“Design and Development of 4X4 Fractal MIMO Antenna For WIFI application”

4x4 HkXu MIMO d ,Vhuk d ljpuk vkj fodkl
okbQkb vui;kx d fy,

Rahul Choudhary

Thesis

Master of Technology

In

Electronics and Communication Engineering

(With Specialization in Communication Systems)

2015

DEPARTMENT OF ELECTRONICS AND COMMUNICATION ENGINEERING
COLLEGE OF TECHNOLOGY AND ENGINEERING
MAHARANA PRATAP UNIVERSITY OF AGRICULTURE AND TECHNOLOGY
UDAIPUR

MAHARANA PRATAP UNIVERSITY OF AGRICULTURE AND TECHNOLOGY

COLLEGE OF TECHNOLOGY AND ENGINEERING, UDAIPUR-313 001

Date: ………….

CERTIFICATE-I

This is to certify that **Mr. Rahul Choudhary** has successfully completed the comprehensive examination held on 17/12/2014 as required under the regulation for **Master of Technology** in **Electronics and Communication Engineering.**

Dr. Sunil Joshi
Professor & Head
Department of ECE
C.T.A.E., Udaipur

MAHARANA PRATAP UNIVERSITY OF AGRICULTURE AND TECHNOLOGY

COLLEGE OF TECHNOLOGY AND ENGINEERING, UDAIPUR-313 001

Date: …………

CERTIFICATE-II

This is to certify that this thesis entitled **"Design and Development of 4X4 Fractal MIMO Antenna For WIFI application"** submitted for the degree of **Master of Technology** in the subject of **Electronics and Communication Engineering** embodies bonafide research work carried out by **Mr. Rahul Choudhary** under my guidance and supervision and that no part of this thesis has been submitted for any other degree. The assistance and help received during the course of investigation have been fully acknowledged. The draft of the thesis was also approved by the advisory committee on 28/07/2015.

Dr. Sunil Joshi
Professor & Head
Department of ECE
C.T.A.E., Udaipur

Dr. Sunil Joshi
Major Advisor
C.T.A.E., Udaipur

Dr. B P Nandwana
Dean,
C.T.A.E., Udaipur

MAHARANA PRATAP UNIVERSITY OF AGRICULTURE AND TECHNOLOGY

COLLEGE OF TECHNOLOGY AND ENGINEERING, UDAIPUR-313 001

Dated: ………..

CERTIFICATE - III

This is to certify that this thesis entitled **"Design and Development of 4X4 Fractal MIMO Antenna For WIFI application"** submitted by **Mr. Rahul Choudhary** to the Maharana Pratap University of Agriculture and Technology, Udaipur in partial fulfillment of the requirements for the degree of **Master of Technology** in the subject of Electronics and Communication Engineering**,** after recommendation by the external examiner was defended by the candidate before the following members of the examination committee. The performance of the candidate in the oral examination was satisfactory; we therefore, recommend that the thesis be approved.

Dr. Sunil Joshi
Major Advisor

Dr. Navneet Agrawal
Co-Advisor

Dr. Naveen Chaudhary
Advisor

Dr. N.L. Panwar
DRI Nominee

Dr. Sunil Joshi
Head, Department of ECE
C.T.A.E.

Dr. B. P. Nandwana
Dean
C.T.A.E., Udaipur

Approved

DIRECTOR, RESIDENT INSTRUCTIONS
Maharana Pratap University of Agriculture and Technology
Udaipur (Rajasthan)

MAHARANA PRATAP UNIVERSITY OF AGRICULTURE AND TECHNOLOGY
COLLEGE OF TECHNOLOGY AND ENGINEERING, UDAIPUR-313 001

Dated: …………..

CERTIFICATE - IV

This is to certify that **Mr. Rahul Choudhary** student of **Master of Technology** in the subject of **Electronics and Communication Engineering,** Department of **Electronics and Communication Engineering**, has made all corrections/modifications in the thesis entitled **"Design and Development of 4X4 Fractal MIMO Antenna For WIFI application"** which were suggested by the external examiner and the advisory committee in the oral examination held on …..….. The final copies of the thesis duly bound and corrected were submitted on …… are enclosed for approval.

Dr. Sunil Joshi
Major Advisor
C.T.A.E., Udaipur

ABSTARCT

With the advent of practical implementation of multiple input multiple output technology, several constraints have come into picture, one of them is to define strategies to place multiple antennas on transmitter and receiver side in such a way, that they provide least interference with each other. The locations, at which the antennas are to be placed, are not always suitable to place multiple antennas at desired positions. To overcome this problem, MIMO antennas with low vertical beamwidth are designed and placed strategically inside a single radome. This solves the problem of placement of antennas to a great extent.

In this thesis to design such antenna, firstly a dual band microstrip antenna is designed which radiates efficiently in both the WLAN bands. This antenna is designed using a copper sheet of 0.5mm thickness. The dual band characteristics are achieved by cutting two slots in the sheet to create two dipoles, one for each frequency band.

This type of antenna solves the problem of location constraint, which is faced when multiple antennas are to be placed at transmitter and receiver side in such a way, that they provide least interference with each other. The locations, at which the antennas are to be placed, are not always suitable to place multiple antennas at desired positions. To overcome this problem, high gain MIMO antennas can be used which are capable of accepting input from multiple sources without causing interference with each other. This solves the problem of placement of antennas to a great extent

The aim of the research undertaken in this thesis is to develop a high gain fractal antenna which is able to cater with the needs of future communication standards for high data rates and reliable performance at the same time. The developed antennas solve the problem of location constraints of placing multiple antennas in a MIMO system.

सारांश

एकाधिक इनपुट एकाधिक आउटपुट प्रौद्योगिकी के व्यावहारिक कार्यान्वयन के आगमन के साथ, कई बाधाओं तस्वीर में आ गए हैं, उनमें से एक है कि वे कम से कम एक दूसरे के साथ हस्तक्षेप है कि उपलब्ध कराने, इस तरह से ट्रांसमीटर और रिसीवर के पक्ष में एकाधिक एंटेना स्थान के लिए रणनीतियों को परिभाषित करने के लिए है। एंटेना, रखा जा रहे हैं, जिस पर स्थानों, हमेशा वांछित पदों पर एकाधिक एंटेना स्थान के लिए उपयुक्त नहीं हैं। इस समस्या को दूर करने के लिए, कम ऊर्ध्वाधर **fcefoM~r** साथ **feeks** के एंटेना बनाया गया है और एक भी **js.Me** अंदर रणनीतिक रूप से रखा जाता है। यह काफी हद तक एंटेना की नियुक्ति की समस्या हल करती है।

इस शोध में दोनों WLAN के बैंड में कुशलता से jfM,Vl जो सबसे पहले एक दोहरी बैंड ekbØkLØhIV ऐन्टेना बनाया गया है इस तरह के एंटीना, डिजाइन करने के लिए। इस एंटीना 0.5 मिमी मोटाई का एक ताम्र पत्र का उपयोग कर बनाया गया है। दोहरी बैंड विशेषताओं दो द्विध्रुव, प्रत्येक आवृत्ति बैंड के लिए एक बनाने के लिए चादर में दो स्थान काटने से प्राप्त कर रहे हैं।

एंटीना की इस प्रकार एकाधिक एंटेना वे कम से कम एक दूसरे के साथ हस्तक्षेप है कि उपलब्ध कराने, इस तरह से ट्रांसमीटर और रिसीवर के पक्ष में रखा जा करने के लिए कर रहे हैं, जब सामना करना पड़ रहा है, जो पांच बाधा की समस्या हल करती है। एंटेना, रखा जा रहे हैं, जिस पर स्थानों, हमेशा वांछित पदों पर एकाधिक एंटेना स्थान के लिए उपयुक्त नहीं हैं। इस समस्या को दूर करने के लिए, उच्च लाभ feek के एंटेना एक दूसरे के साथ हस्तक्षेप के कारण के बिना कई स्रोतों से इनपुट को स्वीकार करने के लिए सक्षम हैं, जो इस्तेमाल किया जा सकता है। यह काफी हद तक एंटेना की नियुक्ति की समस्या का हल

इस शोध में किए गए शोध का उद्देश्य उच्च डेटा दरों में और एक ही समय में विश्वसनीय प्रदर्शन के लिए भविष्य संचार मानकों की जरूरतों के साथ पूरा करने में सक्षम है जो एक उच्च लाभ भग्न एंटीना विकसित करना है। विकसित एंटेना एक feek प्रणाली में एकाधिक एंटेना रखने के स्थान की कमी की समस्या का समाधान।

CHAPTER 1

INTRODUCTION

1.1 Antenna Background

Antenna (radio), also known as an aerial, a transducer designed to transmit or receive electromagnetic (e.g. TV or radio) waves. (N. Cohen, 19997) Television antenna (or TV aerial), is an antenna specifically designed for the reception of broadcast television signals. Antennae Galaxies, the name of two colliding galaxies NGC 4038 and NGC 4039. Antenna (biology), one of one or more pairs of appendages used for sensing in arthropods; also applied to cilium structures present in most eukaryote cell types. Antenna (journal), the journal of the Royal Entomological Society. The Institute of Electrical and Electronics Engineers (IEEE) defines an antenna as “that part of a transmitting or receiving system that is designed to radiate or receive electromagnetic waves”. (N. Cohen, 19997)

1.2 Why the need of using Antennas

With the continuously increasing number of users who connect to the Internet wirelessly, it has become a challenge to provide connectivity everywhere and that too with high data rates. Several measures have been taken to meet this increasing need of high speed connectivity. In 2009, IEEE defined the 802.11n standard for wireless data connections. According to this standard, the maximum possible speed for WLAN was increased to 600Mbps (IEEE, 2009). This standard also permits use of MIMO to improve data rate (IEEE, 2009).Along with the high data rate, there is also the requirement of providing connectivity at the places like hotels, offices, college campuses etc. with high quality service. To solve this problem, best solution is to install sector antennas within these areas. But the problem involved with installing sector antennas is that the locations, at which the antennas are to be placed, are not always suitable to place multiple antennas at desired positions. To overcome this problem, multi band MIMO sector antennas are designed which are capable of accepting input from multiple sources and work on a wide band of frequency.

1.3 Antenna Technology

- Antenna tower, a tall tower designed to support antennas (also known as aerials in the UK) for telecommunications and broadcasting.
- Dipole antenna, a simple antenna usually constructed from two wires in opposite phases placed end to end.
- Horn antenna, a type of directional antenna shaped like a horn.

- Metamaterial antenna, a class of antenna incorporating metamaterials to increase performance of a miniaturized (electrically small) antenna systems.
- Parabolic antenna, an antenna shaped like a parabola in one or both planes
- Power antenna (automotive) A power antenna is an electrically motorized automotive radio antenna that raises and lowers either manually with a dashmounted switch or automatically by turning the radio on or off.
- Antenna (film), a satirical 1969 Dutch film directed by Adriaan Ditvoorst.
- “Antenna”, an episode of the Adult Swim animated television series, Aqua Teen Hunger Force
- Antenna Awards, an annual awards ceremony thatrecognizes outstanding community television programs broadcast on Australia’s Channel 31 stations.

1.3.1 Antenna Broadcasting

- ANT1, a Greek-language terrestrial channel7
- Antena Internațional, a Romanian television channel
- Antena 1 (Romania), a Romanian television channel
- Antena 2 (Romania), a Romanian television channel
- Antena 3 (Romania), a Romanian television channel
- Antena 3 (Spain), a Spanish terrestrial television channel
- Antenna TV, a U.S. television channel established in 2011 by Tribune Broadcasting
- RDP Antena 1, Portuguese public radio station
- RDP Antena 2, Portuguese public radio station
- RDP Antena 3, Portuguese public radio station

1.4 Radio Wave

Radio wave is about the radiation. For the generic oscillation, see Radio frequency. For the electronics, see Radio frequency engineering. For other uses, see Radio Wave (disambiguation). Radio waves are a type of electromagnetic radiation with wavelengths in the electromagnetic spectrum longer than infrared light. Radio waves have frequencies from 300 GHz to as low as 3 kHz, and corresponding wavelengths ranging from 1 millimeter (0.039 in) to 100 kilometers (62 mi). Like all other electromagnetic waves, they travel at the speed of light. Naturally occurring radio waves are made by lightning, or by astronomical objects. (Karl Rawer, 1993)

Artificially generated radio waves are used for fixed and mobile radio communication, broadcasting, radar and other navigation systems, communications satellites, computer networks and innumerable other applications. Different frequencies of radio waves have different propagation characteristics in the Earth's atmosphere; long waves may cover a part of the Earth very consistently, shorter waves can reflect off the ionosphere and travel around the world, and much shorter wavelengths bend or reflect very little and travel on a line of sight. To prevent interference between different users, the artificial generation and use of radio waves is strictly regulated by law, coordinated by an international body called the International Telecommunications Union (ITU). The radio spectrum is divided into a number of radio bands on the basis of frequency, allocated to different uses. (Karl Rawer, 1993)

1.4.1 Radio propagation

The study of electromagnetic phenomena such as reflection, refraction, polarization, diffraction, and absorption is of critical importance in the study of how radio waves move in free space and over the surface of the Earth. Different frequencies experience different combinations of these phenomena in the Earth's atmosphere, making certain radio bands more useful for specific purposes than others.

