a handset may have 4 cellular bands, GPS and Bluetooth TM. Sometimes WLAN radios are also present. This means that more RF filtering of signals is necessary. It is also becoming common for each radio to use more than one antenna in order to create diversity or for

MIMO applications. Antenna diversity is already used with WLAN radio in order to counter multipath, reduce outages and improve the quality and reliability of the communications link.

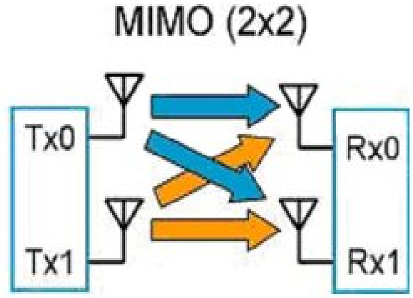

Fig.1.1 MIMO Antenna

Diversity in current WLAN systems is usually restricted to two antennas for each radio as this is enough to ensure that if one antenna is in an RF null. The other is generally not, there by providing better performance in multipath environments. Only one radio is present and so the receiver listens to one antenna at a time and a RF switch is used to select the antenna giving the best signal. While simple diversity switching seeks to minimize the effects of multipath, MIMO makes use of multipath in order to improve the signal quality and reliability. A MIMO system generally uses more than two antennas, typically four, and is a more powerful technique than diversity switching for improving a communications link. The technique is powerful and can be improved further by employing a larger number of antennas than those actually used and then using an optimal subset selected on the basis of the quality of the channel.

1.1.2 THE NEED FOR ANTENNA INTEGRATION

In general, the space available for multiple antennas is no greater than that available before for a single antenna. Indeed, there is great pressure for space inside handsets and the space available for the antenna is shrinking all the time. Similarly with WLAN antennas - such as those fitted inside the lids of laptop computers - the size requirements placed on the antenna (especially the width) are continually being reduced. Furthermore, there is increasing pressure from both OEMs and tier1 equipment manufacturers for further integration of components, including the antenna.

1.1.3 ANTENNA DESIGN FACTORS AFFECTING ANTENNA PERFORMANCE

Good diversity performance between two antennas depends on several factors,

1. The antennas must have some degree of directivity that can be controlled.
2. The antennas must have some level of cross-polar discrimination.

3. The antenna should have differently-directed spatial radiation patterns.
4. Coupling between the antennas must be minimized.
5. The multiple antenna system must be as efficient as a single antenna, or the diversity.
6. The antennas must be electrically small to minimize interaction between them.
7. The antennas must have properly matched terminations.

1.2 MIMO TYPES

MULTI ANTENNA TYPES

The different forms of antenna technology refer to single or multiple inputs and outputs. These are related to the radio link. In this way the input is the transmitter as it transmits into the link or signal path, and the output is the receiver. It is at the output of the wireless link.Therefore the different forms of single / multiple antenna links are defined as below,

1. SISO - Single Input Single Output
2. SIMO - Single Input Multiple Output
3. MISO - Multiple Input Single Output
4. MIMO -Multiple Input Multiple Output

1.3 MIMO FUNCTIONS

MIMO functions are sub-divided into three main categories. They are given as follows

- Precoding,
- Spatial Multiplexing or SM and
- Diversity Coding.

1.3.1 PRECODING

It is multi-stream beam forming, in the narrowest definition. In more general terms, it is considered to be all spatial processing that occurs at the transmitter. In (single-layer) beam forming, the same signal is emitted from each of the transmit antennas with appropriate phase (and sometimes gain) weighting such that the signal power is maximized at the receiver input. The benefits of beam forming are to increase the received signal gain, by making signals emitted from different antennas add up constructively, and to reduce the multipath fading effect. In the absence of scattering, beam forming results in a well defined directional pattern, but in typical cellular conventional beams are not a good analogy. When the receiver has multiple antennas, the transmit beam forming cannot simultaneously maximize the signal level at all of the receive antennas, and precoding with multiple streams is used. Note that precoding requires knowledge of channel state information (CSI) at the transmitter.

1.3.2 SPATIAL MULTIPLEXING

It requires MIMO antenna configuration. In spatial multiplexing, a high rate signal is split into multiple lower rate streams and each stream is transmitted from a different transmit antenna in the same frequency channel. If these signals arrive at the receiver antenna array with sufficiently different spatial signatures, the receiver can separate these streams into (almost) parallel channels. Spatial multiplexing is a very powerful technique for increasing channel capacity at higher signal-to-noise ratios (SNR). The maximum number of spatial streams is limited by the lesser of the number of antennas at the transmitter or receiver. Spatial multiplexing can be used with or without transmit channel knowledge.

1.3.3 DIVERSITY CODING

It is used when there is no channel knowledge at the transmitter. In diversity methods a single stream (unlike multiple streams in spatial multiplexing) is transmitted, but the signal is coded using techniques called space-time coding. The signal is emitted from each of the antennas using certain principles of full or near orthogonal coding. Diversity exploits transmit the independent fading in the multiple antenna links to enhance signal diversity. Because there is no channel knowledge, there is no beam forming or array gain from diversity coding.

1.4 SPECIFICATIONS OF GOOD ANTENNAS FOR MIMO

A desirable antenna would have,

- Wide bandwidth
- Occupy minimal space
- Very low cost
- High efficiency (not too much Loss)
- High gain
- Low correlation between fading signal in realistic channel condition

1.5 APPLICATIONS FOR MIMO

Spatial multiplexing techniques make the receivers very complex, and therefore they are typically combined with orthogonal frequency-division multiplexing (OFDM) or with Orthogonal Frequency Division Multiple Access (OFDMA) modulation, where the problems created by a multi-path channel are handled efficiently. The IEEE 802.16e standard incorporates MIMO-OFDMA. The IEEE 802.11n standard, released in October 2009, recommends MIMO-OFDM.

MIMO is also planned to be used in Mobile radio telephone standards such as recent 3GPP and 3GPP2. In 3GPP, High-Speed Packet Access plus (HSPA+) and Long Term Evolution (LTE) standards take MIMO into account.

CHAPTER 2
LITERATURE SURVEY

2.1. INTRODUCTION

This chapter presents the literature surveyed in the area of MIMO Antenna. The purpose of this is to choose an appropriate design and geometry for MIMO antenna with WLAN application and better performance in terms of return loss, Voltage Standing Wave Ratio (VSWR).

[1] DESIGN AND ANALYSIS OF 2X2 MIMO SYSTEM FOR 2.4GHZ ISM BAND APPLICATIONS

Harshal Nigam & Mithilesh Kumar, compact antennas have been designed and implemented in a 2X2 Multiple-Input Multiple-Output (MIMO) system. The antennas are compact double-sided printed microstrip patch antennas and fed by a microstrip line designed for a frequency of 2.4 GHz used for industrial, scientific and medical (ISM) band applications. The antennas are designed on CST Microwave studio simulation software with return loss less than -10dB. Furthermore, the MIMO system is designed using polarization diversity of the individual antennas which yields better result in terms of return loss (S11 and S22) and mutual coupling (S12 and S21). The system is designed for 802.11n Wi-Fi family of standards that has an operation frequency of 2.4 GHz but with MIMO system that offers an increased data rate.

[2] DESIGN AND ANALYSIS OF I-SHAPED MIMO ANTENNA FOR WIRELESS APPLICATIONS

In this paper I-shaped MIMO antenna is designed in Ansoft HFSSv13 and fabricated. Now a day's an array of antenna plays a wide role since it is very much useful to reduce the interference when the multipath propagation signal exists. In practical it can be helpful to our hand-held device called mobile phones since there is a need of array of antenna in base stations. The proposed antenna is designed over an operating frequency range of 2.57 GHz using the substrate material as FR-4 which has the dielectric constant of 4.4. This new shape of antenna has the swastika shaped slot between the patches which improves the efficiency and helps to reduce the prioritized parameter of MIMO antenna which is nothing but the mutual coupling. This antenna can be applicable to the wireless communication areas such as Wi-Fi and WiMAX.

The parameters such as return loss, VSWR, mutual coupling, directivity and gain has been simulated and analyzed. The mutual coupling has been achieved of about -30.5673 dB.

[3] DESIGN AND REALIZATION OF 1.8-2.4 GHZ MIMO 2 X 2 ANTENNA FOR HANDSET APPLICATION

In this paper, a dual antennas has designed and implemented for 2 x 2 MIMO handset application .The antenna element of the proposed dual port antennas of 2 x 2 MIMO handset is based on a Planar Inverted F-Antenna (PIFA) using meandering shorting strip which optimized to have frequency band operation at between 1.8 to 2.4 GHz for $|S11| \leq -10$dB. Each of the PIFA antenna used in this research has 20.5mm x 16 mm x 9.5 mm size which is compact and small enough for the placement in handset which has a limited space. Several MIMO configuration applied for the two PIFAs to meet the required return loss (S11 and S22), mutual coupling (S12 and S21), and correlation coefficient while maintaing its size to be small enough for the placement in handset. Then, the proposed 2x 2 MIMO antenna has been implemented on a low cost FR4 substrate. Moreover, effects of the usage of the antenna near human head and hand to the antenna parameters are also investigated.

[4] ANTENNA ARRAY FOR IEEE 802.11/A/B MIMO APPLICATION

In this paper, antenna array for WiFi IEEE 802.11a/b with frequency at 2.4 GHz»2.5 GHz and 5.2 GHz » 5.8 GHz is implemented. The results from both simulation and measurement are compared. The geometry of the antenna array is simulated by GEMS. Top patch arrays is dual polarizations with frequency at 5.5 GHz. The second layer patch array is dual polarizations with frequency at 2.4 GHz. The 5.5 GHz array is located on the top of 2.4 GHz array. The return loss, power pattern, effciency for two orthogonal polarizations at 2.4 GHz and 5.5 GHz will be discussed.

[5] A MULTI SLOT PATCH ANTENNA FOR 4G MIMO COMMUNICATIONS

A compact two element MIMO (Multiple Input Multiple Output) system is proposed using a multi slot patch antenna employing polarization diversity. The proposed MIMO system offers improved bandwidth, return loss and isolation characteristics. The system resonates at 5.35GHz and 5.81GHz frequencies for VSWR≤2, which can be used for 4G & WiMAX applications. The simulation results of return loss, mutual coupling, correlation coefficient and gain are presented. The channel capacities for the developed system are also estimated for indoor propagation.

[6] Soham Ghosh*, StudentMember, IEEE*, Thanh-Ngon Tran, and Tho Le-Ngoc*, Fellow, IEEE,*They designed two very compact designs of miniaturized four-element planar inverted-F antennas (PIFAs) are proposed for 2.45 GHz multiple-input–multiple-output (MIMO) applications. The first configuration exhibits pattern diversity, while the second exploits hybrid pattern and polarization diversity. Both the configurations are designed over a small ground plane measuring 105 55 mm in area, while each antenna element occupies a volume of only 0.455 cm . Diversity performance criteria, namely envelope correlation coefficient (ECC)
and mean effective gain (MEG), are studied. Effective diversity gain (EDG) using maximal ratio combining (MRC) and selection combining (SC) are then derived for a Rayleigh fading environment.

[7] Reza Karimian, Homayoon Oraizi*, Senior Member, IEEE*, Saeed Fakhte, and Mohammad Farahani.They designed A novel F-shaped microstrip slot antenna for WLAN and WiMAX multiple-input–multiple-output (MIMO) systems is presented. The proposed antenna structure consists of both openended and short-ended slots connected by a metal "via" to a microstrip line. The open-ended slot is exploited to obtain resonant mode at 2.4 GHz, and three short-ended slots are aimed to obtain resonant modes at 3.5, 5.2, and 5.8 GHz, whose center frequencies can be adjust by the slot lengths. The parametric studies show that the center frequencies are independent of each other. A four-element array configuration of the proposed antenna for MIMO applications is also studied. The simulation and measurement results of reflection coefficient, mutual coupling, and radiation pattern are presented, which attest to the applicability of antenna.

[8] S. Dumanli, C.J. Railton, D.L. Paul.They studied about the effect of correlation between four closely spaced slot antennas on the capacity of a MIMO system is demonstrated for several different channel scenarios and a practical decorrelation network consisting of a rat-race hybrid is proposed. The effectiveness of this network is independent of the element type or spacing. The properties of the array and decorrelation network are investigated by means of a Finite.difference Time Domain (FDTD) analysis. The decorrelation network is shown to reduce the envelope correlation and give improved capacity when the elements are close.

[9] Sema Dumanl, Chris J. Railton, Dominique L. Paul.They says that an array of four slot antennas backed with substrate integrated waveguide (SIW) cavities is presented for application to multiple input multiple output (MIMO) systems. Two 0.18_ spaced antennas are decorrelated by the use of a rat race hybrid. An investigation based on simulations and measurements has been carried out. The impedance matching and the radiation characteristics of these structures were studied using the Finite Difference Time Domain (FDTD) technique. The array performance is judged by considering the correlation coefficients between the elements and the MIMO channel capacity.