1.4.2 Speed, wavelength and frequency

Radio waves travel at the speed of light. When passing through an object, they are slowed according to that object's permeability and permittivity. The wavelength is the distance from one peak of the wave's electric field to the next, and is inversely proportional to the frequency of the wave. The distance a radio wave travels in one second, in a vacuum, is 299,792,458 meters (983,571,056 ft) which is the wavelength of a 1 hertz radio signal. A 1 megahertz radio signal has a wavelength of 299.8 meters (984 ft). (Karl Rawer, 1993)

1.4.3 Radio communication

In order to receive radio signals, for instance from AM/FM radio stations, a radio antenna must be used. However, since the antenna will pick up thousands of radio signals at a time, a radio tuner is necessary to tune in a particular signal. This is typically done via a resonator (in its simplest form, a circuit with a capacitor, inductor, or crystal oscillator, but many modern radios use Phase Locked Loop systems). The resonator is configured to resonate at a particular frequency, allowing the tuner to amplify sine waves at that radio frequency and ignore other sine waves. Usually, either the inductor or the capacitor of the resonator is adjustable, allowing the user to change the frequency at which it resonates. (Karl Rawer, 1993)

1.5 Bandwidth (signal processing)

1.5.1 Overview

Bandwidth is a key concept in many telephony applications. In radio communications, for example, bandwidth is the frequency range occupied by a modulated carrier wave, whereas in optics it is the width of an individual spectral line or the entire spectral range. In many signal processing contexts, bandwidth is a valuable and limited resource. For example, an FM radio receiver’s tuner spans a limited range of frequencies. A government agency (such as the Federal Communications Commission in the United States) may apportion the regionally available bandwidth to broadcast license holders so that their signals do not mutually interfere. Each transmitter owns a slice of bandwidth, a valuable (if intangible) commodity.

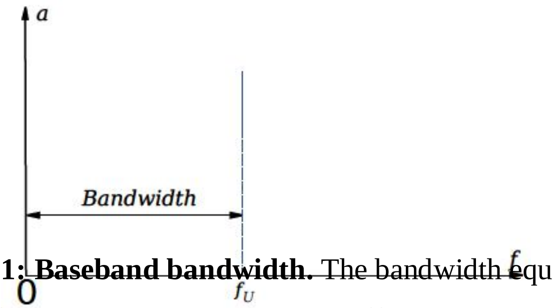


Fig.1.1: Baseband bandwidth. The bandwidth equals the upper frequency.

For different applications there are different precise definitions, which are necessarily different for signals than for systems. For example, one definition of bandwidth, for a system, could be the range of frequencies beyond which the frequency response is zero. This would correspond to the mathematical notion of the support of a function (i.e., the total “length” of values for which the function is nonzero). (Van Valkenburg, 2008) A less strict and more practically useful definition will refer to the frequencies beyond which frequency response is small. Small could mean less than 3 dB below the maximum value, or more rarely 10 dB below, or it could mean below a certain absolute value. Bandwidth is the difference between the upper and lower frequencies in a continuous set of frequencies. It is typically measured in hertz, and may sometimes refer to passband bandwidth, sometimes to baseband bandwidth, depending on context. Passband bandwidth is the difference between the upper and lower cutoff frequencies of, for example, a bandpass filter, a communication channel, or a signal spectrum. In the case of a low-pass filter or baseband signal, the bandwidth is equal to its upper cutoff frequency. (Van Valkenburg, 2008)

1.6 Radiation pattern

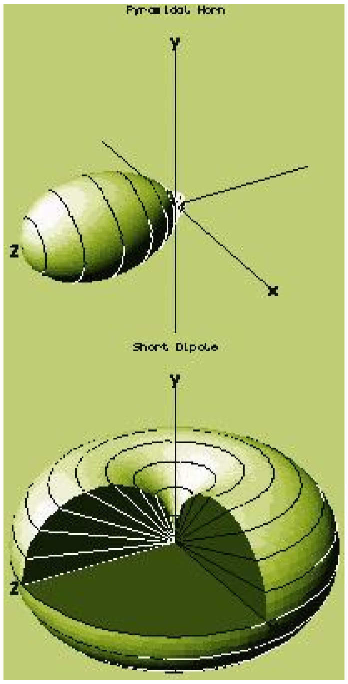


FIg. 1.2 : *Three-dimensional antenna radiation patterns. The radial distance from the origin in any direction represents the strength of radiation emitted in that direction. The top shows the directive pattern of a horn antenna, the bottom shows the omnidirectional pattern of a simple vertical antenna (Narren L., 1998).*

In the field of antenna design the term radiation pattern (or antenna pattern or far-field pattern) refers to the directional (angular) dependence of the strength of the radio waves from the antenna or other source. Particularly in the fields of fiber optics, lasers, and integrated optics, the term radiation pattern may also be used as a synonym for the near-field pattern or Fresnel pattern. This refers to the positional dependence of the electromagnetic field in the near-field, or Fresnel region of the source. The near-field pattern is most commonly defined over a plane placed in front of the source, or over a cylindrical or spherical surface enclosing it. (Warren L., 1998)

The far-field pattern of an antenna may be determined experimentally at an antenna range, or alternatively, the near-field pattern may be found using a near-field scanner, and the radiation pattern deduced from it by computation. The far-field radiation pattern can also be calculated from the antenna shape by computer programs such as NEC. Other software, like HFSS can also compute the near field. (Warren L., 1998)

The far field radiation pattern may be represented graphically as a plot of one of a number of related variables, including; the field strength at a constant (large) radius (an amplitude pattern or field pattern), the power perunit solid angle (power pattern) and the directive gain. Very often, only the relative amplitude is plotted, normalized either to the amplitude on the antenna boresight, or to the total radiated power. The plotted quantity may be shown on a linear scale, or in dB. The plot is typically represented as a three-dimensional graph (as at right), or as separate graphs in the vertical plane and horizontal plane. This is often known as a polar diagram. (Warren L., 1998)

1.6.1 Antenna Lobes

It is a fundamental property of antennas that the receiving pattern (sensitivity as a function of direction) of an antenna when used for receiving is identical to the far-field radiation pattern of the antenna when used for transmitting. This is a consequence of the reciprocity theorem of electromagnetics and is proved below. Therefore in discussions of radiation patterns the antenna can be viewed as either transmitting or receiving, whichever is more convenient.

1.6.2 Typical patterns

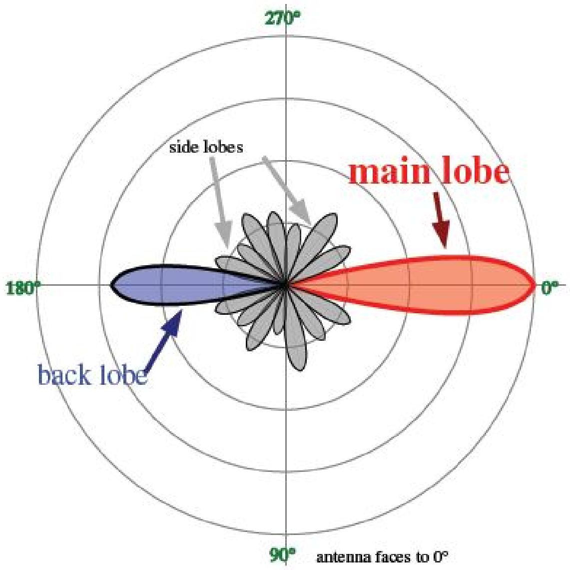


Fig. 1.3 : *Typical polar radiation plot. Most antennas show a pattern of "lobes" or maxima of radiation. In a directive antenna, shown here, the largest lobe, in the desired direction of propagation, is called the "main lobe". The other lobes are called "sidelobes" and usually represent radiation in unwanted directions.*

Since electromagnetic radiation is dipole radiation, it is not possible to build an antenna that radiates equally in all directions, although such a hypothetical isotropic antenna is used as a reference to calculate antenna gain. The simplest antennas, monopole and dipole antennas, consist of one or two straight metal rods along a common axis. These axially symmetric antennas have radiation patterns with a similar symmetry, called omnidirectional patterns; they radiate equal power in all directions perpendicular to the antenna, with the power varying only with the angle to the axis, dropping off to zero on the antenna ’ s axis. This illustrates the general principle that if the shape of an antenna is symmetrical, its radiation pattern will have the same symmetry. In most antennas, the radiation from the different parts of the antenna interferes at some angles. This results in zero radiation at certain angles where the radio waves from the different parts arrive out of phase, and local maxima of radiation at other angles where the radio waves arrive in phase. Therefore the radiation plot of most antennas shows a pattern of maxima called “ lobes ” at various angles, separated by "*nulls*" at which the radiation goes to zero.

The larger the antenna is compared to a wavelength, the more lobes there will be. In a directive antenna in which the objective is to direct the radio waves in one particular direction, the lobe in that direction is larger than the others; this is called the "*main lobe*".

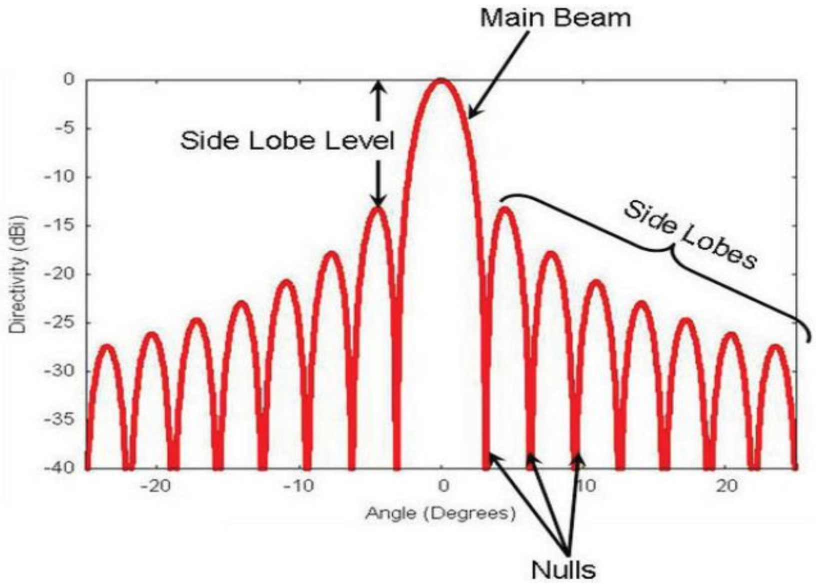


Fig. 1.4 *: A rectangular radiation plot, an alternative presentation method to a polar plot.*

The axis of maximum radiation, passing through the center of the main lobe, is called the "*beam axis*" or *boresight axis*". In some anten-nas, such as split-beam antennas, there may exist more than one major lobe. A minor lobe is any lobe except a major lobe. The other lobes, representing unwanted radiation in other directions, are called "*side lobes*". The side lobe in the opposite direction (180 °) from the main lobe is called the "*back lobe*". Usually it refers to a minor lobe that occupies the hemisphere in a direction opposite to that of the major (main) lobe. Minor lobes usually represent radiation in undesired directions, and they should be minimized. Side lobes are normally the largest of the minor lobes. The level of minor lobes is usually expressed as a ratio of the power density in the lobe in question to that of the major lobe. This ratio is often termed the side lobe ratio or side lobe level. Side lobe levels of −20 dB or smaller are usually not desirable in many applications. Attainment of a side lobe level smaller than −30 dB usually requires very careful design and construction. In most radar systems, for example, low side lobe ratios are very important to minimize false target indications through the side lobes.

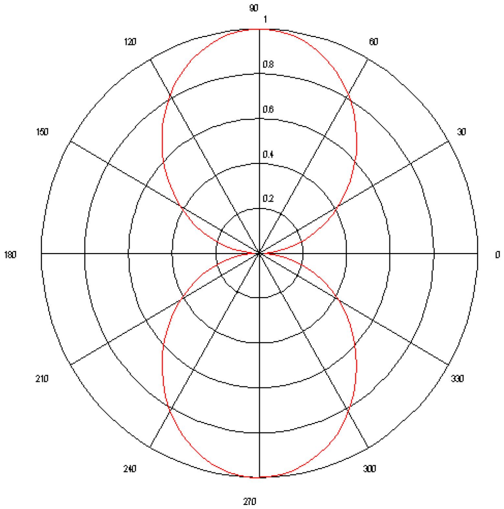


Fig. 1.5 : Radiation pattern of half-wave dipole antenna

On the basis of Radiation pattern, Antennas are classified as:

a. **Isotropic :** An antenna is isotropic, if the radiation pattern is the same in all directions. Antennas with isotropic radiation patterns don't exist in practice, but are sometimes discussed as a means of comparison with real antennas(Balanis, 2009). Fig. 1.6 shows the radiation pattern of a hypothetical isotropic antenna.

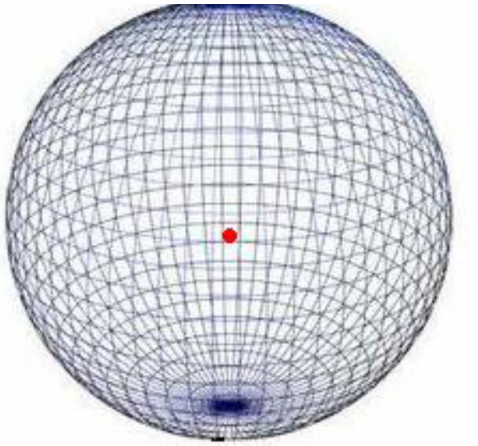


Fig. 1.6. : Radiation pattern of Isotropic antenna

b. **Omnidirectional:** An antenna is said to be omnidirectional, if the radiation pattern is isotropic in a single plane, i.e. they radiate uniformly in all directions in one plane, with the radiated power decreasing with elevation angle above or below the plane, dropping to zero on the antenna's axis. Examples of omnidirectional antennas include the dipole antenna and the slot antenna. Fig. 1.7 shows an omnidirectional radiation pattern.

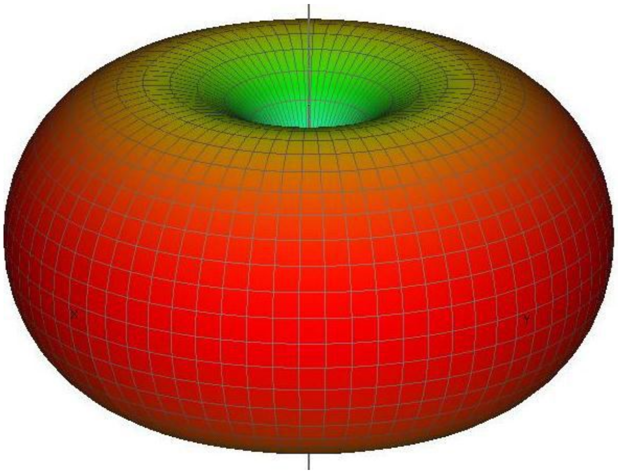


Fig. 1.7. : Radiation pattern of an omnidirectional antenna

1. 7.1 Directivity

In electromagnetics, directivity is a figure of merit for an antenna. It measures the power density the antenna radiates in the direction of its strongest emission, versus the power density radiated by an ideal isotropic radiator (which emits uniformly in all directions) radiating the same total power. An antenna's directivity is a component of its gain; the other component is its (electrical) efficiency. Directivity is an important measure because most emissions are intended to go in a particular direction or at least in a particular plane (horizontal or vertical); emissions in other directions or planes are wasteful (or worse). The directivity of an actual antenna can vary from 1.76 dBi for a short dipole, to as much as 50 dBi for a large dish antenna.

1. 7.1.1 Definition

The directivity, D, of an antenna is the maximum value of its directive gain. Directive gain is represented as$D(\theta;\phi)$, and compares the radiation intensity (power per unit solid angle) $U(\theta;\phi)$ that an antenna creates in a particular direction against the average value over all directions:

$$D(\theta, \phi) = \frac{U(\theta, \phi)}{P_{\text{tot}}/\,(4\pi)}$$

Here θ and ϕ are the standard spherical coordinate angles, U ($\theta;\phi$) is the radiation intensity, which is the power density per unit solid angle, and Plot is the total radiated power. The quantities U ($\theta;\phi$) and Plot satisfy the relation:

$$P_{\text{tot}} = \int_{\phi=0}^{\phi=2\pi} \int_{\theta=0}^{\theta=\pi} U \sin\theta \, d\theta \, d\phi;$$

that is, the total radiated power Ptot is the power per unit solid angle U(θ;ϕ) integrated over a spherical surface. Since there are 4π steradians on the surface of a sphere, the quantity Ptot/4 π represents the average power per unit solid angle. In other words, directive gain is the radiation intensity of an antenna at a particular (θ;ϕ) coordinate combination divided by what the radiation intensity would have been had the antenna been an isotropic antenna radiating the same amount of total power into space. Directivity, then, is the maximum directive gain value found among all possible solid angles:

$$\begin{aligned} D &= \max\left(\frac{U}{P_{\text{tot}}/\,(4\pi)}\right) \\ &= \frac{U(\theta, \phi)|_{\text{max}}}{\frac{1}{4\pi}\int_0^{2\pi}\int_0^{\pi} U(\theta, \phi) \sin\theta \, d\theta \, d\phi} \end{aligned}$$

The word directivity is also sometimes used as a synonym for directive gain. This usage is readily understood, as the direction will be specified, or directional dependence implied. Later editions of the IEEE Dictionary specifically endorse this usage; nevertheless it has yet to be universally adopted.

1.7.1.2 Relation to beam width

The beam solid angle, represented as ΩA , is defined as the solid angle which all power would flow through if the antenna radiation intensity were constant and maximum value. If the beam solid angle is known, then directivity can be calculated as:

$$D = \frac{4\pi}{\Omega_A}$$

...which simply calculates the ratio of the beam solid angle to the total surface area of the sphere it intersects. The beam solid angle can be approximated for antennas with one narrow major lobe and very negligible minor lobes, by simply multiplying the half-power beamwidth (in radians) in two perpendicular planes. The half-power beamwidth is simply the angle in which the radiation intensity is at least half of the peak radiation intensity. The same calculations can be performed in degrees rather than in radians:

$$D \approx 4\pi \frac{(\frac{180}{\pi})^2}{\Theta_{1d}\Theta_{2d}} = \frac{41253}{\Theta_{1d}\Theta_{2d}}$$

...where _1d is the half-power beamwidth in one plane (degrees) and_2d is the half-power beamwidth in a plane at a right angle to the other (degrees). In planar arrays, a better approximation is:

$$D \approx \frac{32400}{\Theta_{1d}\Theta_{2d}}$$

1.7.1.3 Expression in decibels

The directivity is rarely expressed as the unitless number D . Rather, the directivity is usually expressed as a decibel comparison to a reference antenna:

$$D_{dB} = 10 \cdot \log_{10} \left[\frac{D}{D_{reference}} \right]$$

The reference antenna is usually the theoretical perfect isotropic radiator which radiates uniformly in all directions and hence has a directivity of 1. The calculation is therefore simplified to:

$$D_{dBi} = 10 \cdot \log_{10} \left[D \right]$$

Another common reference antenna is the theoretical perfect half-wave dipole which radiates perpendicular to itself with a directivity of 1.64:

$$D_{dBd} = 10 \cdot \log_{10} \left[\frac{D}{1.64} \right]$$

1.7.1.4 Accounting for polarization

When polarization is taken under consideration, three additional measures can be calculated:

1.7.1.5 Partial directive gain

Partial directive gain is the power density in a particular direction and for a particular component of the polarization, divided by the average power density for all directions and all polarizations. For any pair of orthogonal polarizations (such as left-hand-circular and right-handcircular), the individual power densities simply add to give the total power density. Thus, if expressed as dimensionless ratios rather than in dB, the total directive gain is equal to the sum of the two partial directive gains.

1.7.1.6 Partial directivity

Partial directivity is calculated in the same manner as the partial directive gain, but without consideration of antenna efficiency (i.e. assuming a lossless antenna). It is similarly additive for orthogonal polarizations. (Coleman, 2004)

1.7.1.7 Partial gain

Partial gain is calculated in the same manner as gain, but considering only a certain polarization. It is similarly additive for orthogonal polarizations. Main article: Antenna gain. (Christopher, 2004)

1.8 Antenna aperture

In electromagnetics and antenna theory, antenna aperture or effective area is a measure of how effective an antenna is at receiving the power of radio waves. The aperture is defined as the area, oriented perpendicular to the direction of an incoming radio wave, which would intercept the same amount of power from that wave as is produced by the antenna receiving it. At any point, a beam of radio waves has an irradiance or power flux density (PFD) which is the amount of radio power passing through a unit area. If an antenna delivers an output power of Po watts to the load connected to its output terminals when irradiated by a uniform field of power density PFD watts per square metre, the antenna’s aperture Aeff in square metres is given by (Narayan, 2007)

$$A_{eff} = \frac{P_o}{PFD}$$

1.8.1 Aperture efficiency

In general, the aperture of an antenna is not directly related to its physical size. However some types of antennas, for example parabolic dishes and horns, have a physical aperture (opening) which collects the radio waves. In these aperture antennas, the effective aperture Aeff must always be less than the area of the antenna's physical aperture Aphys, as can be seen from the definition above. An antenna's aperture efficiency, e_a is defined as the ratio of these two areas:

$$e_a = \frac{A_{eff}}{A_{phys}}$$

The aperture efficiency is a dimensionless parameter between 0 and 1.0 that measures how close the antenna comes to using all the radio power entering its physical aperture. If the antenna were perfectly efficient, all the radio power falling within its physical aperture would be converted to electrical power delivered to the load attached to its output terminals, so these two areas would be equal *Aeff* = *Aphys* and the aperture efficiency would be 1.0. But all antennas have losses, such as power dissipated as heat in the resistance of its elements, non uniform illumination by its feed, and radio waves scattered by structural supports and diffraction at the aperture edge, which reduce the power output. Aperture efficiencies of typical antennas vary from 0.35 to 0.70 but can range up to 0.90. (Sophocles J. 2010)

1.9 Antenna efficiency

In antenna theory, antenna efficiency is a loose term usually meaning radiation efficiency, often abbreviated to efficiency. It is a measure of the efficiency with which a radio antenna converts the radio-frequency power accepted at its terminals into radiated power. (Sophocles J. 2010)

1.9.1 Definition

Radiation efficiency is defined by IEEE Std 145-1993 “Standard Definitions of Terms for Antennas” as “The ratio of the total power radiated by an antenna to the net power accepted by the antenna from the connected transmitter.” It is sometimes expressed as a percentage (less than 100), and is frequency dependent. It can also be described in decibels. For wire antennas which have a defined radiation resistance the radiation efficiency is the ratio of the radiation resistance to the total resistance of the antenna including ground loss and conductor resistance.

In practical cases the resistive loss in any tuning and/or matching network is often included, although network loss is strictly not a property of the antenna. For other types of antenna the radiation efficiency is less easy to calculate and is usually determined by measurements. The gain of an antenna is the directivity multiplied by the radiation efficiency, as described in Std 145-1993.

1.9.2 Ground loss

For monopole and other ground-based antennas, ground loss occurs due to ohmic resistance in the antenna's connection to its ground plane/counterpoise, including its mast or stalk and its bonding connections, as well as the ohmic resistance encountered by radio-frequency currents in the ground plane in the vicinity of the antenna.

1.9.3 Other definitions of efficiency in antennas

The IEEE standard defines several other antenna parameters which include the word efficiency, such as :

- Aperture illumination efficiency for apertureantennas.
- Polarization efficiency; polarization mismatch factor.
- These are unconnected and should not be confused with radiation efficiency, which is the most commonly used and implied term.

1.9.4 Aperture efficiency

This is applied to aperture antennas such as a parabolic antenna and is a measure of the reduction in power gain caused by non-uniform aperture illumination. In a typical situation the reflector is illuminated with a reduced power-density at the edge compared with the centre, in order to reduce sidelobes and other effects. This causes a reduction in gain: the ratio of the gain of the tapered aperture distribution to the theoretical gain of a uniformly illuminated aperture is the aperture efficiency. (Bakshi, K.A, 2009)

1.10 Polarization

An antenna will generate an electromagnetic wave that varies in time as it travels through space. If a wave traveling “outward” varies “up and down” in time with the electric field always in one plane, that wave (or antenna) is said to be linearly polarized (vertically polarized since the variation is up and down rather than side to side). Fig. 1.8 shows the locus of a linearly polarized wave at origin. If that wave rotates or “spins” in time as it travels through space, the wave (or antenna) is said to be elliptically polarized. As a special case, if that wave spins out in a circular path, the wave (or antenna) is circularly polarized. This implies that certain antennas are sensitive to particular types of electromagnetic waves.

Fig. shows the E-field variations of a circularly polarized wave.

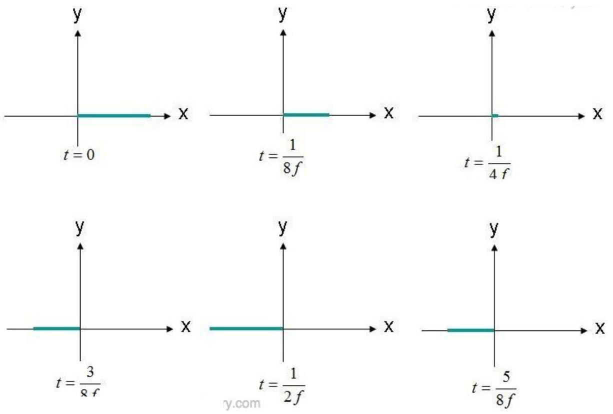


Fig. 1.8 : E-field strength at (x,y,z)=(0,0,0) for field of a linearly polarized wave

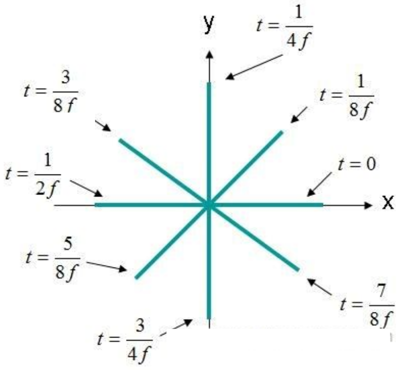


Fig. 1.9 : E-field strength at (x,y,z)=(0,0,0) for field of a circularly polarized wave

The practical implication of this concept is that antennas with the same polarization provide the best transmission/reception path (Jacob, 2008). This simple concept is important for antenna to antenna communication. First, a horizontally polarized antenna will not communicate with a vertically polarized antenna. Due to the reciprocity theorem, antennas transmit and receive in exactly the same manner. Hence, a vertically polarized antenna transmits and receives vertically polarized fields. Consequently, if a horizontally polarized antenna is trying to communicate with a vertically polarized antenna, there will be no reception. In general, for two linearly polarized antennas that are rotated from each other by an angle φ, the power loss due to this polarization mismatch will be described by the Polarization Loss Factor (PLF) (Likul, 2004).

$$PLF = cos^2\varphi \ldots \text{ (1)}$$

Hence, if both antennas have the same polarization, the angle between their radiated E-fields is zero and there is no power loss due to polarization mismatch. If one antenna is vertically polarized and the other is horizontally polarized, the angle is 90 degrees and no power will be transferred. If two antennas that are both circularly polarized, communicate with each other, they do not suffer signal loss due to polarization mismatch.

As a special case, If a linearly polarized antenna is trying to receive a circularly polarized wave, or equivalently, if a circularly polarized antenna is trying to receive a linearly polarized wave, the linearly polarized (LP) antenna will simply pick up the in-phase component of the circularly polarized (CP) wave. As a result,the linearly polarized antenna will have a polarization mismatch loss of 0.5 (-3dB), no matter what the angle the linearly polarized antenna is rotated to (Likul, 2004). Therefore:

PLF (Linear to Circular) = 0.5 = -3dB

The Polarization Loss Factor is sometimes referred to as polarization efficiency, antenna mismatch factor, or antenna receiving factor. All of these names refer to the same concept.