[10] Jian-Feng Li, Qing-Xin Chu, *Senior Member, IEEE*, Zhi-Hui Li, and Xing-Xing Xia. They proposed a compact dual band-notched ultra-wideband (UWB) multiple-input multiple-output (MIMO) antenna with high isolation is designed on a FR4 substrate (27 × 30 × 0.8 mm3). To improve the input impedance matching and increase the isolation for the frequencies ≥ 4.0 GHz, the two antenna elements with compact size of 5.5 × 11 mm2 are connected to the two protruded ground parts, respectively. A 1/3 λ rectangular metal strip producing a 1.0 λ loop path with the corresponding antenna element is used to obtain the notched frequency from 5.15 to 5.85 GHz. For the rejected band of 3.30-3.70 GHz, a 1/4 λ open slot is etched into the radiator. Moreover, the two protruded ground parts are connected by a compact metal strip to reduce the mutual coupling for the band of 3.0-4.0 GHz. The simulated and measured results show a bandwidth with $|S11| \leq -10$ dB, $|S21| \leq -20$ dB and frequency ranged from 3.0 to 11.0 GHz excluding the two rejected bands, is achieved, and all the measured and calculated results show the proposed UWB MIMO antenna is a good candidate for UWB MIMO systems.

[11] P.N. Fletcher, M. Dean and A.R. Nix.They says The effects of mutual coupling between receive elements in multielement antenna on multiple-input multiple-output (MIMO) system capacity are reported. The results are based upon analysis of mutual coupling calculated for a measured linear array of five printed dipole elements with 0.56 wavelcngth spacing. It is shown that the presence of mutual coupling at the receive amy antenna leads to additional correlation between spatial channels and results in a loss of MIMO system capacity.

[12] Kasra Payandehjoo, Member, IEEE, and Ramesh Abhari, Senior Member, IEE**E.**They says that miniaturized tunable two-antenna systems composed of printed inverted-F antennas (PIFAs) are developed for a semi-populated mobile phone handset. The compact 32mm-long PIFAs

demonstrate tuning range of more than 240MHz covering personal telecommunication bands from LTE-band13 to GSM900MHz. As well a miniaturized tunable parasitic element is integrated in the handset to efficiently suppress coupling between the PIFAs to below -28dB across the entire operational bandwidth of the antennas. Simulation and measurement results demonstrate the successful implementation of a tunable MIMO system with passive adjustable coupling reduction mechanism for mobile handsets and achievement of a channel capacity profile close to that of an un-correlated system.

CHAPTER 3

MASSIVE MIMO ANTENNA

3.1 INTRODUCTION

Massive MIMO (also known as Large-Scale antenna System, very large MIMO) helps by focusing the transmission and reception of signal (MIMO ɔ ever smaller regions of space. This brings huge improvements in throughput, energy efficiency. Massive MIMO system originally envisioned for time division duplex (TDD) operation but can potentially be applied also in frequency division duplex (FDD) operation.

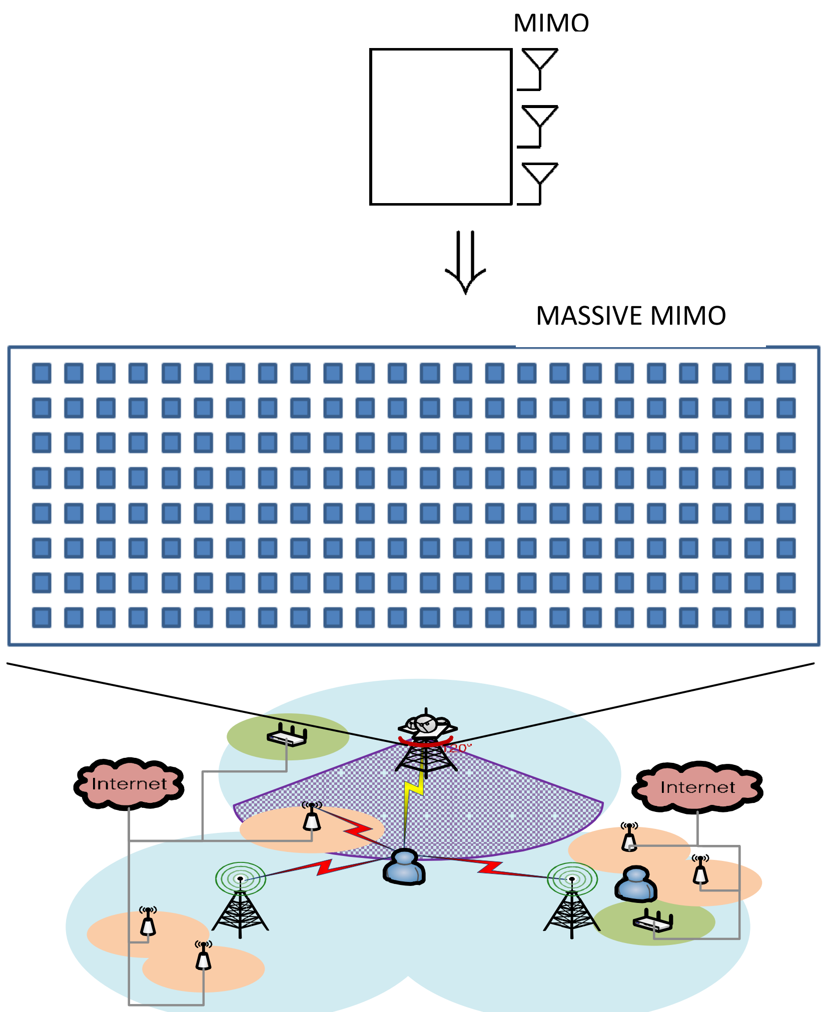

Fig.3.1 MASSIVE MIMO

Massive MIMO is an emerging technology, which scales up MIMO by an order of magnitude. Antenna array with few hundred elements. It has been observed that massive MIMO networks can provide higher performance than partial multi-user MIMO since the multiple antenna used much smarter. Massive MIMO system can be termed as the scenario of multi user MIMO in which the number of transmitter terminals is very less than the number of BS (base station) antenna. For scattered environment, merits of Massive MIMO technology could be developed by using simple ZF (zero forcing) or MRT (Maximum Ratio Transmission). Practically for orthogonal channels to various machines maintaing orthogonality optimal multiplexing. It can be argued that in the current text of disruption of emerging technology Massive MIMO is the best choice for future generation wireless evolution for 5G. By using Massive MIMO,

Increased:

- Rate
- Transmission reliability
- Energy efficiency

3.1.1 PRACTICAL ISSUES IN MASSIVE MIMO

Antenna elements are cheap. But the multiple RF chains associated with multiple antennas are costly in terms of size, power and hardware. The number of RF chains is restricted in massive MIMO system.

3.1.2 ADVANTAGES OF MASSIVE MIMO ANTENNA

- High throughput
- Energy efficiency
- Reduced latency
- Robustness to interference and internal jamming

3.2 APPLICATIONS

- 5G
- Signal Processing Applications

CHAPTER 4

SINGLE ANTENNA DESIGN

4.1 MICROSTRIP PATCH ANTENNA

Microstrip patch antenna is a key building in wireless communication and Global positioning system. A Patch antenna is a radio antenna with low profile, which can be mounted on a flat surface. A patch antenna is a narrowband and it consists of a flat rectangular sheet mounted over a larger sheet of metal called as ground plane. Patch antenna is simple to fabricate and easy to modify and customize. Compared with conventional antenna Microstrip patch antenna have advantages. They are light weight, low cost and low profile planer configuration.

A Microstrip patch antenna is well suited for wireless communication due to its light weight and low planer configuration. The impedance bandwidth of a patch antenna is the spacing between the patch and ground plane. Patch arrays can provides higher gain then a single patch. Such an array of patch antenna is an easy way to make a phases array of antenna with dynamic beam forming ability.

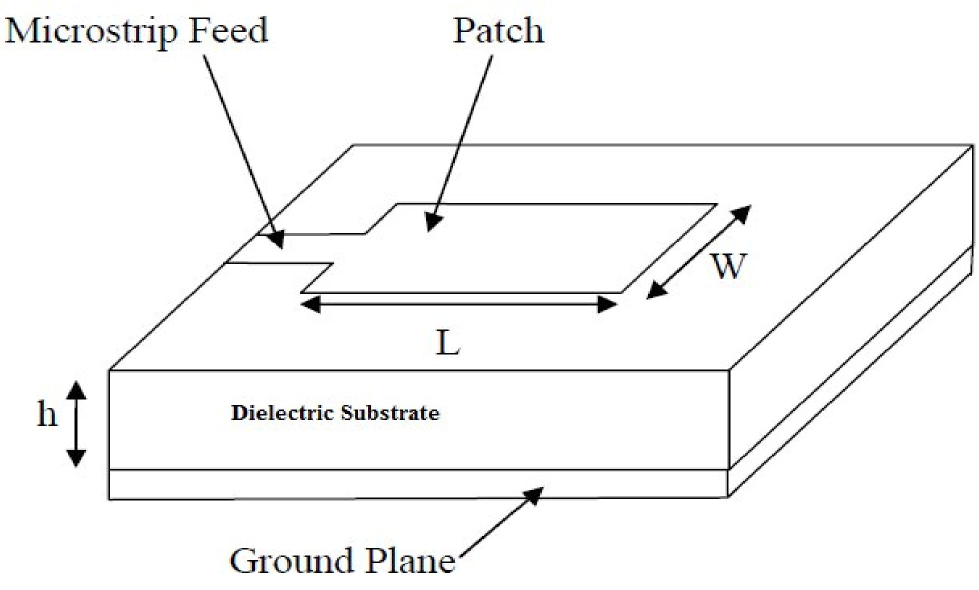

Fig.4.1 Microstrip patch antenna

The industrial, scientific and medical (ISM) bands are operated at the frequency range 2.4GHZ for industrial, scientific and medical purposes. The antenna is designed for 2.4 GHZ and it can be used for various applications like WLAN, Wi-Fi family of standard (802.11 a, b, g, n) and Bluetooth short range wireless application. Common microstrip antenna shapes are square, rectangular, circular and elliptical, but any continuous shape is possible. Some patch antennas do not use a dielectric substrate and instead made of a metal patch mounted above a ground plane using dielectric spacers; the resulting structure is less rugged but has a wider bandwidth. Because such antennas have a very low profile, are mechanically rugged and can be shaped to conform to the curving skin of a vehicle, they are often mounted on the exterior of aircraft and spacecraft, or are incorporated into mobile radio communications devices. The most commonly employed Microstrip patch antenna is rectangular patch antenna. An advantage inherent to patch antenna is the ability to have polarization diversity. As the dielectric constant of the substrate increases, the antenna beam width decreases.

Microstrip antennas are relatively inexpensive to manufacture and design because of the simple 2-dimensional physical geometry. They are usually employed at UHF and higher frequencies because the size of the antenna is directly tied to the wavelength at the resonant frequency. Patch arrays can provide much higher gains than a single patch at little additional cost; matching and phase adjustment can be performed with printed microstrip feed structures, again in the same operations that form the radiating patches. The ability to create high gain arrays in a low-profile antenna is one reason that patch arrays are common on airplanes and in other military applications. An advantage inherent to patch antennas is the ability to have polarization diversity. Patch antennas can easily be designed to have vertical, horizontal, right hand circular (RHCP) or left hand circular (LHCP) polarizations, using multiple feed points, or a single feed point with asymmetric patch structures.

The most commonly employed microstrip antenna is a rectangular patch. The rectangular patch antenna is approximately a one-half wavelength long section of rectangular microstrip transmission line. When air is the antenna substrate, the length of the rectangular microstrip antenna is approximately one-half of a free-space wavelength. As the antenna is loaded with a dielectric as its substrate, the length of the antenna decreases as the relative dielectric constant of the substrate increases. The resonant length of the antenna is slightly shorter because of the extended electric "fringing fields" which increase the electrical length of the antenna slightly. An early model of the microstrip antenna is a section of microstrip transmission line with equivalent loads on either end to represent the radiation loss.

4.2 ANALYTICAL APPROACH- DESIGN EQUATIONS

The Performance of the Microstrip patch antenna depends on its resonant frequency, dimension. Depending on the dimension, the operating frequency, radiation efficiency, directivity, return loss are influenced. For an efficient radiation, the practical width of the patch can be calculated by using the following.

$$W = \frac{1}{2f_r\sqrt{\mu_0\epsilon_0}} \times \sqrt{\frac{2}{\varepsilon_r+1}}$$

And the length (L) of the antenna becomes,

$$L = \frac{1}{2f_r\sqrt{\varepsilon_{eff}}\sqrt{\mu_0\varepsilon_0}} - 2\Delta L$$

Where,

$$\varepsilon_{eff} = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2\sqrt{1+12\frac{h}{W}}}$$

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

Where,

λ is the wave length,

fr is the resonant frequency,

L and W are the length and width of the patch element respectively and

εr is the dielectric constant.