1.10.1 Half Power Beamwidth

In a plane containing the direction of maximum of a beam, the angle between the two directions in which the radiation intensity is one half the maximum value of the beam is called half power beamwidth. Fig. 1.10 shows a radiation pattern with its half power beamwidth

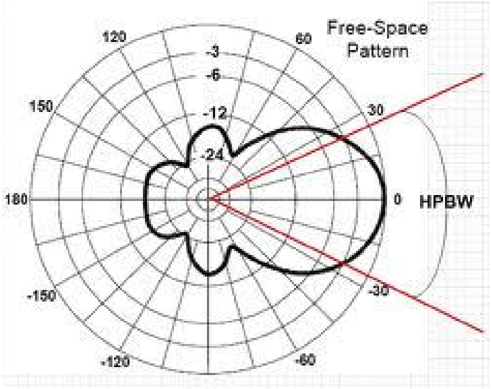


Fig. 1.10 : Half power beamwidth of a radiation pattern

When the beamwidth is measured in Horizontal plane it is Horizontal half power beamwidth. When the HPBW is measured in vertical plane, it is vertical half power beam width. (CISCO, 2008).

1.10.2 Voltage Standing Wave Ratio (VSWR)

When a transmitter is connected to an antenna by a feed line, the impedance of the antenna and feed line must match exactly for maximum energy transfer from the feed line to the antenna to be possible. The impedance of the antenna varies based on many factors including the antenna’s natural resonance at the frequency being transmitted, the antenna's height above the ground, and the size of the conductors used to construct the antenna. When an antenna and feed line do not have matching impedances, some of the electrical energy cannot be transferred from the feed line to the antenna. Energy not transferred to the antenna is reflected back towards the transmitter. It is the interaction of these reflected waves with forward waves which causes standing wave patterns. Voltage standing wave ratio (SWR) is the ratio of the amplitude of a partial standing wave at an antinode (maximum) to the amplitude at an adjacent node (minimum), in an electrical transmission line. Table 1 shows the fraction of transmitted power with VSWR(CISCO, 2008).

Table 1.1: Percentage of power transmitted with VSWR

VSWR	Power transmission
1.01	100%
1.10	99.8%
1.50	96.0%
2.10	88.9%
3.01	75.0%
8.72	36.5%
17.7	19.9%

1.10.3 Front to back ratio

For directional antennas, front to back ratio is an important parameter since it defines the ratio of peak power obtained in the main lobe to the power available just 180^{o} opposite to the main lobe. If the power is defined in dB, FBR is obtained by subtracting the two power levels (CISCO, 2008).

$$FBR = \frac{\text{Peak power in main lobe}}{\text{Peak power in back lobe}} \qquad \dots (2)$$

1.11 Near and far field

This article is about the electromagnetic concept. For the mathematical, see Near-field (mathematics). The near field (or near-field) and far field (or far-field)

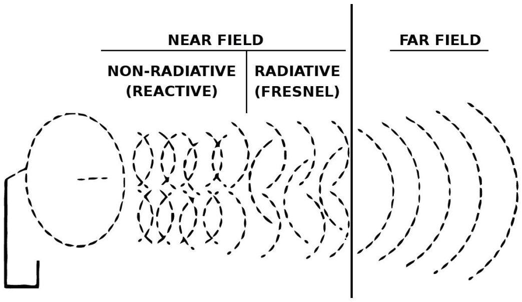


Fig. 1.11 : Differences between Fraunhofer diffraction and Fresnel diffraction

1.11.1 Summary of regions and their interactions

The boundary between the two regions is only vaguely defined, and it depends on the dominant wavelength (λ) emitted by the source. In the far-field region of an antenna, radiation decreases as the square of distance, and absorption of the radiation does not feed back to the transmitter. However, in the near-field region, absorption of radiation does affect the load on the transmitter. Magnetic induction (for example, in a transformer) can be seen as a very simple model of

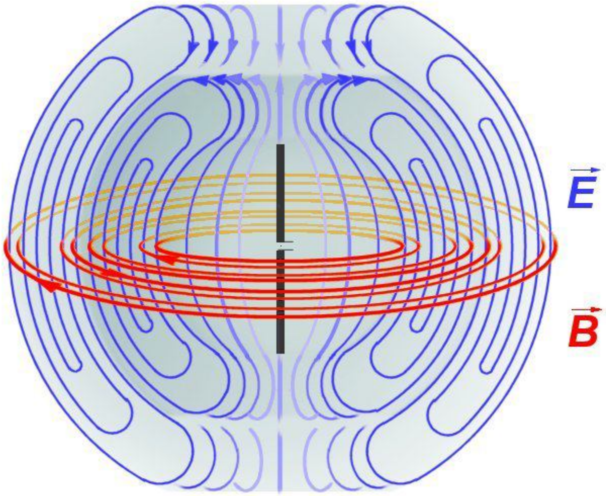


Fig 1.12 : Near-field: *This dipole pattern shows a magnetic field* $\vec{B}$ *in red. The potential energy momentarily stored in this magnetic field is indicative of the reactive near-field.*

In a normally-operating antenna, positive and negative charges have no way of leaving and are separated from each other by the excitation “ signal ” (a transmitter or other EM exciting potential). This generates an oscillating (or reversing) electrical dipole, which affects both the near-field and the far-field. In general, the purpose of antennas is to communicate wirelessly for long distances using far-fields, and this is their main region of operation (however, certain antennas specialized for near-field communication do exist). Also known as the radiation-zone field, the far-field carries a relatively uniform wave pattern. The radiation zone is important because far-fields in general fall off in amplitude by $1/r$. This means that the total energy per unit area at a distance r is proportional to $1/r2$.

The interaction with the medium (e.g. body capacitance) can cause energy to deflect back to the source, as occurs in the *reactive* near-field. Or the interaction with the medium can fail to return energy back to the source, but cause a distortion in the electromagnetic wave that deviates significantly from that found in a hard vacuum, and this indicates the *radiative* near-field region, which is somewhat further away. Another intermediate region, called the *transition zone*, is defined on a somewhat different basis, namely antenna geometry and excitation wavelength (CISCO, 2008).

1.11.2 Definitions

The term " near-field region " (also known as the " nearfield " or " near-zone ") has the following meanings with respect to different telecommunications technologies:

- The close-in region of an antenna where the angular field distribution is dependent upon the distance from the antenna.
- In the study of diffraction and antenna design, the near-field is that part of the radiated field that is below distances shorter than the Fraunhofer distance $df = 2D^2/\lambda$ from the source of the diffracting edge or antenna of longitude or diameter D.
- In optical fiber communications, the region near a source or aperture that is closer than the Rayleigh length. (Presuming a Gaussian beam, which is appropriate for fiber optics) Because of these nuances, special care must be taken when comprehending the literature about near-fields and far-fields.

1.11.3 Regions according to electromagnetic length

Electromagnetically short antennas

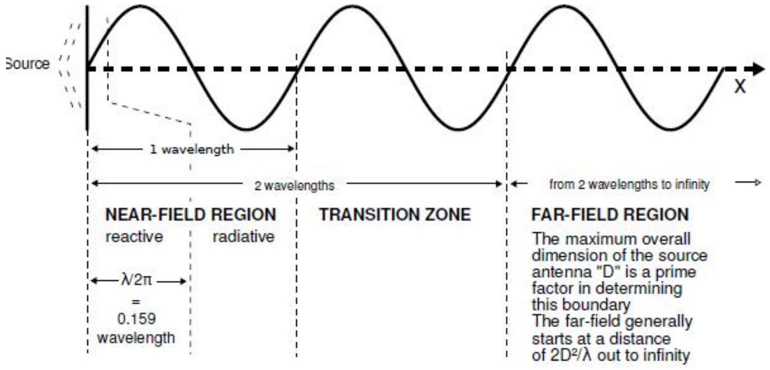


***Fig. 1.13:** Field regions for antennas equal to, or shorter than, one-half wavelength of the radiation they emit, such as the whip antenna of a citizen's band radio, or an AM radio broadcast tower.*

For antennas shorter than half of the wavelength of the radiation they emit (i.e., "electromagnetically short" antennas), the far and near regional boundaries are measured in terms of a simple ratio of the distance r from the radiating source to the wavelength λ of the radiation. For such an antenna, the near-field is the region within a radius (r □ λ), while the far-field is the region for which r □ 2λ. The transition zone is the region between r = λ and r = 2λ .

1. 12. Types of Antenna

1. Microstrip antenna
2. Fractal antenna
3. Horn antenna
4. Slot antenna
5. Wire Antenna
6. Log Periodic Antennas
7. Reflector antennas

1. 12.1 Microstrip antenna

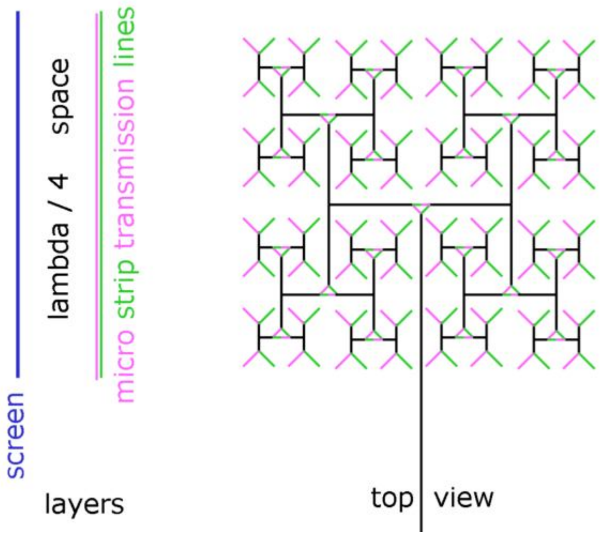


Fig. 1.14

In telecommunication, there are several types of **microstrip antennas** (also known as **printed antennas**) the most common of which is the **microstrip patch antenna** or patch antenna

1. 12.1.1 Patch antenna

Fabricated by etching the antenna element pattern in metal trace bonded to an insulating dielectric substrate, such as a printed circuit board, with a continuous metal layer bonded to the opposite side of the substrate which forms a ground plane. 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 are 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. (Di Nallo, 2005)

1. 12.1.2 Advantages

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. A single patch antenna provides a maximum directive gain of around 6-9 dBi. It is relatively easy to print an array of patches on a single (large) substrate using lithographic techniques. 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. (Di Nallo, 2005)

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 feedpoint with asymmetric patch structures. This unique property allows patch antennas to be used in many types of communications links that may have varied requirements. (Di Nallo, 2005)

1.12.1.3 Rectangular patch

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. (Di Nallo, 2005)

1.12.1.4 Specifications

The dielectric loading of a microstrip antenna affects both its radiation pattern and impedance bandwidth. As the dielectric constant of the substrate increases, the antenna bandwidth decreases which increases the Q factor of the antenna and therefore decreases the impedance bandwidth. This relationship did not immediately follow when using the transmission line model of the antenna, but is apparent when using the cavity model which was introduced in the late 1970s by Lo et al. The radiation from a rectangular microstrip antenna may be understood as a pair of equivalent slots. These slots act as an array and have the highest directivity when the antenna has an air dielectric and decreases as the antenna is loaded by material with increasing relative dielectric constant. The half-wave rectangular microstrip antenna has a virtual shorting plane along its center. This may be replaced with a physical shorting plane to create a quarterwavelength microstrip antenna. This is sometimes called a half-patch. The antenna only has a single radiation edge (equivalent slot) which lowers the directivity/gain of the antenna. The impedance bandwidth is slightly lower than a half-wavelength full patch as the coupling between radiating edges has been eliminated (Di Nallo, 2005).

1.12.1.5 Other types

Another type of patch antenna is the Planar Inverted-F Antenna (PIFA). The Planar Inverted-F antenna (PIFA) is common in cellular phones (mobile phones) with builtin antennas. The antenna is resonant at a quarterwavelength (thus reducing the required space needed on the phone), and also typically has good SAR properties. This antenna resembles an inverted F, which explains the PIFA name. The Planar Inverted-F Antenna is popular because it has a low profile and an omnidirectional pattern. The PIFA is shown from a side view in Figure 4. These antennas are derived from a quarterwave half-patch antenna. The shorting plane of the halfpatch is reduced in length which decreases the resonance frequency. Often

PIFA antennas have multiple branches to resonate at the various cellular bands. On some phones, grounded parasitic elements are used to enhance the radiation bandwidth characteristics. The Folded Inverted Conformal Antenna (FICA) has some advantages with respect to the PIFA, because it allows a better volume reuse (Di Nallo, 2005).

1.12.2 Fractal antenna

A **fractal antenna** is an antenna that uses a fractal, selfsimilar design to maximize the length, or increase the perimeter (on inside sections or the outer structure), of material that can receive or transmit electromagnetic radiation within a given total surface area or volume. Such fractal antennas are also referred to as multilevel and space filling curves, but the key aspect lies in their repetition of a motif over two or more scale sizes, or “ iterations ” . For this reason, fractal antennas are very compact, multiband or wideband, and have useful applications in cellular telephone and microwave communications. A good example of a fractal antenna as a spacefilling curve is in the form of a shrunken fractal helix. Here, each line of copper is just a small fraction of a wavelength. A fractal antenna ’ s response differs markedly from traditional antenna designs, in that it is capable of operating with good-to-excellent performance at many different frequencies simultaneously. Normally standard antennas have to be “ cut ” for the frequency for which they are to be used–and thus the standard antennas only work well at that frequency. This makes the fractal antenna an excellent design for wideband and multiband applications. In addition the fractal nature of the antenna shrinks its size, without the use of any components, such as inductors or capacitors. (N. Cohen, 2002)

1.12.2.1 Fractal element antennas and performance

Antenna elements (as opposed to antenna arrays) made from self-similar shapes were first created by Nathan Cohen then a professor at Boston University, starting in 1988. Cohen's efforts with a variety of fractal antenna designs were first published in 1995 (Cohen N., 1995) (thus the first scientific publication on fractal antennas), and a number of patents have been issued from the 1995 filing priority of invention. Most allusions to fractal antennas make reference to these "fractal element antennas". Many fractal element antennas use the fractal structure as a virtual combination of capacitors and inductors.

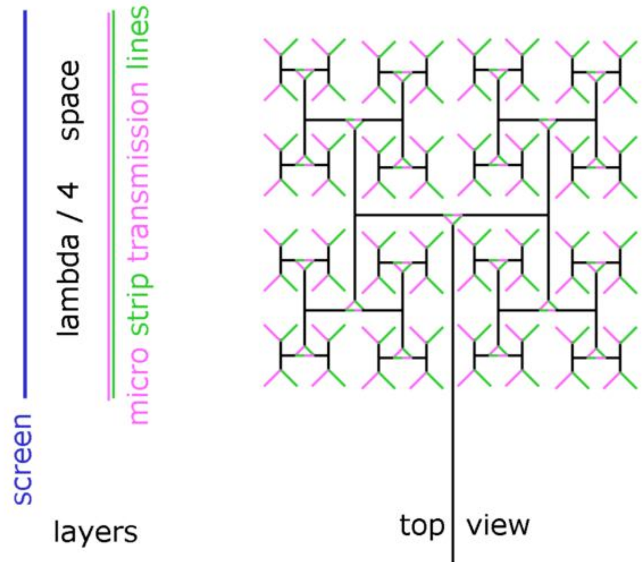


Fig. 1.15 : A planar array fractal antenna

This makes the antenna so that it has many different resonances which can be chosen and adjusted by choosing the proper fractal design. This complexity arises because the current on the structure has a complex arrangement caused by the inductance and self capacitance. In general, although their effective electrical length is longer, the fractal element antennas are themselves physically smaller, again due to this reactive loading. Thus fractal element antennas are shrunken compared to conventional designs, and do not need additional compo-nents, assuming the structure happens to have the desired resonant input impedance. In general the fractal dimension of a fractal antenna is a poor predictor of its performance and application. Not all fractal antennas work well for a given application or set of applications. Computer search methods and antenna simulations are commonly used to identify which fractal antenna designs best meet the need of the application. Although the first validation of the technology was publishedas early as 1995, recent independent studies show advantages of the fractal element technology in reallife applications, such as RFID and cell phones (Reneez A., 2012).

One researcher has stated to the contrary that fractals do not perform any better than "meandering line" (essentially, fractals with only one size scale, repeating in translation) antennas. Specifically quoting researcher Steven Best: “ Differing antenna geometries, fractal or otherwise, do not, in a manner different than other geometries, uniquely determine the EM behavior of the antenna. ” (Best,S, 2003). However, in the last few years, dozens of studies have shown superior performance with fractals, (Reneez A., 2012) and the below reference of frequency invariance conclusively demonstrates that geometry is a key aspect in uniquely determining the EM behavior of frequency independent antennas (Reneez A., 2012).

1.12.2.2 Fractal antennas, frequency invariance, and Maxwell's equations

A different and also useful attribute of some fractal element antennas is their self-scaling aspect. In 1957, V.H. Rumsey presented results that angle-defined scaling was one of the underlying requirements to make antennas "invariant" (have same radiation properties) at a number, or range of, frequencies. Work by Y. Mushiake in Japan starting in 1948 demonstrated similar results of frequency independent antennas having self complementarity. It was believed that antennas had to be defined by angles for this to be true, but in 1999 it was discovered that *self-similarity was one of the underlying requirements to make antennas frequency and bandwidth invariant*. In other words, the self-similar aspect was the underlying requirement, along with origin symmetry, for frequency 'independence'. Angle-defined antennas are self-similar,but other self-similar antennas are frequency independent although not angle-defined.

This analysis, based on Maxwell ' s equations, showed fractal antennas offer a closed-form and unique insight into a key aspect of electromagnetic phenomena. To wit: the invariance property of Maxwell ' s equations. This is now known as the HCR Principle. Mushiake's earlier work on self complementarity was shown to be limited to impedance smoothness, as expected from Babinet's Principle, but not frequency invariance.

- **Sierpinski Gasket**

The triangular shaped fractal, Sierpinski gasket, is named after the Polish mathematicianwho first described its properties (Puente, 1998). With few exceptions, we typically use a single antenna (size) foreach application (frequency band) as depicted in figure 1.16. This structure, withsimilarity dimension about 1.58 (log 3 / log 2), is a common study among researchersin fractal antennas (Krzysztofik, 2009)

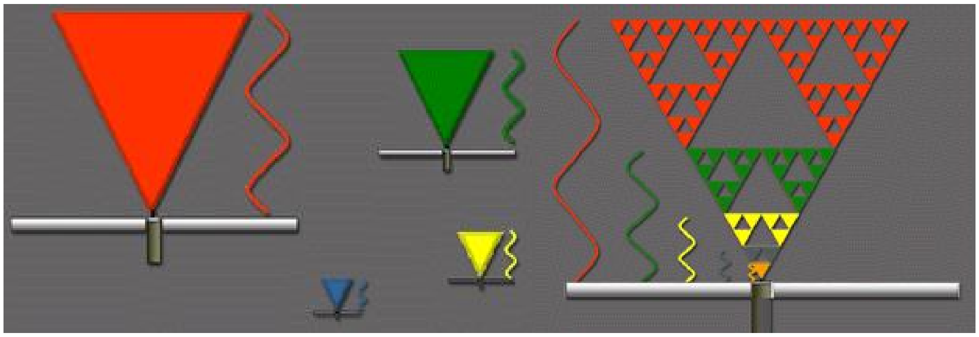


Fig. 1.16 : Sierpinski gasket pattern (N. Cohen, 1995)

- **The Von Koch Monopole Antenna**

The method of creating this shape is to repeatedly replace each line segment with the following 4 line segments. The process starts with a single line segment and continues for ever. The first few iterations of this procedure are shown in Figure 1.17 First five iterations in the construction of the Koch curve are illustrated. Fractal dimension contains information about the self-similarity and the space-filling properties.

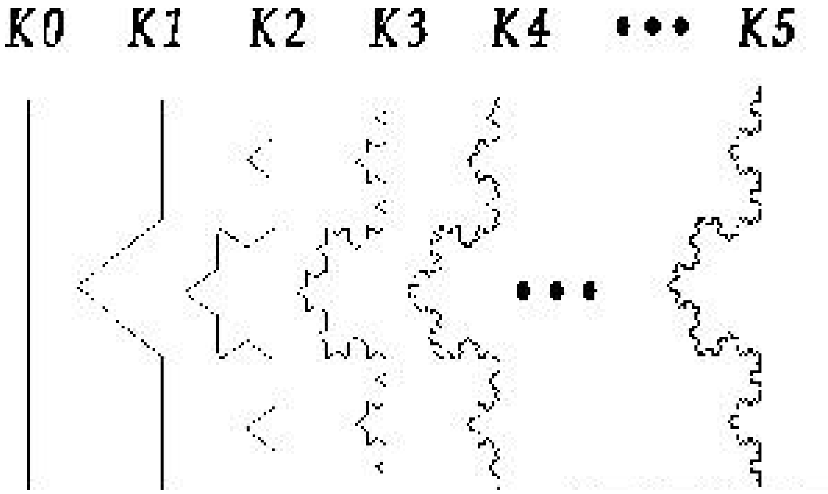


Fig 1.17 : Iterations of the Koch Curve (N. Cohen, 1995)

Where N is the total number of distinct copies, and (1/e) is the reduction factor value whichmeans how will the length of the new side be, with respect to the original side length. Fractalshapes thus are defined as self-similar shapes which are independent of size or scaling.

1.12.2.3 Other uses

In addition to their use as antennas, fractals have also found application in other antenna system components including loads, counterpoises, and ground planes. Confusion by those who claim " grain of rice"-sized fractal antennas arises, because such fractal structures serve the purpose of loads and counterpoises, rather than bona fide antennas.

Fractal inductors and fractal tuned circuits (fractal resonators) were also discovered and invented simultaneously with fractal element antennas. An emerging example of such is in metamaterials. A recent invention demonstrates using close-packed fractal resonators to make the first wideband metamaterial invisibility cloak at microwave frequencies (US patent 8,253,639). Peer reviewed publication may be found in the scholarly journal 'FRACTALS'.

Fractal filters (a type of tuned circuit) are another example where the superiority of the fractal approach for smaller size and better rejection has been proven (N. Cohen, 1995).

1.12.3 Horn antenna

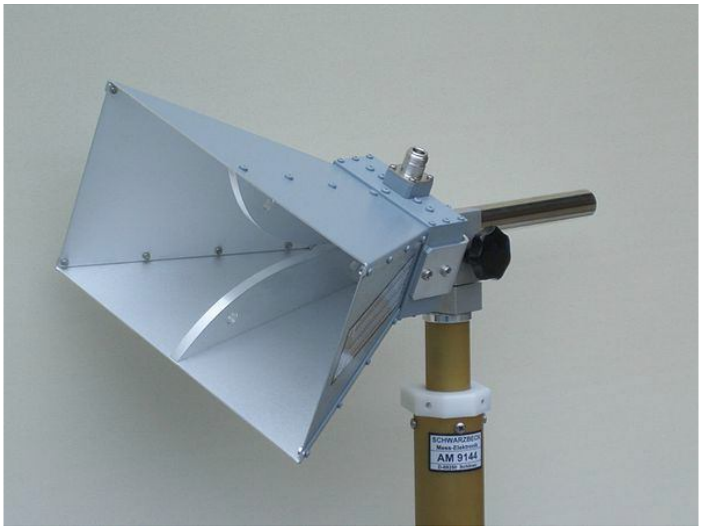


Fig. 1.18: *Pyramidal microwave horn antenna, with a bandwidth of 0.8 to 18 GHz. A coaxial cable feedline attaches to the connector visible at top. This type is called a ridged horn; the curving fins visible inside the mouth of the horn increase the antenna's bandwidth* (D.H. Werner, 2013)

An advantage of horn antennas is that since they have no resonant elements, they can operate over a wide range of frequencies, a wide bandwidth. The usable bandwidth of horn antennas is typically of the order of 10:1, and can be up to 20:1 (for example allowing it to operate from 1 GHz to 20 GHz). The input impedance is slowly varying over this wide frequency range, allowing low voltage standing wave ratio (VSWR) over the bandwidth. The gain of horn antennas ranges up to 25 dBi, with 10 - 20 dBi being typical (D.H. Werner, 2013).

1.12 3.1 Description

Waveguide (a metal pipe used to carry radio waves) outinto space, or collect radio waves into a waveguide for reception. It typically consists of a short length of rectangular or cylindrical metal tube (the waveguide), closed at one end, flaring into an open-ended conical or pyramidal shaped horn on the other end. The radio waves are usually introduced into the waveguide by a coaxial cable attached to the side, with the central conductor projecting into the waveguide to form a quarter-wave monopole antenna. The waves then radiate out the horn end in a narrow beam. In some equipment the radio waves are conducted between the transmitter or receiver and the antenna by a waveguide; in this case the horn is attached to the end of the waveguide. In outdoor horns, such as the feed horns of satellite dishes, the open mouth of the horn is often covered by a plastic sheet transparent to radio waves, to exclude moisture.

1.12.3.2 How it works

Fig. 1.19 : Corrugated conical horn antenna used as a feed horn on a Hughes Direcway home satellite dish. A transparent plastic sheet covers the horn mouth to keep out rain
(D.H. Werner, 2013)

A horn antenna serves the same function for electromagnetic waves that an acoustical horn does for sound waves in a musical instrument such as a trumpet. It provides a gradual transition structure to match the impedance of a tube to the impedance of free space, enabling the waves from the tube to radiate efficiently into space.

1.12.3.3 Radiation pattern

The waves travel down a horn as spherical wavefronts, with their origin at the apex of the horn, a point called the phase center. The pattern of electric and magnetic fields at the aperture plane at the mouth of the horn, which determines the radiation pattern, is a scaled-up reproduction of the fields in the waveguide. Because the wavefronts are spherical, the phase increases smoothly from the edges of the aperture plane to the center, because of the difference in length of the center point and the edge points from the apex point. The difference in phase between the center point and the edges is called the phase error. This phase error, which increases with the flare angle, reduces the gain and increases the beamwidth, giving horns wider beamwidths than similar-sized plane-wave antennas such as parabolic dishes. (Peter, 2009).

1.12.3.4 Types

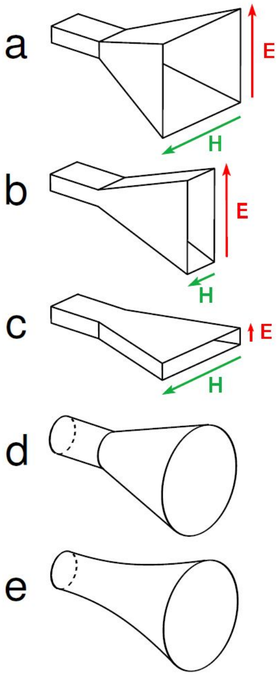


Fig. 1.20 : Horn antenna types

This list contains both the common types of horn antenna as well as more specialist types. Horns can have different flare angles as well as different expansion curves (elliptic, hyperbolic, etc.) in the E-field and H-field directions, making possible a wide variety of different beam profiles. (Peter, 2009).