Characteristic impedance of the patch can be found by,

$$Z_a = 90\frac{\varepsilon_r^2}{\varepsilon_r-1}\left(\frac{L}{W}\right)^2$$

Impedance of transition section:

$$Z_T = \sqrt{50 * Za}$$

Width of transition line WT:

$$Z_T = \frac{60}{\sqrt{\varepsilon_r}} \ln\left(\frac{8d}{W_T} + \frac{W_T}{4d}\right)$$

W_T-Width of Edge Feed

Length of transition line:

$$l = \frac{\lambda}{4} = \frac{\lambda_0}{\sqrt{\varepsilon_{eff}}}$$

l- Length of Feed Line

Length of the microstrip transmission line

$$R_{in\,(x=0)} = \frac{Z_0}{Z_T} = \mathrm{Cos}^2\left(\frac{\pi}{L}\right) x_0$$

x_0-Length of Edge Feed

Width of 50Ω microstrip transmission line:

$$Z_0 = \frac{120\pi}{\sqrt{\varepsilon_{eff}\left(1.393 + \frac{W}{h} + \frac{2}{3}\ln\left(\frac{W}{h} + 1.444\right)\right)}}$$

W- Width of Feed Line

Where,

Z_0=50Ω

4.3 ANTENNA FEEDING TECHINIQUES

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 .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).

4.3.1 Probe Feed

The Coaxial feed or probe feed is a very common technique used for feeding Microstrip patch antennas. As seen from Figure 2.6, 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. The main advantage of this type of feeding scheme is that the feed can be placed at any desired location inside the patch in order to match with its input impedance. This feed method is easy to fabricate and has low spurious radiation. However, a major disadvantage is that it provides narrow bandwidth and is difficult to model since a hole has to be drilled in the substrate and the connector protrudes outside the ground plane, thus not making it completely planar for thick substrates ($h > 0.02\lambda o$).

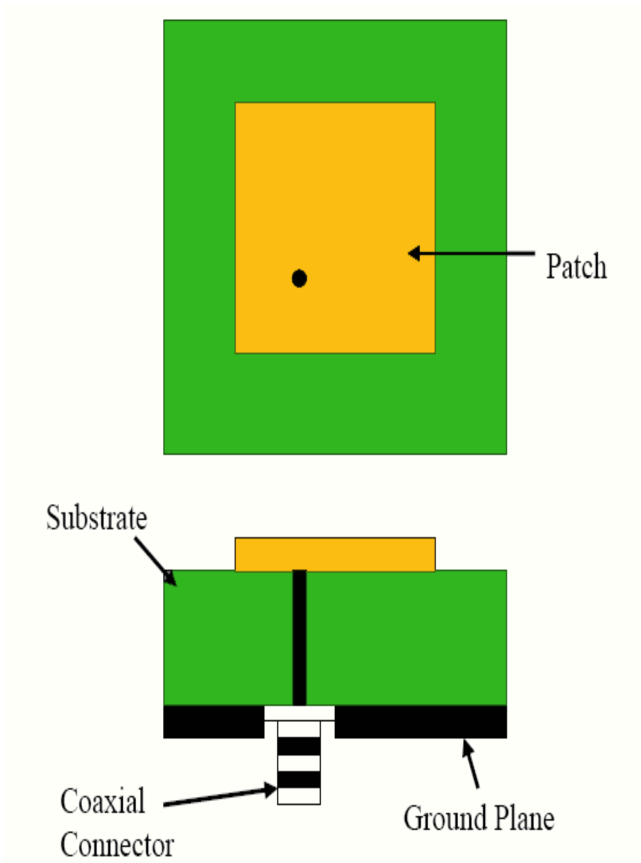

Fig.4.2 Coaxial Feed

4.3.2 Microstrip Feed Line

In this type of feed technique, a conducting strip is connected directly to the edge of the microstrip patch as shown in Figure 2.7. 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. The purpose of the inset cut in the patch is to match the impedance of the feed line to the patch without the need for any additional matching element. This is achieved by properly controlling the inset position. Hence this is an easy feeding scheme, since it provides ease of fabrication and simplicity in modeling as well as impedance matching. However as the thickness of the dielectric substrate being used, increases, surface waves and spurious feed radiation also increases, which hampers the bandwidth of the antenna .The feed radiation also leads to undesired cross polarized radiation.

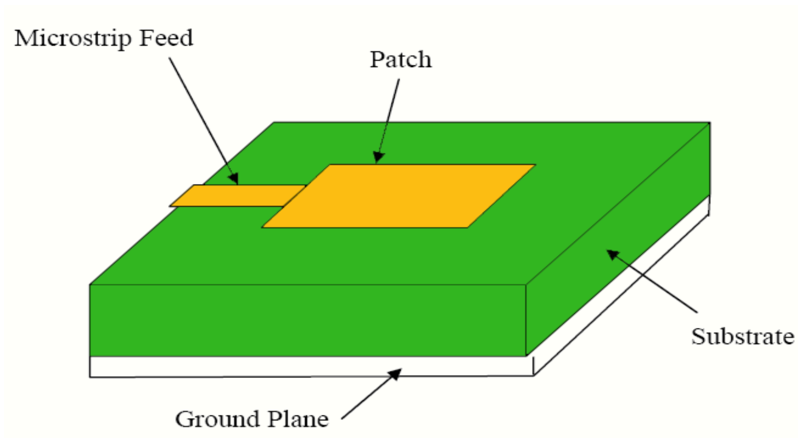

Fig 4.3 Microstrip Line Feed

4.3.3 Proximity Coupled Feed

This type of feed technique is also called as the electromagnetic coupling scheme. As shown in Figure 2.8, 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%), due to overall increase in the thickness of the micro strip 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. 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.

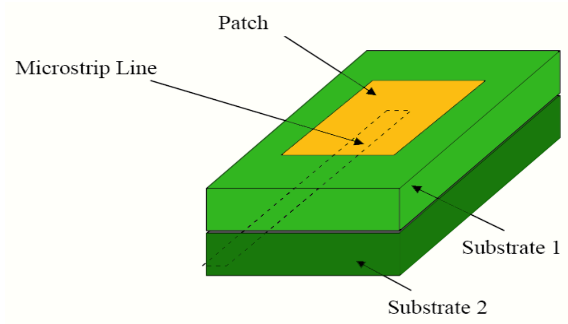

Fig.4.4 Proximity-coupled Feed

4.3.4 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 2.9. Coupling between the patch and the feed line is made through a slot or an aperture in the ground plane. The coupling aperture is usually centered under the patch, leading to lower cross-polarization due to symmetry of the configuration. The amount of coupling from the feed line to the patch is determined by the shape, size and location of the aperture. Since the ground plane separates the patch and the feed line, spurious radiation is minimized. Generally, a high dielectric material is used for bottom substrate and a thick, low dielectric constant material is used for the top substrate to optimize radiation from the patch. 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.

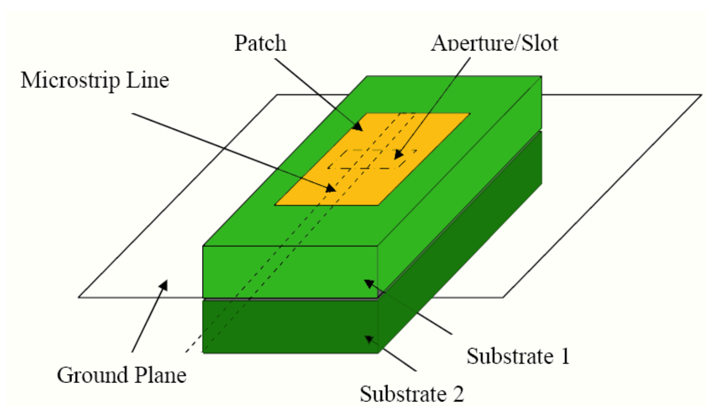

Fig 4.5 Aperture-coupled feed

4.4 ANTENNA PARAMETERS AND TERMS

- **Antenna**: A device for the radiation or reception of EM waves.
- **Antenna Efficiency**: The ratio of the power radiated (Pr) to the power fed into the antenna (Pt).
- **Antenna Resistance**: The real part of the antenna input impedance.
- **Array Antenna**: An arrangement of antenna elements, usually identical, used to obtain specific antenna characteristics.
- **Antenna Bandwidth**: The frequency over which the antenna characteristics conform to a desired standard.
- **Antenna Beam**: The major lobe of the radiation pattern of an antenna.
- **Broadside Array Antenna**: A linear or planar array whose direction of maximum radiation is perpendicular to the line or plane of the array.
- **Directional Antenna**: An antenna which radiates or receives EM waves more effectively in a perpendicular direction.
- **Directivity**: The ratio of the maximum intensity to the average radiation intensity.
- **Endfire Array Antenna**: A linear array antenna whose direction of maximum radiation is parallel to the line of array.
- **Half Power Beamwidth**: In a plane containing the direction of the maximum of a beam, the angle between the two directions in which the radiation intensity is one half the maximum value of the beam.
- **Isotropic Radiator**: A hypothetical antenna radiating equally well in all direction.
- **Polarization of an Antenna**: This is the polarization of the wave radiated by the antenna is that particular direction. When the direction is not specified, the polarization is taken to be the polarization in the direction of maximum radiation.
- **Radiation Resistance**: The ratio of the square of the RMS antenna voltage to the power radiated. It may be expressed as Rr =V^2/(2Pr).
- **Resonant Frequency**: A frequency at which the input impedance of the antenna has no reactive component.
- **Side Lobe**: A radiation lobe is any direction other than the intended lobe.
- **Side Lobe Level**: The relative level to the highest side lobe.

4.5 ANTENNA DESIGN STRUCTURE

The designed antenna is printed on both sides, one side is patch and other side is ground plane. Microstrip patch antennas can be fed by a variety of methods. The antenna is designed by using a microstrip feed line because it is one of the easier method to fabricate. The geometry of the given antenna is illustrated in Fig.4.8. The antenna is fabricated on 76.8 X 57.8 mm^2 FR-4 substrate with a dielectric constant of 4.4 (ε_r) and substrate thickness 1.8mm.

The top and bottom patches printed on the substrate are the radiating structure and the ground plane. The top patch of the substrate has dimension of 39.4x28.9mm^2 which is fed by strip line having a width of 3.1mm. The bottom of the substrate is just a ground plane. The proposed antenna has been simulated by HFSS software.

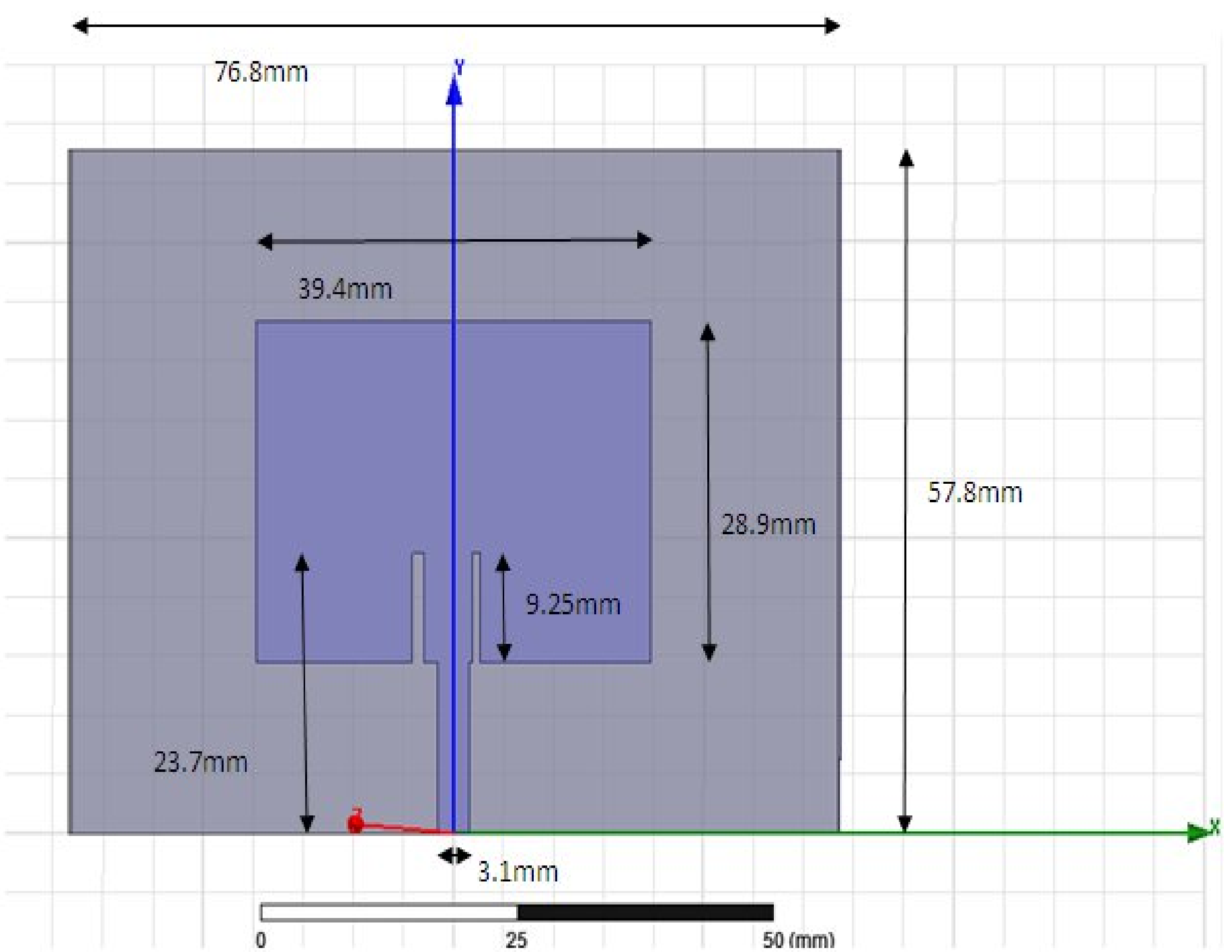

Fig.4.6 Front view of the single patch antenna dimensions in mm

The geometry of the given antenna is illustrated in Fig.4.9. The antenna is fabricated on 124.95 X 57.8 mm^2 FR-4 substrate with a dielectric constant of 4.4 (ε_r) and substrate thickness 1.8mm.

- Thickness of substrate should be very much less than guided wavelength
- Dielectric constant εr for RF and microwave bands should satisfy the conditions

$$2.2 \leq \varepsilon r \leq 16$$

- Dielectric loss tangent which is the imaginary part of εr and denoted as tanδ should be such that

$$0.0001 \leq \tan\delta \leq 0.06$$

- High dielectric constant result in low radiation

The top and bottom patches printed on the substrate are the radiating structure and the ground plane. The top patch of the substrate has dimension of 39.4x28.9mm^2 which is fed by strip line having a width of 3.1mm.The two patch antennas are separated at the spacing is 0.162λ.

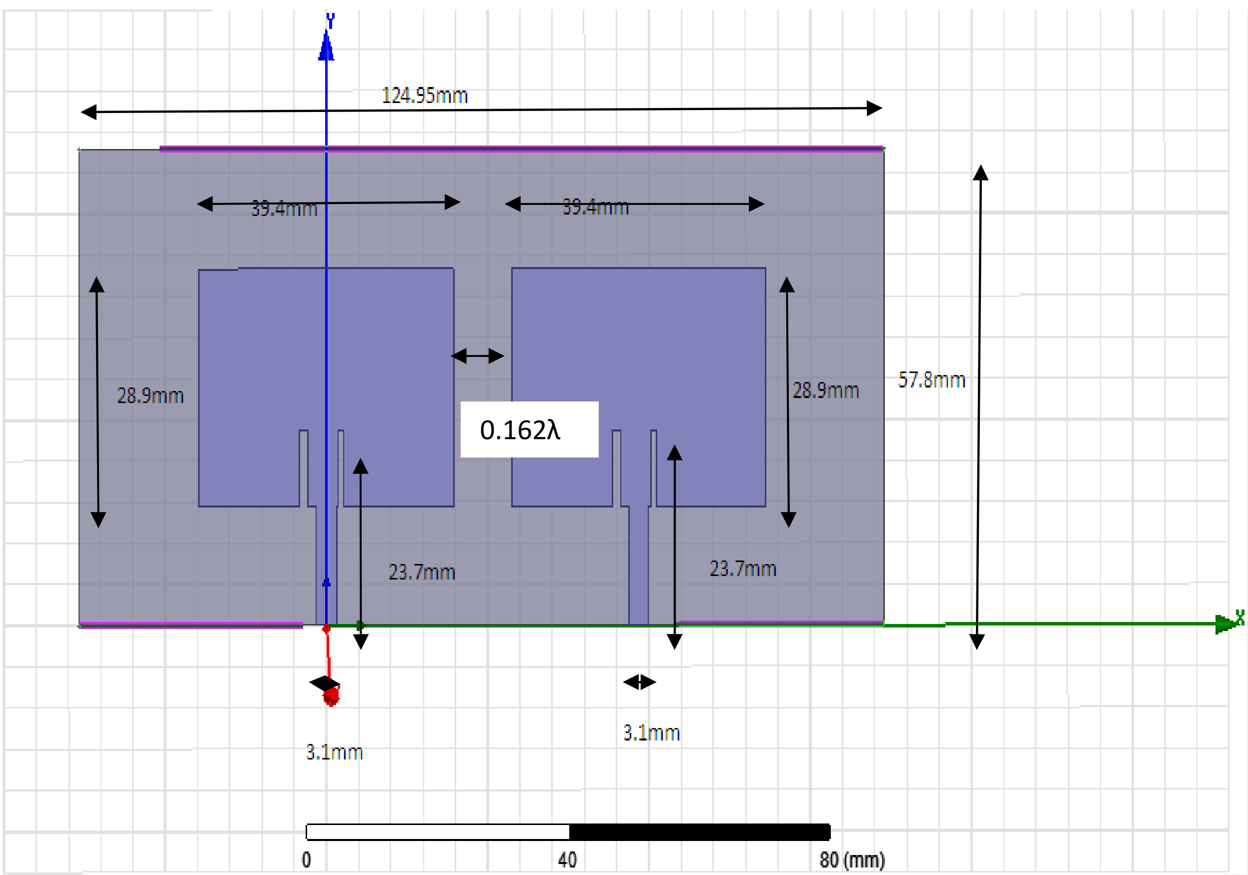

Fig.4.7 Front view of the Two patch antenna dimensions in mm

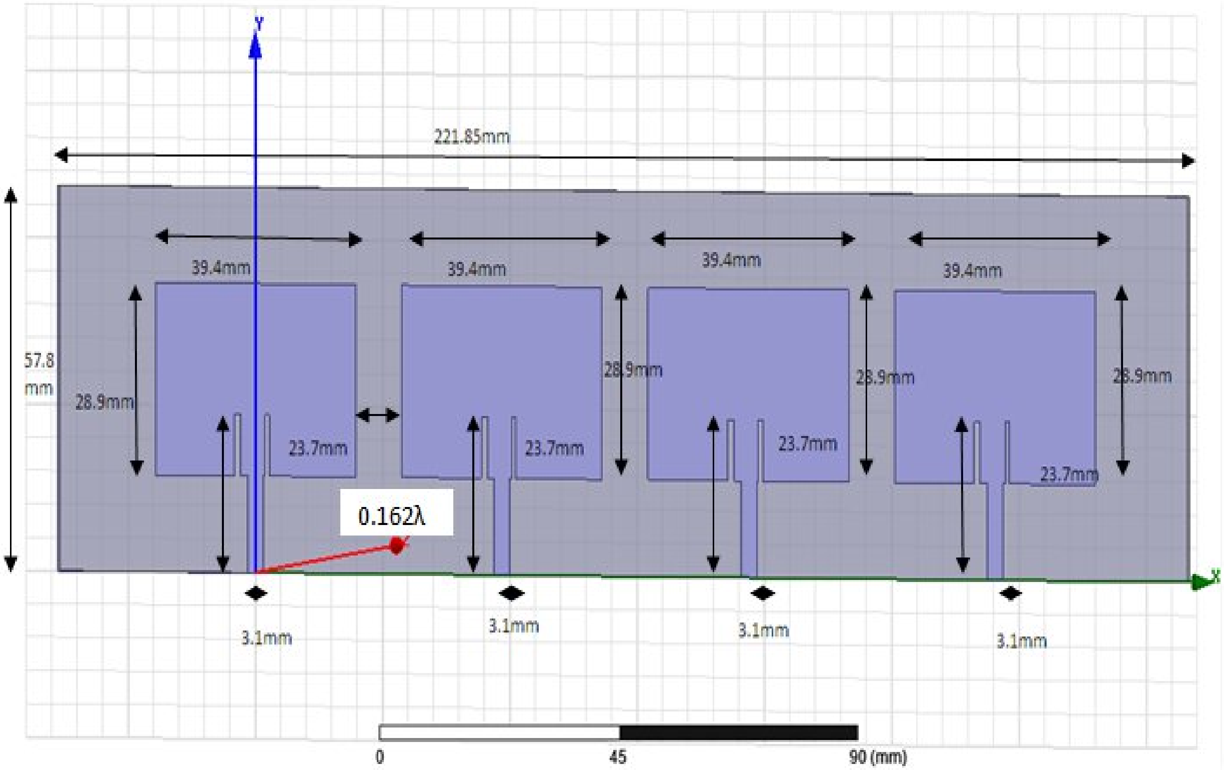

FIG.4.8 Front view of the Four patch antenna dimensions in mm

The geometry of the given antenna is illustrated in Fig.4.10. The antenna is fabricated on 221.85 X 57.8 mm^2 FR-4 substrate with a dielectric constant of 4.4 (ε_r) and substrate thickness 1.8mm. The patch antennas are separated at the spacing is 0.162λ.

4.6 ANTENNA PROPERTIES

There are several important antenna characteristics that should be considered when choosing an antenna for your application as follows:

4.6.1 OPERATING FREQUENCY

The operating frequency is the frequency range through which the antenna will meet all functional specifications.

It depends on the structure of the antenna in which each antenna types has its own characteristic towards a certain range of frequency. The operating frequency can be tuned by adjusting the electrical length of the antenna.

4.6.2 RETURN LOSS

Return loss is the ratio, at the junction of a transmission line and a terminating impedance or other discontinuity, of the amplitude of the reflected wave to the amplitude of the incident wave. The return loss value describes the reduction in the amplitude of the reflected energy, as compared to the forward energy. Return loss can be expressed as,

$$RL = 20Log\left|\frac{Z_1 + Z_2}{Z_1 - Z_2}\right|$$

Where,

Z1 = impedance toward the source

Z2 = impedance toward the load

4.6.3 BANDWIDTH

Bandwidth can be defined as "the range of frequencies within which the performance of the antenna, with respect to some characteristics, conforms to a specified standard. The bandwidth of an antenna is the range of frequencies over which it is effective, usually centered on the resonant frequency. Bandwidth is a measure of frequency range and is typically measured in hertz. For an antenna that has a frequency range, the bandwidth is usually expressed in ratio of the upper frequency to the lower frequency where they coincide with the -10 dB return loss value. The formula for calculating bandwidth is given as,

$$\%BW = \frac{f_h - f_l}{\sqrt{f_h f_l}} x100\%$$

Where,

fh= lower frequency that coincide with the -10 dB return loss value

fl= upper frequency that coincide with the -10 dB return loss value

4.6.4 ANTENNA RADIATION PATTERNS

The radiation pattern is a graphical representation of the characteristics of an antenna radiation in a certain direction as shown in Fig 4.11. These characteristics include radiation intensity, field intensity and polarization. It is normally represented with rectangular or polar plots and it is expressed in dB. The radiation pattern is a plane cut and represents one frequency and one polarization.

The radiation pattern of an antenna is the geometric pattern of the relative field strengths of the field emitted by the antenna. An antenna radiation pattern is a 3-D plot of its radiation far from the source. Antenna radiation patterns usually take two forms, the elevation pattern and the azimuth pattern. The elevation pattern is a graph of the energy radiated from the antenna looking at it from the side .The azimuth pattern is a graph of the energy radiated from the antenna as if looking at it from directly above the antenna.

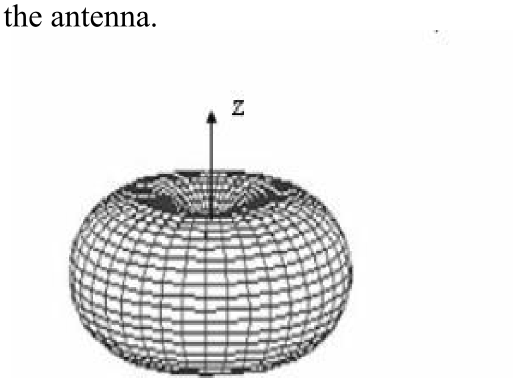

Fig.4.9 Radiation pattern of antenna

4.6.5 HPBW

The HPBW Half Power Beam width is a way of measuring the antenna directivity. This means that if the main lobe of an antenna is too narrow, the directivity is higher. It can be determined by taking out 3dB (half power) with respect to the main lobe power level.