1.12.3.5 Optimum horn

For a given frequency and horn length, there is some flare angle that gives minimum reflection and maximum gain. The internal reflections in straight-sided horns come from the two locations along the wave path where the impedance changes abruptly; the mouth or aperture of the horn, and the throat where the sides begin to flare out. The amount of reflection at these two sites varies with the *flare angle* of the horn (the angle the sides make with the axis). In narrow horns with small flare angles most of the reflection occurs at the mouth of the horn. The gain of the antenna is low because the small mouth approximates an open-ended waveguide. As the angle is in creased, the reflection at the mouth decreases rapidly and the antenna's gain increases. In contrast, in wide horns with flare angles approaching 90^0 most of the reflection is at the throat. The horn ' s gain is again low because the throat approximates an open-ended waveguide. As the angle is decreased, the amount of reflection at this site drops, and the horn ' s gain again increases. This discussion shows that there is some flare angle between 0 ° and 90 ° which gives maximum gain and minimum reflection. This is called the *optimum horn*. Most practical horn antennas are designed as optimum horns. In a pyramidal horn, the dimensions that give an optimum horn are: (Poole, 2010)

$$a_E = \sqrt{2\lambda L_E} \qquad a_H = \sqrt{3\lambda L_H}$$

For a conical horn, the dimensions that give an optimum horn are:

$$d = \sqrt{3\lambda L}$$

where

aE is the width of the aperture in the E-field direction

aH is the width of the aperture in the H-field direction

LE is the slant length of the side in the E-field direction

LH is the slant length of the side in the H-field direction.

d is the diameter of the cylindrical horn aperture

L is the slant length of the cone from the apex.

λ is the wavelength

1.12.3.6 Gain

Horns have very little loss, so the directivity of a horn is roughly equal to its gain. (Bevilaqua, 2009) The gain *G* of a pyramidal horn antenna (the ratio of the radiated power intensity along its beam axis to the intensity of an isotropic antenna with the same input power) is: (Narayan, 2007)

$$G = \frac{4\pi A}{\lambda^2} e_A$$

Large pyramidal horn used in 1951 to detect the 21 cm (1.43 GHz) radiation from hydrogen gas in the Milky Way galaxy. For conical horns, the gain is :

$$G = \left(\frac{\pi d}{\lambda}\right)^2 e_A$$

where

A is the area of the aperture,

d is the aperture diameter of a conical horn λ is the wavelength,

eA is a dimensionless parameter between 0 and 1 called the *aperture efficiency*.

1.12.3.7 Horn-reflector antenna

A type of antenna that combines a horn with a parabolic reflector is the Hogg or horn-reflector antenna, invented by Alfred C. Beck and Harald T. Friis in 1941 and further developed by David C. Hogg at Bell labs in 1961. It is also referred to as the " sugar scoop " due to its characteristic shape. It consists of a horn antenna with a reflector mounted in the mouth of the horn at a 45 degree angle so the radiated beam is at right angles to the horn axis. The reflector is a segment of a parabolic reflector, and the focus of the reflector is at the apex of the horn, so the device is equivalent to a parabolic antenna fed off-axis. (Meeks, 1976) The advantage of this design over a standard parabolic antenna is that the horn shields the antenna from radiation coming from angles outside the main beam axis, so its radiation pattern has very small sidelobes. Also, the aperture isn't partially obstructed by the feed and its supports, as with ordinary frontfed parabolic dishes, allowing it to achieve aperture efficiencies of 70% as opposed to 55-60% for front-fed dishes. (Meeks, 1976)

1.12.4 Slot antenna

A slot antenna consists of a metal surface, usually a flat plate, with a hole or slot cut out. When the plate is driven as an antenna by a driving frequency, the slot radiates electromagnetic waves in a way similar to a dipole antenna. The shape and size of the slot, as well as the driving frequency, determine the radiation distribution pattern. Often the radio waves are provided by a waveguide, and the antenna consists of slots in the waveguide. Slot antennas are often used at UHF and microwave frequencies instead of line antennas when greater control of the radiation pattern is required. Slot antennas are widely used in radar antennas, for the sector antennas used for cell phone base stations, and are often found in standard desktop microwave sources used for research purposes. A slot antenna ' s main advantages are its size, design simplicity, robustness, and convenient adaptation to mass production using PC board technology. The slot antenna was invented in 1938 by Alan Blumlein, while working for EMI. He invented it in order to produce a practical type of antenna for VHF television broadcasting that would have horizontal polarization, an omni-directional horizontal radiation pattern and a narrowvertical radiation pattern.

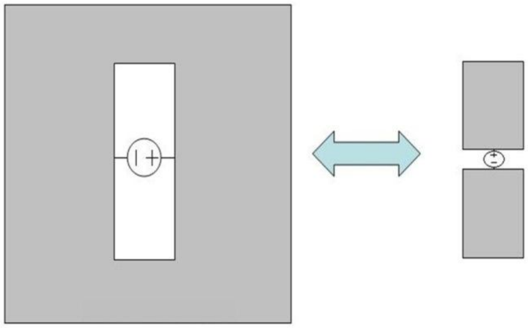


Fig. 1.21 : A Slot Antenna (left) and its Dual Antenna (right)

1.12.5 Wire Antenna

As the name suggests, Wire antennas are made up of a wires of suitable length. They serve the purpose of transmission and reception of a particular frequency based on the length of wire. Wire antennas can be further classified into following categories

1.12.5.1 Half Wave Dipole Antenna

A half wave dipole antenna is the simplest and most widely-used class of antenna. It consists of two identical conductive elements such as metal wires or rods, which are usually bilaterally symmetrical. The driving current from the transmitter is applied, or for receiving antennas the output signal to the receiver is taken, between the two halves of the antenna. Each side of the feed line to the transmitter or receiver is connected to one of the conductors.

Dipoles are resonant antennas, meaning that the elements serve as resonators, with standing waves of radio current flowing back and forth between their ends. So the length of the dipole elements is related to the wavelength of the radio waves used. In the half-wave dipole, each of the two rod elements is 1/4 wavelength long so the whole antenna is a half-wavelength long.

$$Z_{in} = 73 + j42.5\Omega \qquad \dots (3)$$

1.12.5.2 Monopole Antenna

A monopole antenna is one half of a dipole antenna, almost always mounted above some sort of ground plane. The case of a monopole antenna of length L mounted above an infinite ground plane is shown in Fig.

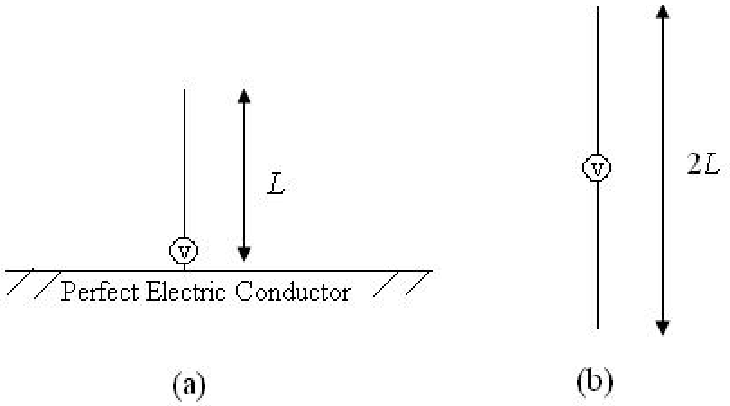


Fig. 1.22: Monopole above a PEC, (b) the equivalent source in free space

Using image theory, the fields above the ground plane can be found by using the equivalent source (antenna) in free space as shown in Fig. 1.22. This is simply a dipole antenna of twice the length. The fields above the ground plane in Fig. 1.22(a) are identical to the fields in Fig. 1.22(b). The monopole antenna fields below the ground plane in Fig.1.22(a) are zero. The radiation pattern of monopole antennas above a ground plane are also known from the dipole result. The only change that needs to be noted is that the impedance of a monopole antenna is one half of that of a dipole antenna. For a quarter-wave monopole ($L=0.25x\ \lambda$), the impedance is half of that of a half-wave dipole, so

$$Z_{in} = 36.5 + j21.25\Omega \qquad \ldots (4)$$

1.12.5 3 Folded Dipole Antenna

A folded dipole is a dipole antenna with the ends folded back around and connected to each other, forming a loop as shown in Fig.1.23.

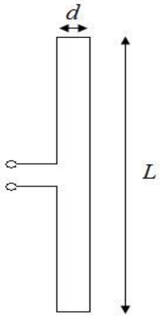


Fig. 1.23 : A Folded Dipole Antenna

Typically, the width'd' of the folded dipole antenna is much smaller than the length 'L'.

Because the folded dipole forms a closed loop, one might expect the input impedance to depend on the input impedance of a short-circuited transmission line of length 'L'. However, the folded dipole antenna can be imagined as two parallel short-circuited transmission lines of length 'L/2' (separated at the midpoint by the feed in Fig. 1.23). It turns out the impedance of the folded dipole antenna will be a function of the impedance of a transmission line of length 'L/2'.

The input impedance Z_A of the folded dipole is given by:

$$Z_A = \frac{4Z_t Z_d}{Z_t + 2Z_d} \qquad \dots (5)$$

Where Z_d is the impedance of a dipole antenna of length L and Z_t is the impedance of a transmission line impedance of length L/2.

The folded dipole antenna is resonant and radiates well at odd integer multiples of a half-wavelength (0.5λ, 1.5λ ...), when the antenna is fed in the center as shown in Fig. 1.11. Although it can be made resonant at even multiples of a half-wavelength (1.0λ, 2.0λ,...) by offsetting the feed of the folded dipole closer to the top or bottom edge of the folded dipole (Balanis, 2009).

1.12.6 Log Periodic Antennas

Log-Periodic antennas are designed for the specific purpose of having a very wide bandwidth. The achievable bandwidth is theoretically infinite; the actual bandwidth achieved is dependent on how large the structure is (to determine the lower frequency limit) and how precise the finer (smaller) features are on the antenna (which determines the upper frequency limit).

1.12.7 Reflector antennas

Reflector antennas use a metal surface to reflect the beam, either to focus it at one point, or to disperse it in the environment.

1.12.7.1 Parabolic Reflectors

The basic structure of a parabolic dish antenna is shown in Fig. 1.24. It consists of a feed antenna pointed towards a parabolic reflector. The feed antenna is often a horn antenna with a circular aperture.

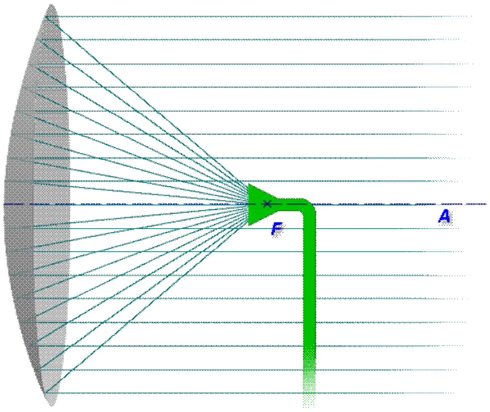


Fig. 1.24 A parabolic reflector antenna (D.H. Werner, 2013)

The parabola is completely described by two parameters, the diameter *D* and the focal length *F*. Other than this, there are two auxiliary parameters, the vertical height of the reflector (*H*) and the max angle between the focal point and the edge of the dish (θ_0). These parameters are related to each other by the following equations:

$$\frac{F}{D} = \frac{1}{4\tan\left(\frac{\theta_0}{2}\right)} \quad \ldots (6)$$

$$F = \frac{D^2}{16H} \quad \ldots (7)$$

Parabolic reflectors typically have a very high gain (30-40 dB is common) and low cross polarization. They also have a reasonable bandwidth, with the fractional bandwidth being at least 5% on commercially available models, and can be very wideband in the case of huge dishes.

The smaller dish antennas typically operate somewhere between 2 and 28 GHz. The large dishes can operate in the VHF region (30-300 MHz), but typically need to be extremely large at this operating band.

1.12.7.2 Sector Antenna

A sector antenna is a type of directional antenna which has a sector shaped radiation pattern. It is typically used in mobile phone base-stations. A sectorized system subdivides a cell area into different sectors with the help of sector antennas. This technique is called cell-sectoring. In cell sectoring, a single omnidirectional antenna is replaced by several sector antennas.

A sectored system is proved to be better than an omnidirectional system since each sector is treated as a different cell in the system. Thus the power can be focused onto a smaller area. Moreover, sectored systems can enhance the possibility of reusing a frequency channel by dropping interferences across the original cell. Typically 3 or 6 sector antennas of 120^0 or 60^0 horizontal beam width respectively are used to cover a cell (Rappaport, 2006). Fig. 1.25 shows the radiation patterns of a typical sector antenna.

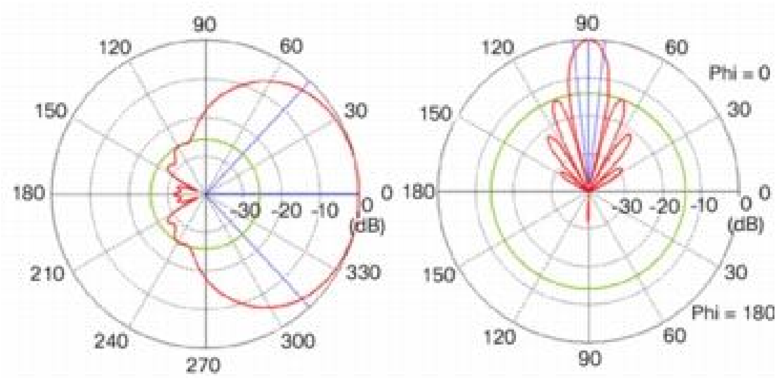


Fig. 1.25: Radiation patterns of a sector antenna

In a sectored system, capacity is largely increased by reducing the number of cells, leading to better frequency reuse. The interference is also greatly eliminated as, unlike in an omnidirectional system, only two neighboring cells interfere with the signal, whereas this number is six in case of an omnidirectional system (Balanis, 2009).