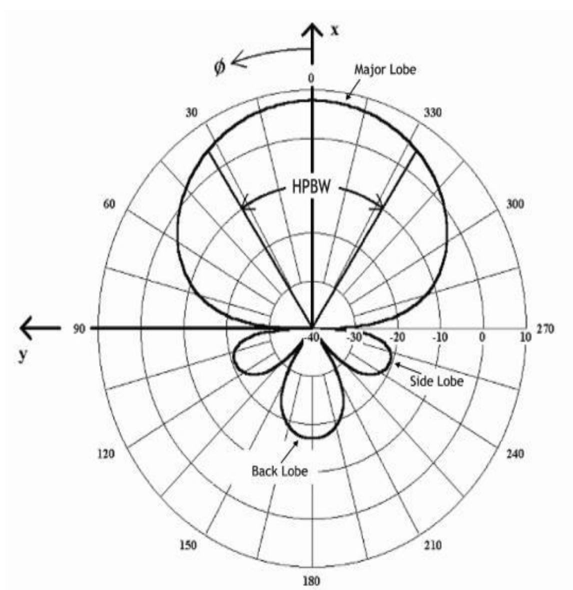

Fig.4.10 HPBW

4.6.6 GAIN

There are two types of gain, Absolute Gain and Relative Gain.

The Absolute Gain of an antenna is defined as the ratio between the antennas radiation intensity in a certain direction and the intensity that would be generated by an isotropic antenna fed by the same input power, therefore it can be given as,

$$G(\theta,\phi) = \frac{U(\theta,\phi)}{U_0}$$

$$U_0 \text{ is given by} : U_0 = \frac{P_{in}}{4\pi}$$

where $G(\theta,\phi)$ is the gain of the antenna in a certain direction, $U(\theta,\phi)$ is the radiation intensity in a certain direction and U0 is the radiation intensity of an isotropic antenna. Pin is the input power. The Absolute Gain is expressed in dBi as its reference is an isotropic antenna.

The Relative Gain of an antenna is defined as the ratio between the antenna radiation intensity in a certain direction and the intensity that would be generated by a reference antenna. The Relative Gain is expressed according to reference antenna.

4.6.7 DIRECTIVITY

The directive gain of an antenna is a measure of the concentration of the radiated power in a particular direction. It may be regarded as the ability of the antenna to direct radiated power in a given direction. It is usually a ratio of radiation intensity in a given direction to the average radiation intensity. The maximum directive gain is called as the directivity of an antenna and is denoted by D. This is an important parameter that allows us to measure the concentration of radiated power in a certain direction. It is given by,

$$D(\theta,\phi) = \frac{U(\theta,\phi)}{U_0}$$

Where D(q;f) is the directivity of the antenna in a certain direction U(q;f) is the radiation intensity in a certain direction and U0 is the radiation intensity of an isotropic antenna. Another way of measuring the directivity of an antenna is to calculate the HPBW.

4.6.8 VOLTAGE STANDING WAVE RATIO (VSWR)

The voltage standing wave ratio (VSWR) is defined as the ratio of the maximum voltage to the minimum voltage in a standing wave pattern. The VSWR can also be calculated from the return loss (S11) which means that it is also an indicator of antennas efficiency. With the return loss we can determine the mismatch between the characteristic impedance of the transmission line and the antennas terminal input impedance It is given as,

$$VSWR = \frac{1+|S_{11}|}{1-|S_{11}|}$$

$$VSWR = \frac{V_{max}}{V_{min}}$$

The VSWR increases with the mismatch between the antenna and the transmission line and decreases with a good matching. The minimum value of VSWR is 1:1 and most equipment scan handle a VSWR of 2:1, the bandwidth of an antenna can be determined by the VSWR or the return loss. The best performance of an antenna is achieved when the VSWR under 2:1 or the return loss is -10dB or lower.

4.6.9 RESONANT FREQUENCY

The "resonant frequency" and "electrical resonance" is related to the electrical length of an antenna. The electrical length is usually the physical length of the wire divided by its velocity factor (the ratio of the speed of wave propagation in the wire to the speed of light in a vacuum). Typically an antenna is tuned for a specific frequency, and is effective for a range of frequencies that are usually centered on that resonant frequency.

CHAPTER 5

RESULTS AND DISCUSSION

5.1 HFSS

HFSS is a commercial finite element method solver for electromagnetic structures from Ansys. ANSYS HFSS software is the industry-standard simulation tool for 3-D full-wave electromagnetic field simulation and is essential for the design of high-frequency and high-speed component design. It is one of several commercial tools used for antenna design, and the design of complex RF electronic circuit elements including filters, transmission lines, and packaging.

5.2. DESIGN PROCEDURE

The three essential parameters in the design of an antenna are,

- Frequency of operation
- Dielectric constant of substrate
- Thickness of substrate

5.3 RESULTS

5.3.1 SINGLE ANS TWO PATCH ANTENNA DESIGN STRUCTURE

5.3.1.1 3D-MODEL

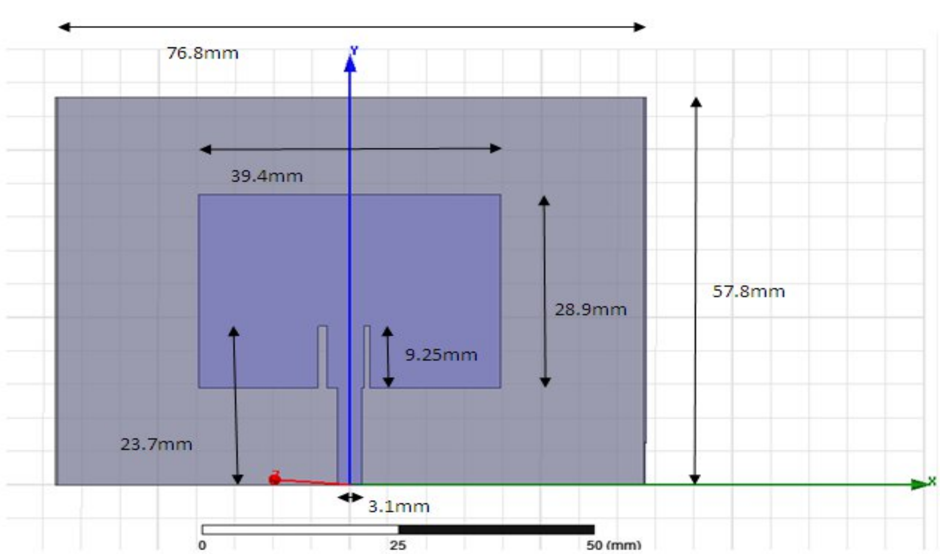

Fig.5.1 Front view of the Single Patch Antenna dimensions in mm

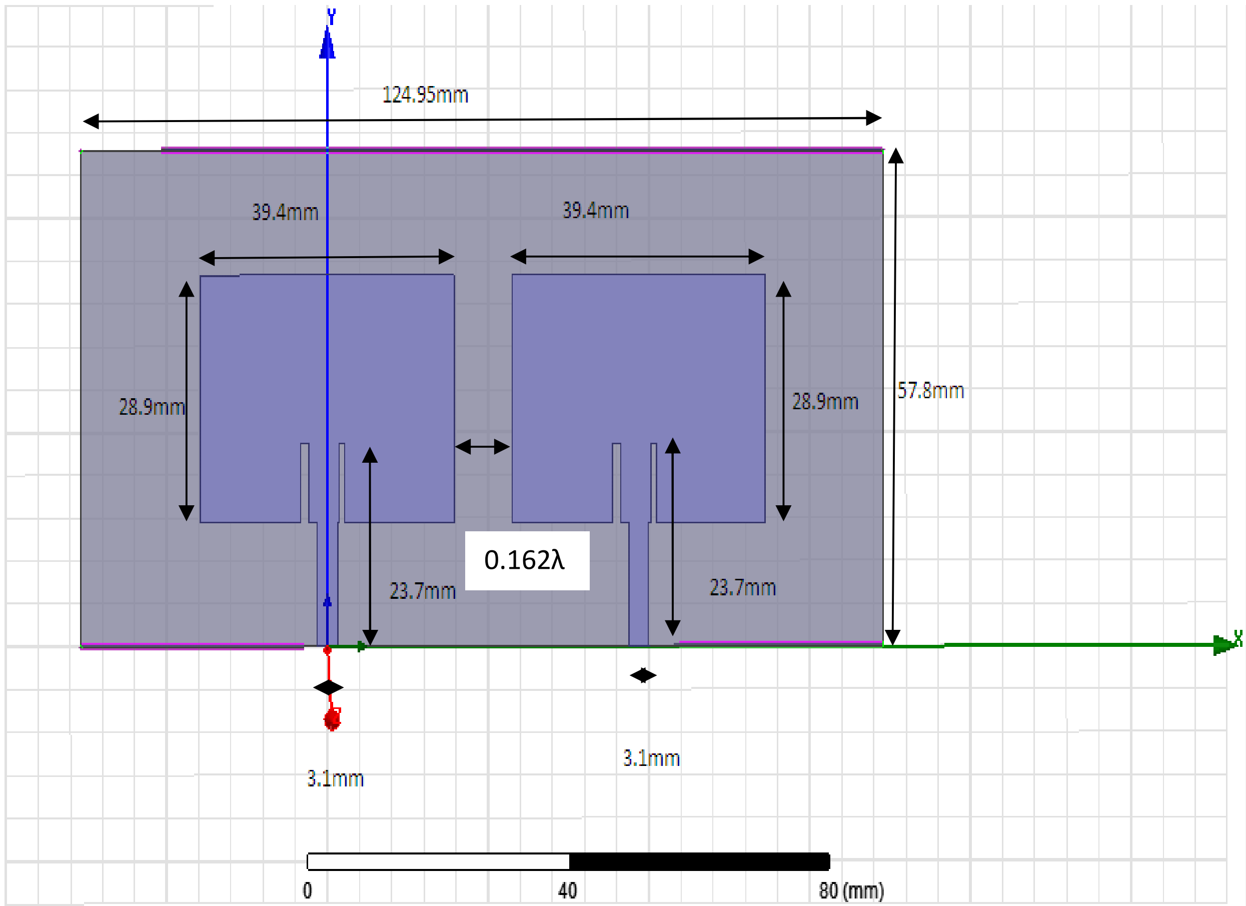

Fig.5.2 Front view of the Two Patch Antenna dimensions in mm

5.3.1.2 RETURN LOSS AND BANDWIDTH

(I). SINGLE PATCH

- For f=2.40 GHz the S11 parameter is shown we note that the bandwidth is 70 MHZ and Return loss s11<-21.5 dB.
- For f=3.7&4.5 GHz the S11 parameter is shown we note that the bandwidth is 90&160MHZ and Return loss s11<-12dB&-19.5dB.

(II). TWO PATCH

- For f=2.40 GHz the S11 parameter is shown we note that the bandwidth is 100 MHZ and Return loss s11<-23.5 dB.
- For f=3.7&4.5 GHz the S11 parameter is shown we note that the bandwidth is 100&180MHZ and Return loss s11<-11dB&-19.5dB.

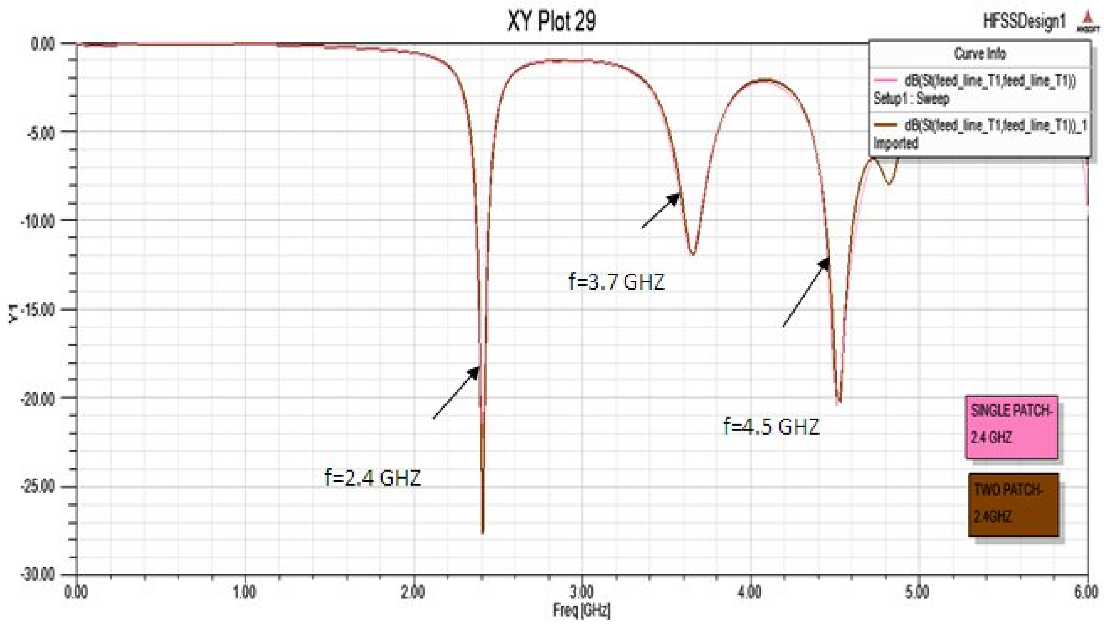

Fig.5.3 Return loss & Bandwidth

5.3.1.3 VOLTAGE STANDING WAVE RATIO (VSWR)

- Voltage Standing Wave Ratio is defined as a measurement of the mismatch between the load and the transmission line. For ideal case the value of VSWR is 1 and for better matching.