1.13 WLAN frequency bands

The IEEE 802.11 standard has been designated for wireless local area network (WLAN) service in 2.4 GHz (2400~2484 MHz) and 5 GHz (5150~5350/5725~5875 MHz) bands.

IEEE standards 802.11a,b,g,n are designated for WLAN applications with the following standards (IEEE notes, 2009).

- IEEE 802.11a : Wireless network bearer operating in the 5 GHz ISM band with data rate up to 54 Mbps
- IEEE 802.11b : Wireless network bearer operating in the 2.4 GHz ISM band with data rate up to 11 Mbps
- IEEE 802.11g : Wireless network bearer operating in the 2.4 GHz ISM band with data rate up to 54 Mbps
- IEEE 802.11n: Wireless network bearer operating in the 2.5GHz and 5 GHz ISM band with data rate up to 600 Mbps and use of multiple antennas.

CHAPTER 2

REVIEW OF LITERATURE

Suh *et al.*, (2006) presented a low profile, dual band WLAN antenna. The Antenna size is 36 mm (L) x 5.5 mm (W) x 1.5 mm (t) corresponding to the electrical size of 0.28 λ (L) x 0.04 λ (W) x 0.01 λ (t) at the lower resonant frequency of 2.4 GHz. A modified meander line was employed to tune the antenna to the desired frequency band at the required bandwidth. Strip lines inserted in the middle of the antenna element determine the operation in the upper band of antenna. The antenna was printed on FR4 dielectric material with a thickness of 1.5 mm. The antenna provides impedance bandwidth of 9.6% and 3% at low(2.38 ~ 2.62 GHz) and upper(5.34 ~ 5.5 GHz) bands respectively which does not cover the entire WLAN band. The antenna provides gain of 1.5 ~ 2.3 dBi over the two bands.

K.L. Wong *et al.* (2007) The antenna incorporates a small portion of the top patch beyond the top edge of the system ground plane of the mobile terminal, which results enhanced bandwidths of the two resonant modes for covering the GSM and DCS bands. The patch antenna which is mounted at the bottom end of the lower ground plane of the mobile phone, and can generate a wide operating band for UMTS operation.

G.Jaworski *et al.* (2008) presents a broadband matching of dual-linear polarization stacked probe-fed micro strip patch antenna. The authors present a novel approach for impedance matching of probe-fed stacked microstrip antenna elements. The matching structure is compact and enables more than doubling of the operational bandwidth. A circuit model for the feeding probes is also developed and its impact on antenna impedance is discussed. The matching circuit comprises coupled strip line structures and the antenna feeding probes are modeled carefully using an equivalent circuit model.

Amir Hossein Yamini *et al.* (2009) presented a bow-tie printed antenna. The paper explains the experimental and simulation results based on dipole antenna concepts and compared with the theoretical results based on FDTD. Antennas for the applications for WLAN/HIPERLAN/ISM triple band.

Yu-Seng Liu *et al.* (2009) presents a mender line antenna excited with inverted planar L-shaped structure which results three resonant modes.

Jingjing Huang *et al.* (2009) proposed multiband fractal patch antenna for the mobile applications. The characteristics of the novel fractal patch antenna is described by means of experimental and computational results and self-similarity properties of the fractal shape are translated into its multiband behavior.

Lafond *et al.* (2010) presents aperture coupled microstrip patch antenna with thick ground plane.The thickness has a strong effect on impedance matching at high frequencies owing to the ratio between the thickness and the wavelength, which increases with frequency. The ground plane thickness is a critical parameter in aperture coupled patch antennas at millimeter wave frequencies due to the reduction of the input impedance when the slot thickness becomes significant with respect to the wavelength. Finally, it appears that it is possible to design a slot fed patch on a thick ground plane which exhibits good impedance matching owing to the proper choice of slot length and patch size for a given ground plane thickness.

Mun *et al.*, (2010) presented a dual band antenna for WLAN. The dual band characteristic is achieved by feeding two different length resonant paths with a 50 Ω Microstrip line. The antenna is fabricated on RT/Duroid 5880 substrate with dielectric constant $\varepsilon r = 2.2$ and thickness of $h = 1.575$ mm. The proposed antenna composed of a meander monopole which accounts for lower band resonance and a planar monopole which resonates for higher band. The meander monopole consists of two horizontal strips of equal width and two unequal length vertical strips. These four strips are designed in such a way to form a resonant path at about quarter wavelength corresponding to 2.4 GHz. The lower band resonance is at 2.44 GHz with return loss of –28.87 dB, while the higher band resonance occurs at 5.21 GHz with return loss of –27.79 dB. Bandwidth (VSWR< 2.0) of 770 MHz (31.6%) and 1580 MHz (30.3%) is achieved at lower and higher resonance band, encompassing frequencies from 2.03 GHz – 2.80 GHz and 4.86 GHz – 6.44 GHz. the gain is above 6 dB throughout the lower resonance band from 2.03 GHz – 2.80 GHz. The gain at higher resonant frequency 5.21 GHz is found to be 2.12 dB and is fairly constant throughout the frequency range.

Su and Chang., (2010) presented a high-gain, three-antenna system suitable to be concealed inside wireless access points for multiple-input multiple-output (MIMO) applications in the WLAN bands. Each of the three antennas occupies a space with the dimensions 10 × 20 × 40 mm3 and is equally spaced along the perimeter of the ground plane. The antenna is situated next to another with the feeding portion facing the grounding portion of the following one. All the antennas are located 15 mm away from the vertex of the ground with equal inclination angles (formed by two adjacent vertices and the center) of 120°, and the center to the vertex is 60 mm long. The isolation between any two antennas is –15 and –20 dB over the 2.4 and 5.2/5.8 GHz bands respectively. Peak gain of about 7 dBi for the three operating bands, and directional radiation patterns in the elevation planes has been observed. The proposed multiple antennas are well suited for internal MIMO antennas embedded in a wireless AP for WLAN operation as a promising alternative to conventional, high-gain patch or Microstrip antennas.

Mark *et al.* (2010) presents the experimental study of a microstrip patch antenna with an L-shaped probe. The L shaped probe is shown to be an attractive feed for the thick microstrip antenna. A parametric study on the rectangular patch antenna is presented and the antenna attains 36% impedance bandwidth and about 7-dBi average gain. The array design with the same configuration can substantially suppress the cross polarization of the proposed antenna. Both the antennas have stable radiation patterns throughout the pass band.

H.Kan *et al.* (2011) in The antenna consists of a synchronous sub array of shorted patches with the required feed network etched on a high dielectric constant substrate located below the ground-plane of the antenna. The circularly polarized antenna has a return loss bandwidth of 8.5%, an axial ratio bandwidth of 11.3% and is relatively compact, with dimensions of 0.195 x 0.195 x 0.052 wave length.

Xuan Chen *et al.* (2011) discusses the dependence of the resonant frequency and input impedance of printed Hilbert antenna in [17]. A multi-band planar inverted-F antenna (PIFA) at UHF band is developed by adding lumped load and employing fractal concept and is presented by Hala Elsadek et al. in [18]. The authors achieved up to 68%-82% size reduction.

Hung Tien *et al* (2011) presents the effect of slot loading on microstrip patch antennas in. The Koch island fractal and H-shape slots are introduced to microstrip patch antennas and their effect on reduction of the resonant frequency is determined. Additional slots of more complex geometry are implemented on the H-shaped patch to further bring down its resonance frequency.

A substantial reduction in antenna size was achieved due to the use of the inverted-F antenna concept combined with a capacitive feeding system presented by Robert Borowiec et al. in. A miniaturized printed monopole antenna suitable for cellular handset terminals is presented which operates in three frequency bands, that is, GSM 1800, PCS 1900, and UMTS. A compact printed hook-shaped monopole antenna for 2.4/5-GHz WLAN.

Chi-Hun Lee *et al.* (2011) The proposed antenna is compact and the radiation patterns are nearly omni-directional in nature. Peng Sun et al. presents a novel compact antenna operating at GSM, DCS, PCS and IMT2000 bands in. A loosely coupled ground branch is used in the antenna, which covers all 2G and 3G wireless communication bands. A coplanar waveguide (CPW)-fed monopole antenna with dual folded strips for the radio frequency identification (RFID).

Cheng-Jung Lee Leong *et al.* (2012) presents a novel approach for the realization of compact antennas in. The antenna utilizes left handed mode of propagation of the composite right/left-handed transmission line. The propagation constant approaches infinity at frequencies near the cutoff and electrically large, small sized antenna can be realized depending on the unit cell optimization and miniaturization.

Liu *et al.*, (2012) The introduction of a suitable notch to a rectangular CPW-fed patch, the desired multi-frequency resonant modes and broad impedance bandwidths can be obtained. Wang-Sang Lee et al. developed a Multiple Band-Notched Planar Monopole Antenna for Wireless Systems in. The antenna consists of a wideband planar monopole antenna and the multiple U-shape slots, producing band-notched characteristics. A simple, low-cost, metal-plate dipole antenna for dual-band WLAN operation in the 2.4 GHz (2400-2484 MHz) and 5.2 GHz (5150-5350 MHz) bands. The dipole antenna has a planar structure stamped from a single metal plate only and comprises two radiating arms and a shorting strip that short-circuits both radiating arms. Furthermore, by cutting an L-shaped slit in each radiating arm, two separate operating bands can easily be achieved for dual-band operation. Better Omni directional radiation patterns for the 2.4 GHz operation can be also obtained, compared with compact coaxial-line-fed metal-plate PIFAs. The antenna is suitable to be assembled in corners of wireless electronics devices or PC peripherals for WLAN applications.

Sun *et al.*, (2012) presented a dual-band planar antenna with a compact radiator for 2.4/5.2/5.8GHz wireless local area network (WLAN) applications. The antenna consists of an L shaped and E shaped radiating elements to generate two resonant modes for dual-band operation. The L element fed directly by a 50Ω Microstrip line is designed to generate a frequency band at around 5.5 GHz to cover the two higher bands of the WLAN system (using the IEEE 802.11a standard). The E element is coupled-fed through the L element and designed to generate a frequency band at 2.44 GHz to cover the lower band of the WLAN system (using the 802.11b/g standards). As a result, the L and E elements together are very compact with a total area of only 8 x 11.3 mm^2. The antenna is fabricated on 40 x 30 x 0.8mm^3 substrate. The paper presented bandwidth and gain for varying dimensions of L and E shaped radiating elements. The suitable measured bandwidths (VSWR < 2.0) for the lower bandwas from 2.39 to 2.51 GHz and for the higher band was from 5 to 6.1 GHz, with both bands satisfying the requirements of the WLAN standards.

Jeong Geum Kim *et al.* (2012) a patch antenna using micromachining technology[103]. The radiating patch and the feed line network can be optimized separately with a substrate. The antenna performance is improved by elevating the patch in the air. A patch antenna is also designed with simle feed network. Since the proposed antenna allows the integration with MMICs, it can be applied for the system on chip(SOC) including an antenna at mm-wave frequency.

CHAPTER-3

CIRCULAR-RECTANGULAR MICROSTRIP ANTENNA

3.1 Antenna Design

This paper proposed triple-band printed circular-rectangular patch antenna. Initially circular patch antenna is designed for 2.4GHz and rectangular patch for 5.5 GHz. Then these two antennas are kept one inside the other and connected using small conducting strips called bridges. These bridges have a great impact in tuning the antenna to the required frequency band. The required resonance frequencies are obtained by parameter variation such as changing the bridge width or position [2].The rectangular patch antenna can be designed [5] using the equations as shown in Equations (l)-(5).

$$\varepsilon_{eff} = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2}\left(1+12\frac{W}{h}\right)^{0.5} \quad (1)$$

$$\Delta L = 0.412h\frac{(\varepsilon_{eff}+0.3)(\frac{W}{h}+0.264)}{(\varepsilon_{eff}-0.258)(\frac{W}{h}+0.8)} \quad (2)$$

$$L_{eff} = L + 2\Delta L \quad (3)$$

$$L_{eff} = \frac{c}{2f_r\sqrt{\varepsilon_{eff}}} \quad (4)$$

The dimensions of the circular patch (4) antenna can be determined using the Equations (6) - (7)

$$f_r = \frac{1.8412c}{2\pi a_e\sqrt{\varepsilon_r}} \quad (6)$$

$$a_e = a\left(\sqrt{1+\frac{2h}{\pi a\varepsilon_r}ln[\frac{\pi a}{2h}+1.7726]}\right) \quad (7)$$

The following are the details of notations used in all the above Equations (I) - (7).

f_r - resonant frequency(GHz)

c - speed of light(m/sec)

a_e - effective radius(mm)

ε_r - relative permittivity.

ε_{eff} - effective permittivity

h - thickness of the subsrVate(mm)

a - radius of patch (mm)

W - Width of the patch (mm)

L - extension of the length (mm)

L_{eff} - effective length of the patch(mm)

The calculated dimensions of these two antennas are listed in the Table 1.