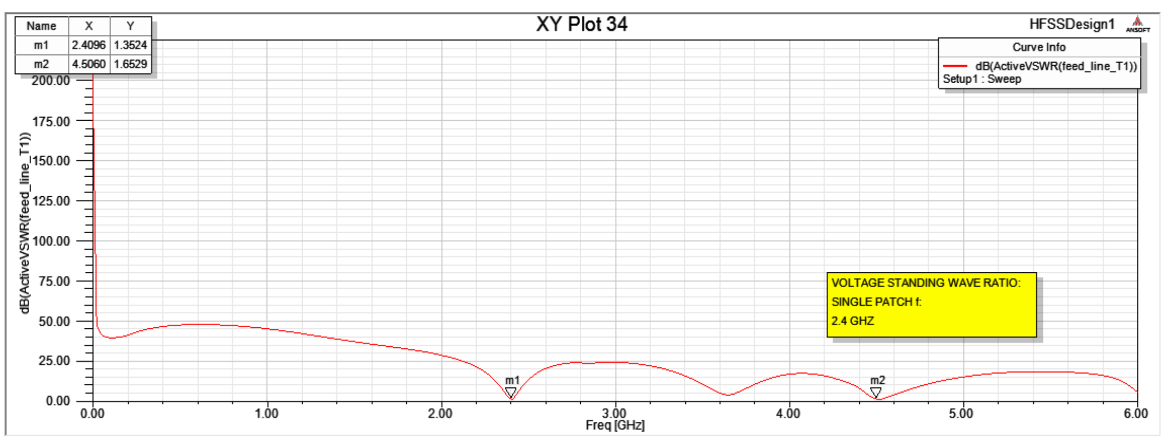

Fig.5.4 Voltage Standing Wave Ratio

- The voltage standing wave ratio at the frequency range of 2.4GHZ is 1.3 and 4.5GHZ is 1.65.

5.3.1.4 DIRECTIVITY

The directive gain of an antenna is a measure of the concentration of the radiated power in a particular direction. It may be regarded as the ability of the antenna to direct radiated power in a given direction. It is usually a ratio of radiation intensity in a given direction to the average radiation intensity. The maximum directive gain is called as the directivity of an antenna and is denoted by D.

The directivity of the single patch antenna is 5.32dB (absolute gain) and 7.26dB (Relative Gain)

(I) SINGLE PATCH

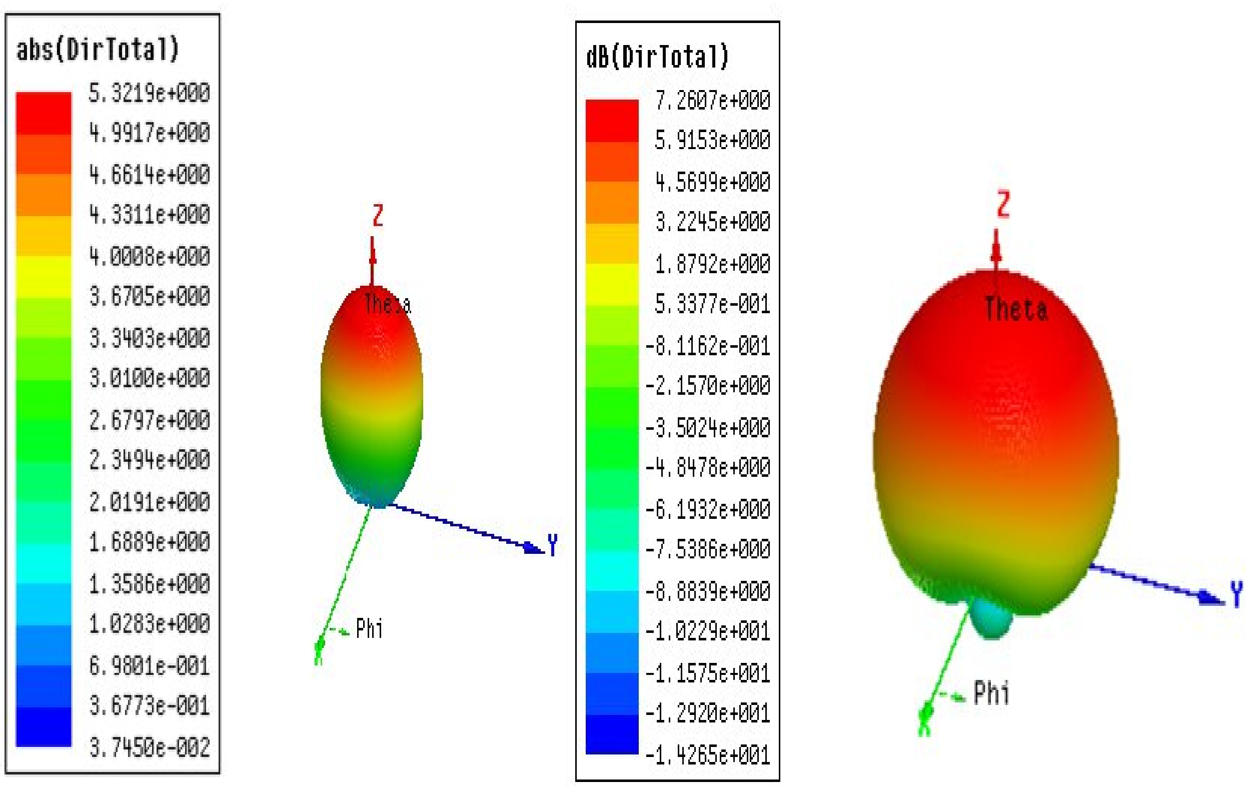

Fig.5.5 Directivity of Single Patch Antenna

(II) TWO PATCH

The directivity of two patch antenna is 5.49dB (absolute gain) and 7.39dB (Relative Gain)

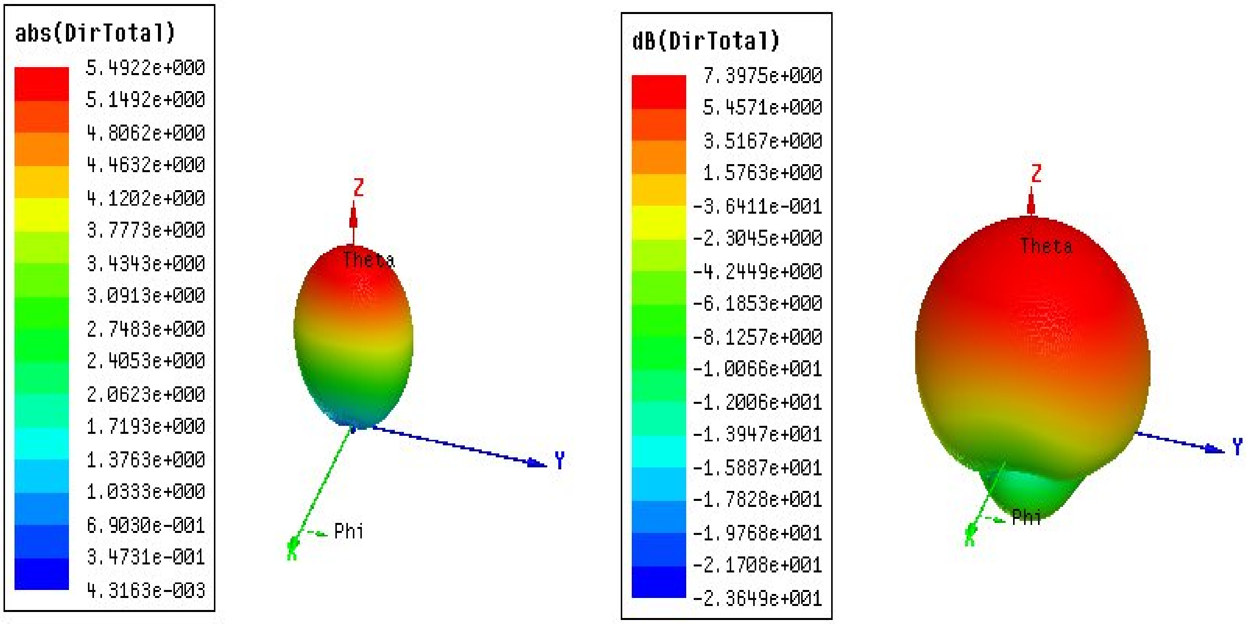

Fig.5.6 Directivity of Two Patch Antenna

5.3.1.5 E-FIELD

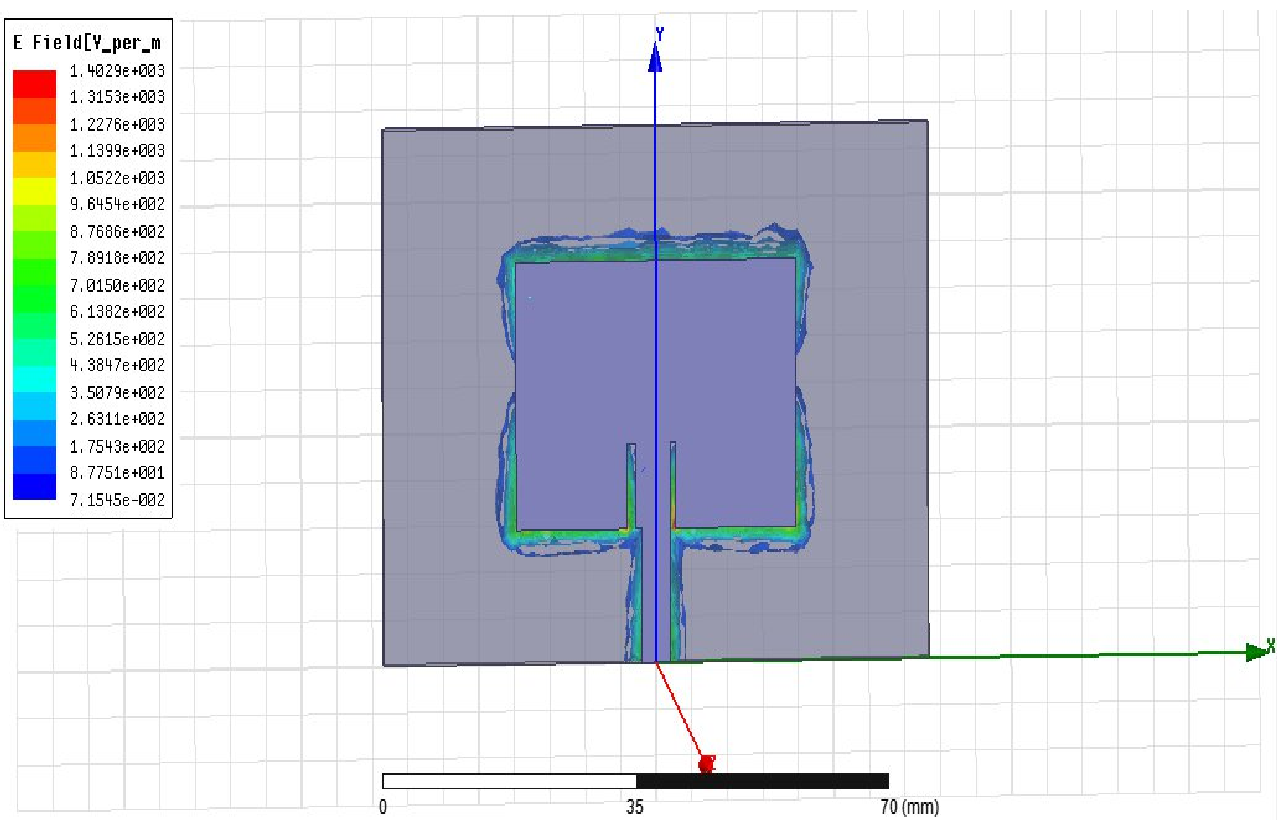

Fig.5.7 E-Field of Single Patch Antenna

5.3.1.6 H-FIELD

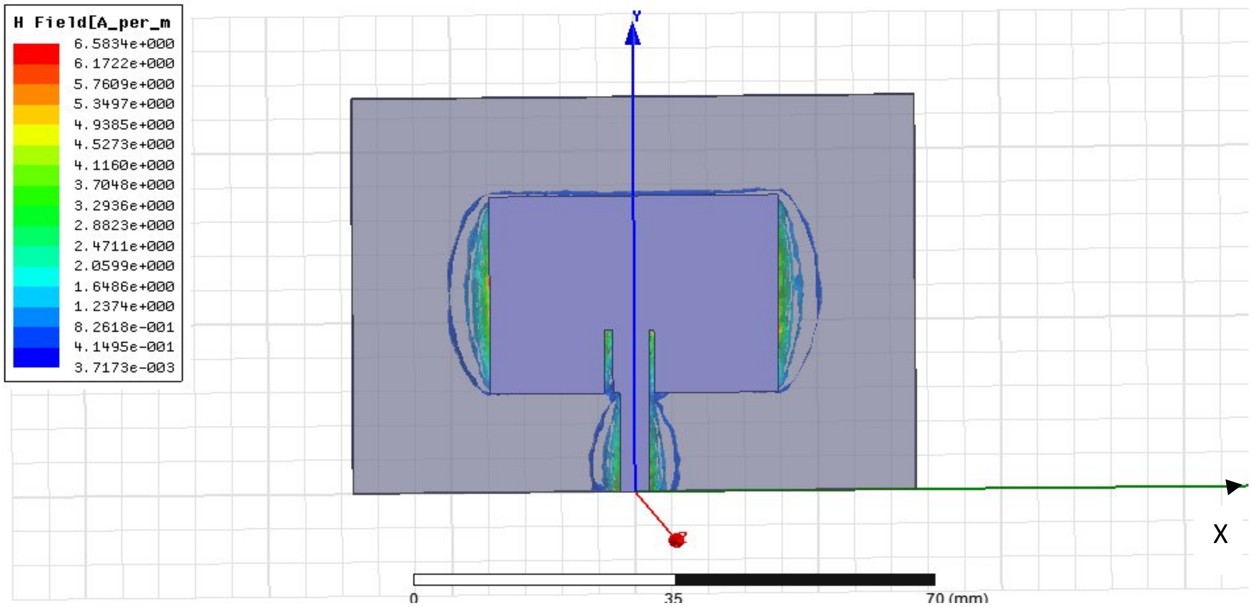

Fig.5.8 H-Field of Single Patch Antenna

5.3.1.7 RADIATION PATTERN

The radiation pattern is a graphical representation of the characteristics of an antenna radiation in a certain direction. The magnitude of the single patch and two patches are 4.19dB& 4.33dB.

(I) SINGLE PATCH & TWO PATCH

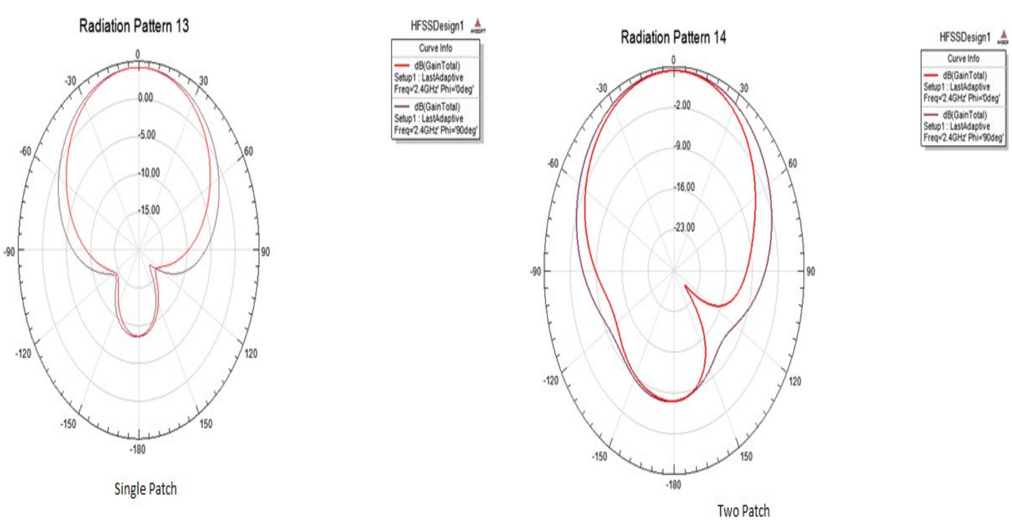

Fig.5.9 Radiation Pattern of single & Two Patch Antenna

5.3.2 FOUR PATCH ANTENNA DESIGN STRUCTURE

5.3.2.1 3D-MODEL

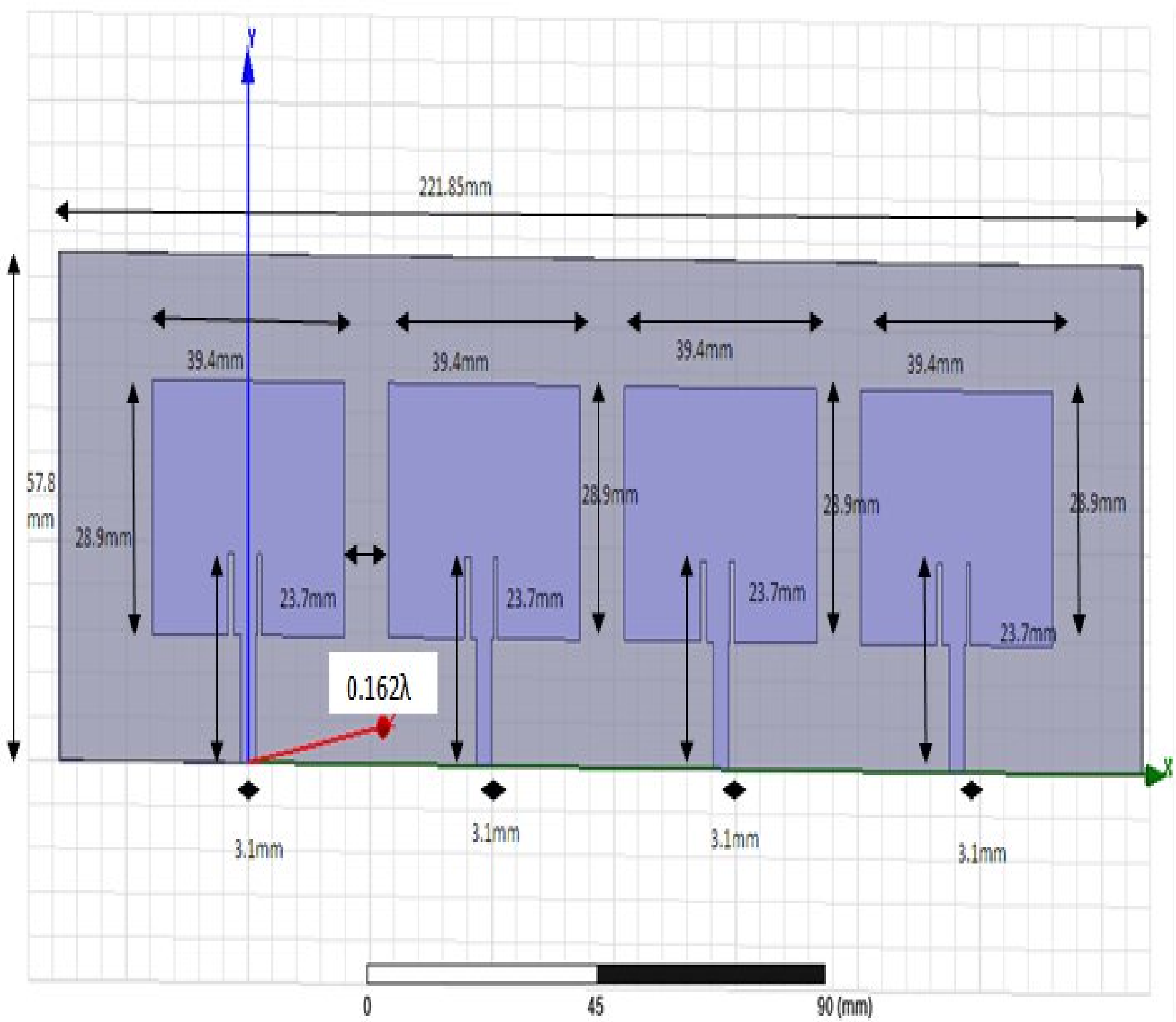

Fig.5.10 Front view of the four patch antenna dimensions in mm

5.3.2.2 RETURN LOSS AND BANDWIDTH

- For f=2.40 GHz the S11 parameter is shown we note that the bandwidth is 120 MHZ and Return loss s11<-24.5 dB.
- For f=3.7&4.5 GHz the S11 parameter is shown we note that the bandwidth is 110&200MHZ and Return loss s11<-11dB&-22dB.

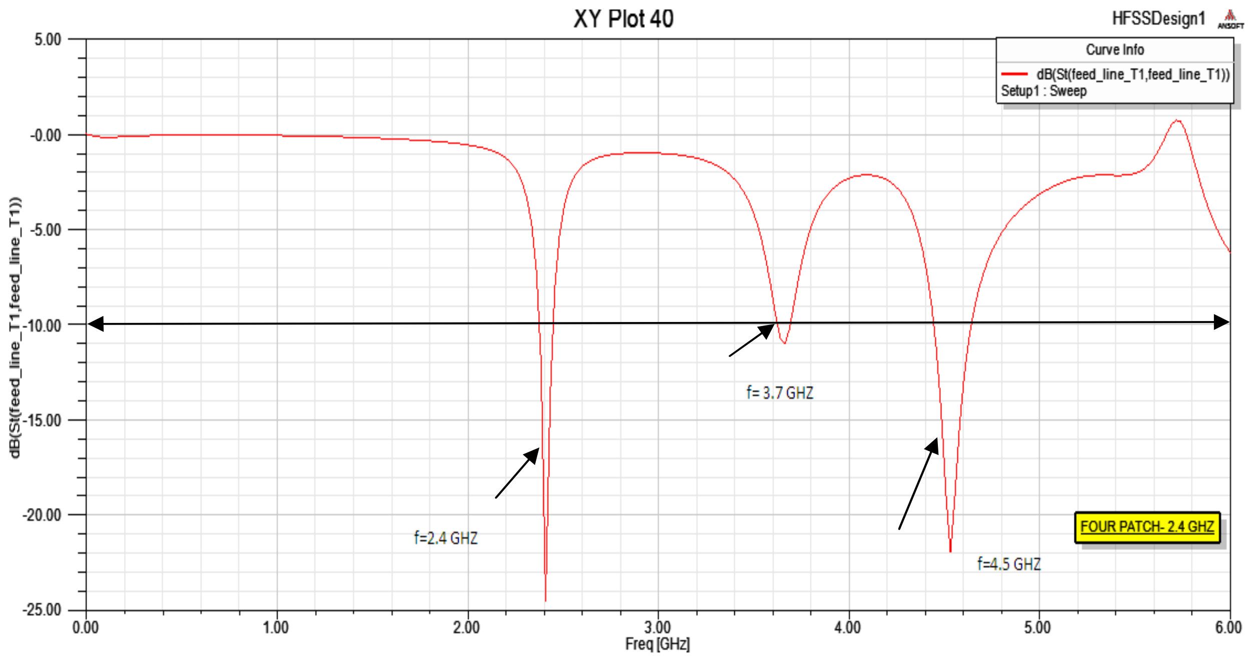

Fig.5.11 Return loss & Bandwidth

5.3.2.3 VOLTAGE STANDING WAVE RATIO (VSWR)

- Voltage Standing Wave Ratio is defined as a measurement of the mismatch between the load and the transmission line. For ideal case the value of VSWR is 1 and for better matching.

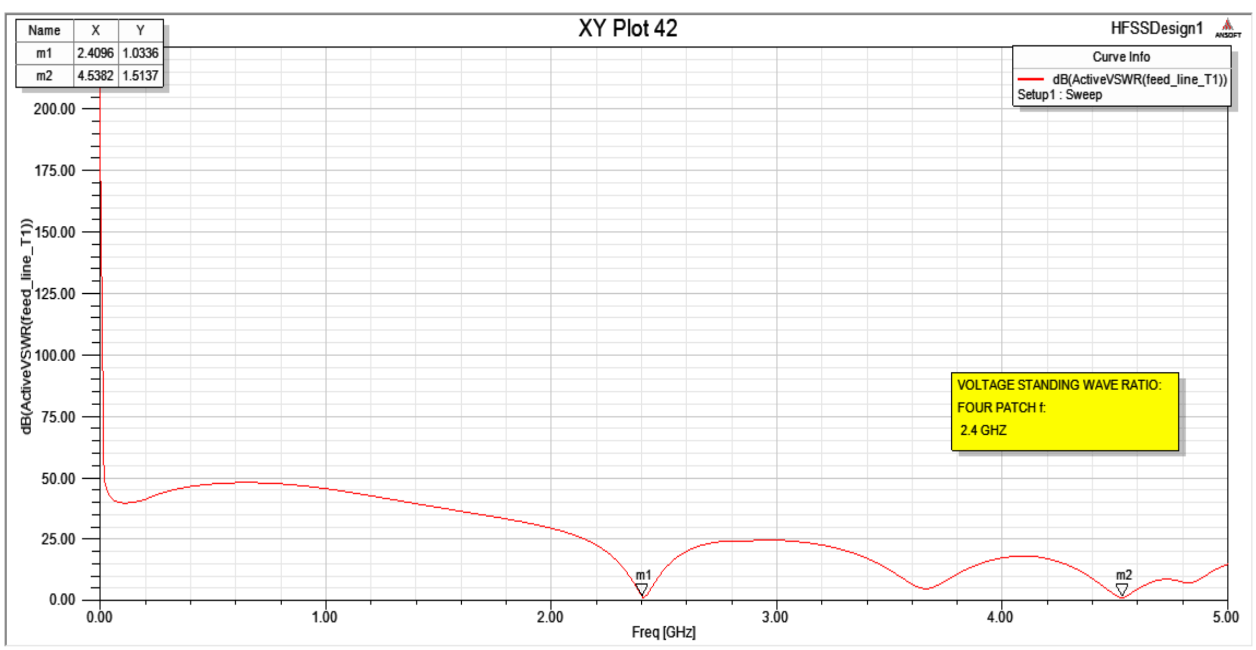

Fig.5.12 Voltage Standing Wave Ratio

- The voltage standing wave ratio at the frequency range of 2.4GHZ is 1.03 and 4.5 GHZ is 1.51.

5.3.2.4 DIRECTIVITY

The directive gain of an antenna is a measure of the concentration of the radiated power in a particular direction. It may be regarded as the ability of the antenna to direct radiated power in a given direction.

It is usually a ratio of radiation intensity in a given direction to the average radiation intensity. The maximum directive gain is called as the directivity of an antenna and is denoted by D.

The directivity of the single patch antenna is 5.71dB (absolute gain) and 7.56dB (Relative Gain).

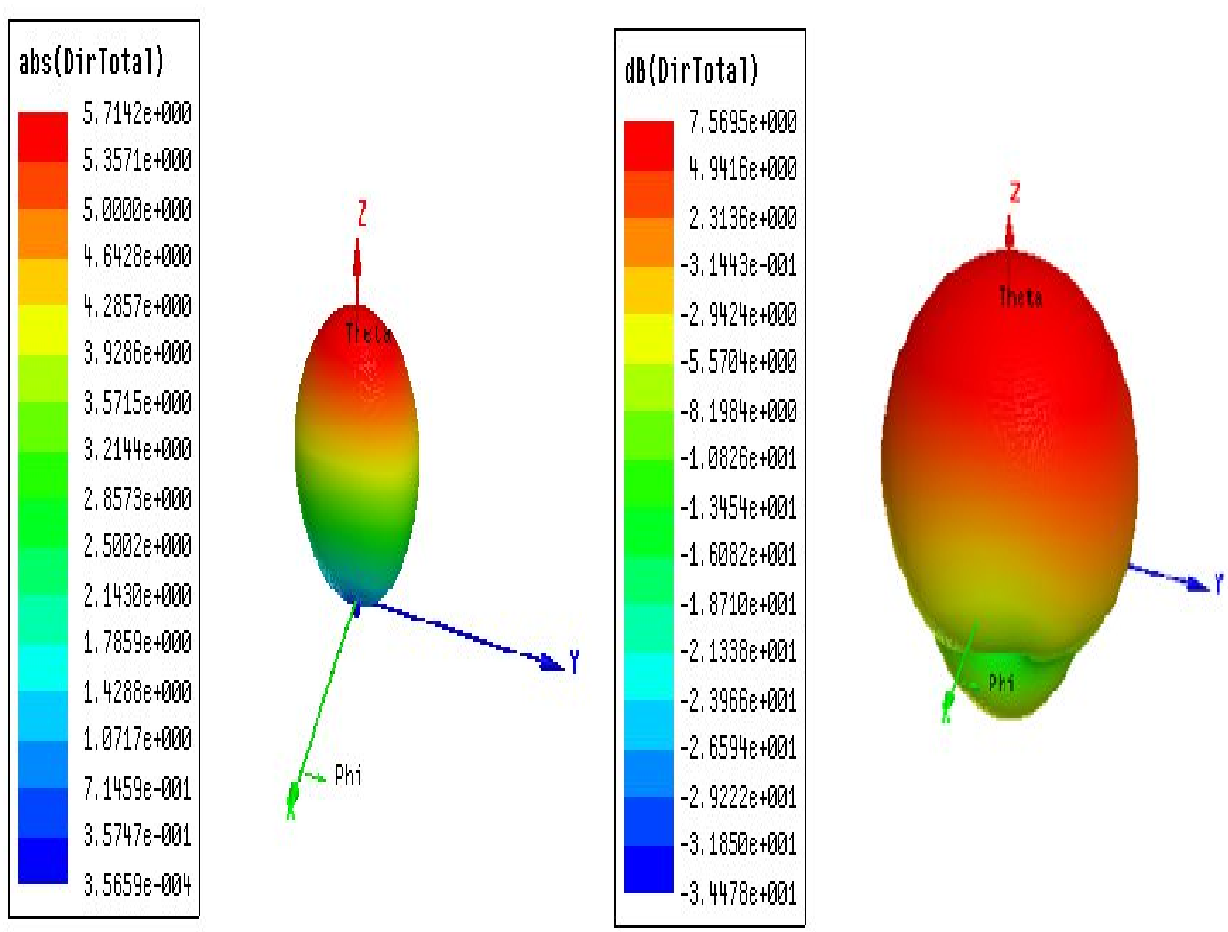

Fig.5.13 Directivity of Four Patch Antenna

5.3.2.5 RADIATION PATTERN

The radiation pattern is a graphical representation of the characteristics of an antenna radiation in a certain direction. The magnitude of the four patch antenna is 4.49dB.

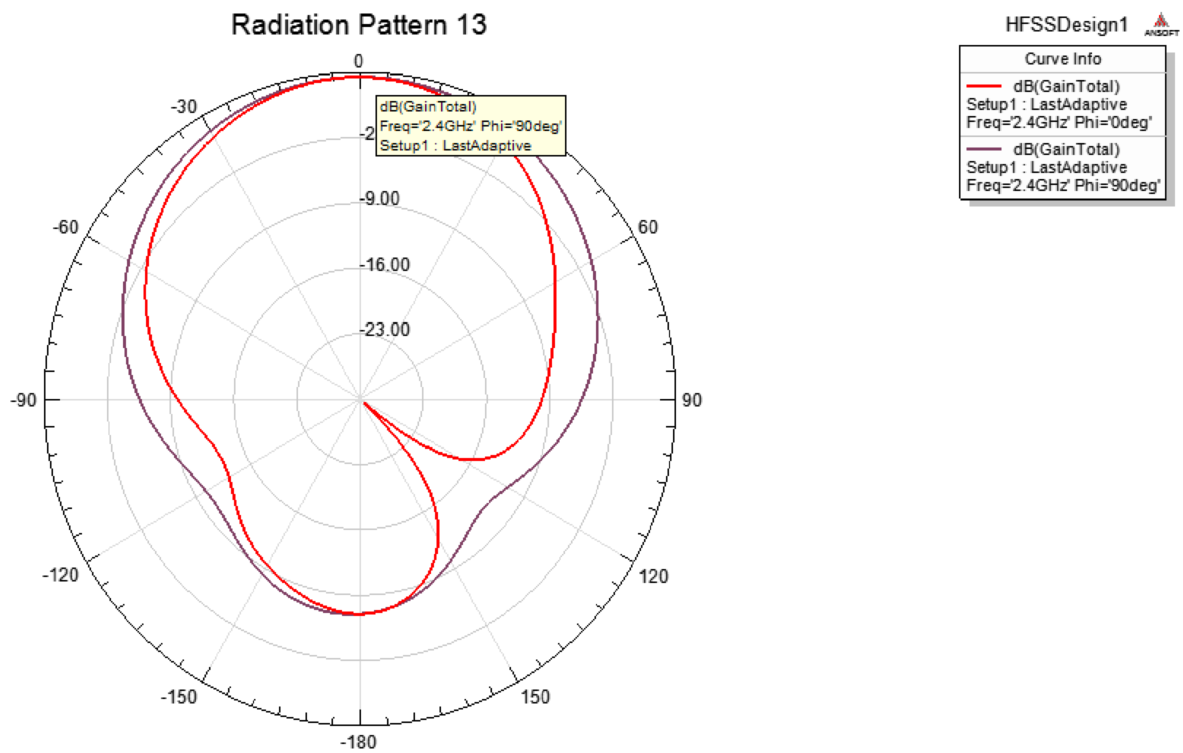

Fig.5.14 Radiation Pattern of Four Patch Antenna

TABLE.1 COMPARISION OF PATCH ANTENNA SIMULATION RESULTS

PARAMETERS	SINGLE PATCH	TWO PATCH	FOUR PATCH
RETURN LOSS	2.4GHZ: -21.5 dB 3.7GHZ: -12 dB 4.5GHZ: -19.5dB	2.4GHZ: -23.5 dB 3.7GHZ: -11 dB 4.5GHZ: -19.5dB	2.4GHZ: -24.5 dB 3.7GHZ: -11 dB 4.5GHZ: -22 dB
BANDWIDTH	2.4GHZ: 70MHZ 3.7GHZ: 90MHZ 4.5GHZ: 160MHZ	2.4GHZ: 90MHZ 3.7GHZ: 100MHZ 4.5GHZ: 180MHZ	2.4GHZ: 120MHZ 3.7GHZ: 110MHZ 4.5GHZ: 200MHZ
VOLTAGE STANDING WAVE RATIO	1.45	1.12	1.03
DIRECTIVITY	7.26dB	7.40dB	7.56dB
RADIATION PATTERN	2.4GHZ: 4.26 dB[0 deg,90 deg]	2.4GHZ: 4.33 dB[0 deg,90 deg]	2.4GHZ: 4.49 dB[0 deg,90 deg]

CHAPTER 6

CONCLUSION AND FUTURE WORK

6.1 CONCLUSION

The objective of this paper is to design a compact MIMO antenna system designed for a ISM Band applications. The system is operating on 2.4GHZ ISM Band frequency using HFSS. Two configuration of antenna array is proposed. The first configuration is the single antenna design structure. The second configuration is the four patch antenna design structure. Two patch antenna are separated at the distance is 0.162λ. The designed four patch antenna offer dual band of operation (2.4GHZ & 4.5GHZ). The designed antenna structure operated at various frequency band like 2.4GHZ, 3.7GHZ and 4.5GHZ. MIMO systems offer an increased capacity. This requires a complex design and problems associated with mutual coupling need to be taken care of otherwise they create huge interference. The cost for designing the system is high. The applications are ISM band, WLAN and WiMAX. It provides better result in terms of Return loss, mutual coupling.

6.2 FUTURE WORK

Furthermore MIMO antenna is designed using polarization diversity of the individual antenna which yields better result in terms of return loss and mutual coupling.

CHAPTER 7

REFERENCES

1. Harshal Nigam, Mithilesh Kumar, Design and analysis of 2X2 MIMO system for 2.4 GHz ISM band applications,International Journal of Advanced Research in Computer Engineering & Technology Vol.3 Issue 5 May 2014.
2. Waldschmidt, C. Kuhnert, S. Schulteis, and W. Wiesbeck, "Compact MIMO-Arrays Based on Polarization-Diversity" Proceedings of IEEE Antennas and Propagation. Symp., vol2 , pp. 499-502, June 2003.
3. Emami-Forooshani 1 S. Noghanian "Semi-deterministic channel model for MIMO systems Part-II: results " IET microwaves, antennas & propagation vol4 pp 26-34 2010
4. Zied Charaabi and Marc Testard , Optimized WiMAX MIMO antenna for base station applications with polarization and spatial diversity, Bell Labs Technical Journal Volume 16, Issue 1, pages 217–234, June 2011.
5. Dau-Chyrh Chang, Yi-Jhen Li, and Chao-Hsiang Liao, Antenna array for IEEE 802.11/a/b MIMO application, PIERS Proceedings, 100-102 Moscow, Russia, August 19-23, 2012.
6. M. A. Jensen, J. W. Wallace, "A review of antennas and propagation for MIMO wireless communications", IEEE Trans Antennas Propagation., vol. 52, pp. 2810-2824, Nov. 2004.
7. G.J.Foschini, "Layered space-time architecture for wireless communication in a fading environment when using multielement antennas," BLTJ, Autumn, 1996.
8. International Telecommunication Union. 19 October 2009. 1.15. "industrial, scientific and medical (ISM) applications (of radio frequency energy): Operation of equipment or appliances designed to generate and use locally radio frequency energy for industrial, scientific, medical, domestic or similar purposes, excluding applications in the field of telecommunications."
9. T. S. Rappaport, Wireless Communications Principles and Practice 2nd Edition. USA: Prentice Hall, 2002.
10. Balanis Constantine., "Antenna theory analysis and design", Third edition, a john wiley & sons, publication 2009.