Table 3.1 : Design Parameters

Antenna	Parameters	Dimensions
	Resonant Frequency	2.4GHz, 5.5 GHz
	Dielectric Constant	4.4
Rectangular Patch	Length of the patch	12.4mm
	Width of the patch	16.59mm
Circular Patch	Radius of the patch	17mm
Connecting Strip	Length of horizontal strip	6.5mm
	Length of vertical strip	3.25mm
Feed-	Length of the strip	15mm
	Width of the strip	2mm
Ground/Substrate plane	Length of the plane	40mm
	Width of the plane	50mm

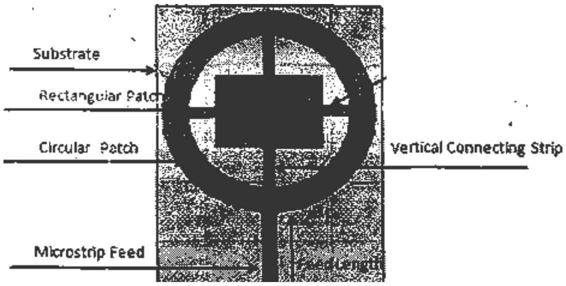


Fig. 3.1:- Structure of Initially Proposed Circular-Rectangular Antenna
(D.H. Werner, 2013)

The detailed parametric study of the design has been discussed in this section. This plays a vital role in obtaining the desired frequency with lower return loss and higher gain [5]. FR4-Epoxy was originally chosen as the substrate as it has a low loss tangent which will not reduce the antenna efficiency, and has a relatively low dielectric constant. Thick dielectric substrate with low dielectric constant provides better efficiency, larger bandwidth and better radiation, but it is against the low profile concept. However thickness variation is also considered in the optimization, in this paper. The simulation results of proposed antenna is discussed in the following sections.

The proposed antenna can be optimized in different stages to obtain the better performance. Mainly parametric analyses are considered in this design which are variation in number of bridges (strips), width of the bridge and substrate height. The analyses were carried out one by one.

A. Increased Number of Connecting Strips

In this stage circular patch and the rectangular patch are connected by using conducting strips called bridges. Initially one bridge was connected and the performance of antenna was analyzed. Similarly in consecutive steps, two, three and four strips were added. From this analyzes it is noted that when four bridges were used, the antenna exhibited better performance. Hence four such bridges were added at equal places at the inner part of the circular patch antenna so that the rectangular patch is fed through the same for connecting circular and rectangular patches, here the Figure 3.1, a comparison of the performance of antenna when number of connecting bridges were added hi consecutive steps is shown. With single connecting strip, the resonance frequency is 5GHz with a return loss value of -24dB. Then for two strips, the fr is 5.8 GHz with a return loss of -19dB. When three connecting strips were added, the return loss becomes- 22dB and the resonant frequency is 5GHz. The red colored line in the graph indicates that the antenna performance when four conducting strips were used. The return loss provided by this structure is very less when compared to the other structures with one, two and three connecting strips. It resonate at frequency of 2.6GHz and 5GHz with return loss of-25dB and -20dB.From the analysis, it is found that the structure performs well when four connecting strips are added. Hence the structure is retained for rest of the parametric analysis.

B. Variation in the width of the connecting strips

From here onwards the structure with four connecting strips is used for further analysis. In this section the width of the bridge is varied so as to determine the better resonance [8]. Variation of the bridge width from 0.5mm to 2.5mm was carried out in steps of 0.5mm. The simulation results are shown in Figure 3.2

From the return loss graph it is clear that when the bridges width is 1.5mm, it give reduced return loss and hence better performance. Thus, we fixed the width of the bridges with 1.5mm.

C) Variation in the thickness of the substrate

The next parametric analysis deals with varying the thickness of the substrate. To obtain better performance we will check the antenna with different substrate heights. The substrate height that was selected is 0.8mm, 1mm, 1.2mm and 1.6mm.

When substrate height is 0.8mm, the circular-rectangular antenna resonates for the designed resonate frequency. That is at frequency of 2.4 GHz and 5.5 GHz the antenna has a return loss of-16.8 dB and -16 dB. So for circular-rectangular antenna the height is fixed with 0.8mm.

3.2 Optimized Antenna

Based upon the variations in the elected parameters and the comparison and final results obtained the final optimized antenna is decided. Hence the antenna with four connecting bridges and each strip of width of 1.5mm and for the substrate thickness of 0.8mm provides better performance. Literature (D.H. Werner, 2013) says that introduction of slots improve the antenna performance in terms of reduced return loss and lowered resonant frequency. Hence, this concept is introduced by etching two arcs like slots and one circular slot on the antenna.

The Fig. 3.2 shows the final optimized design for circular-rectangular microstrip antenna. In this design the feed, patch and the ground plane is assigned copper material. The antenna performance is discussed in the below section.

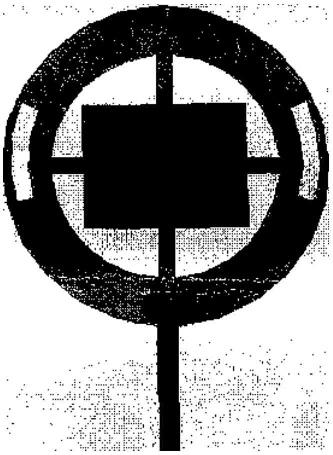


Fig. 3.2: The Structure of circular-rectangular patch Antenna

(C. Puente, 1997)

Circular-rectangular patch has been- developed for the triple band antennas in the wireless communication systems (C. Puente, 1997). Microstrip antenna has wide range of application in the field of mobile and satellite communication, RF1D (radio frequency identification), GPS (global positioning system) and in radar applications. It is widely used because of its low profile and lightweight. There was a recent development in wireless communication in order to convert IEEE WLAN (wireless local area network) standards in 2.4GHz and 5-6 GHz. Hence this paper introduces an antenna that can satisfy operations in all these frequency ranges. This triple-band antenna resonates at 2.4GHz, 5GHz and 5.5GHz (C. Puente, 1997).

The Wireless LAN IEEE 802. llb/g radios utilize the 2.4 GHz frequency band (2.412 - 2.472GHz) and the IEEE 802.1 la radio utilizes the 5.5 GHz frequency band (5.180 -5.825GHz). However, IEEE 802.1 In radios provide the possibility of operation in either frequency band. Till now, the use of the 5.5GHz band in industrial applications has been more or less limited to wireless applications such as smaller access points when compared to 2.4GHz band. As of now, more overlapping wireless channels exist in 2.4GHz band leading to interferences. However when the 5.5GHz band is used, there are some limitations (C. Puente, 1997) mainly with range covered. Particularly, the proposed antenna resonates in 5.5GHz with increased gain and hence it can cover longer range. Hence it can accommodate more non-overlapping channels when -used for smaller access point applications. Therefore this antenna is recommended for applications in various short range wireless devices (C. Puente, 1997).

The Fig. 3.3 shows the basic microstrip antenna structure. This antenna consists of radiating patch, dielectric substrate and a ground plane. The length and width of the patch is represented as L and W, h is the height of the substrate. The radiating patch is placed above the substrate and ground plane on the other side. The patch and ground are made of copper. There are different methods for feeding the antenna such as microstrip line feed, coaxial probe feed, aperture coupled feed and proximity coupled feed. For the improvement of the performance slots on the patch on the antenna structure can be made (N. Cohen, 1997).

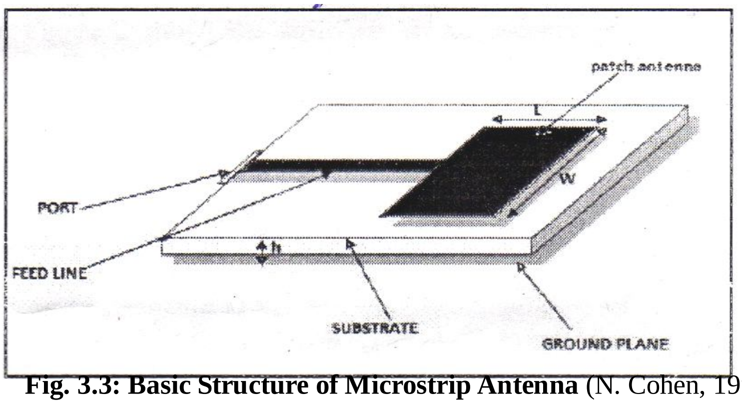


Fig. 3.3: Basic Structure of Microstrip Antenna (N. Cohen, 1997)

CHAPTER 4

FRACTAL ANTENNA DESIGN

4.1 Antenna Design

The metal plate dual band antenna is designed using a thin copper sheet. To design a dipole antenna, the design should be symmetric at both sides from center. In addition, the sum of length and breadth of each radiating arm should be equal to quarter or half wavelength of the operating frequency. In accordance with this fact, there should be two uneven arms acting as radiating arms. The dual band dipole antenna is thus designed using a copper strip having dimensions 39.5 mm (length) x 9.75 mm (width) x 0.5 mm (thickness) as shown in Fig. 1. The center portion of the strip is shorted with a strip. Two L- slots are cut into both the arms to create two radiating dipole arms. Dimensions of the two dipole arms are adjusted to 15.25 mm (length) x 1.85mm (width) and 13.25 mm (length) x 4.25 mm (width) for optimal performance. The antenna is fed using a SMA connector, connected to a 50Ω coaxial cable.

4.2 Software Design

The elementary antenna is designed and simulated using EMSS FEKO v 6.1. The software has different modules for designing and result analysis. CADFEKO is used for designing of the antenna and POSTFEKO is used to view the simulation results.

4.2.1 EMSS FEKO

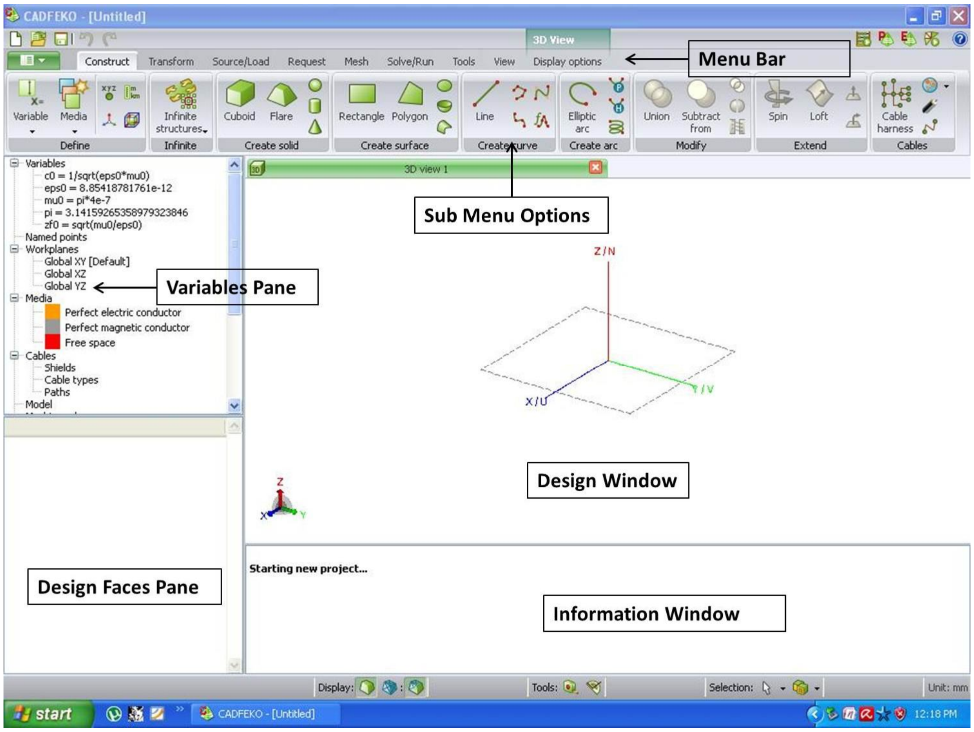
FEKO is a comprehensive electromagnetic simulation software tool, based on state of the art computational electromagnetics (CEM) techniques. It enables users to solve a wide range of electromagnetic problems.

The multiple solution techniques available within FEKO make it applicable to a wide range of problems for a large array of industries. Typical applications include:

- Antennas: analysis of horns, microstrip patches, wire antennas, reflector antennas, conformal antennas, broadband antennas, arrays
- Antenna placement: analysis of antenna radiation patterns, radiation hazard zones, etc. with an antenna placed on a large structure, e.g. ship, aircraft, armoured car
- EMC: analysis of diverse EMC problems including shielding effectiveness of an enclosure, cable coupling analysis in complex environments, e.g. wiring in a car, radiation hazard analysis

- Bio-electromagnetics: analysis of homogeneous or non-homogeneous bodies, SAR extraction
- RF components: analysis of waveguide structures, e.g. filter, slotted antennas, directional couplers
- 3D EM circuits: analysis of microstrip filters, couplers, inductors, etc.
- Radomes: analysis of multiple dielectric layers in a large structure
- Scattering problems: RCS analysis of large and small structures

4.2.1.1 User Interface



Variables
c0 = 1/sqrt(eps0*mu0)
eps0 = 8.85418781761e-12
mu0 = pi*4e-7
pi = 3.14159265358979323846
zf0 = sqrt(mu0/eps0)
Named points
Workplanes
Global XY [Default]
Global XZ
Global YZ
Media
Perfect electric conductor
Perfect magnetic conductor
Free space
Cables
Shields
Cable types
Paths
Model

Starting new project...

Fig. 4.1: Screenshot of EMSS CADFEKO with various interface units

Fig. 4.1 shows the screenshot of EMSS CADFEKO. The CADFEKO v6.1 Window can be divided into following parts

a) Menu Bar : The bar at the top with all the menu options. Clicking on these options will open subsequent submenu options.

b) Sub Menu Options: Just below the Menu bar, lies the sub menu pane. Here we can select all the options for creating, meshing and solving antenna designs.

c) Variables pane: This pane contains definition of all the variables in a design, inclusing the voltage, frequency and other design variables

d) Design Faces Pane: This pane displays the edges and faces of the antenna, which is designed in the design window. This pane is used to access properties of faces and edges of the antenna.

e) Information Window: This pane gives the information about processing and error messages while designing and simulating the antenna.

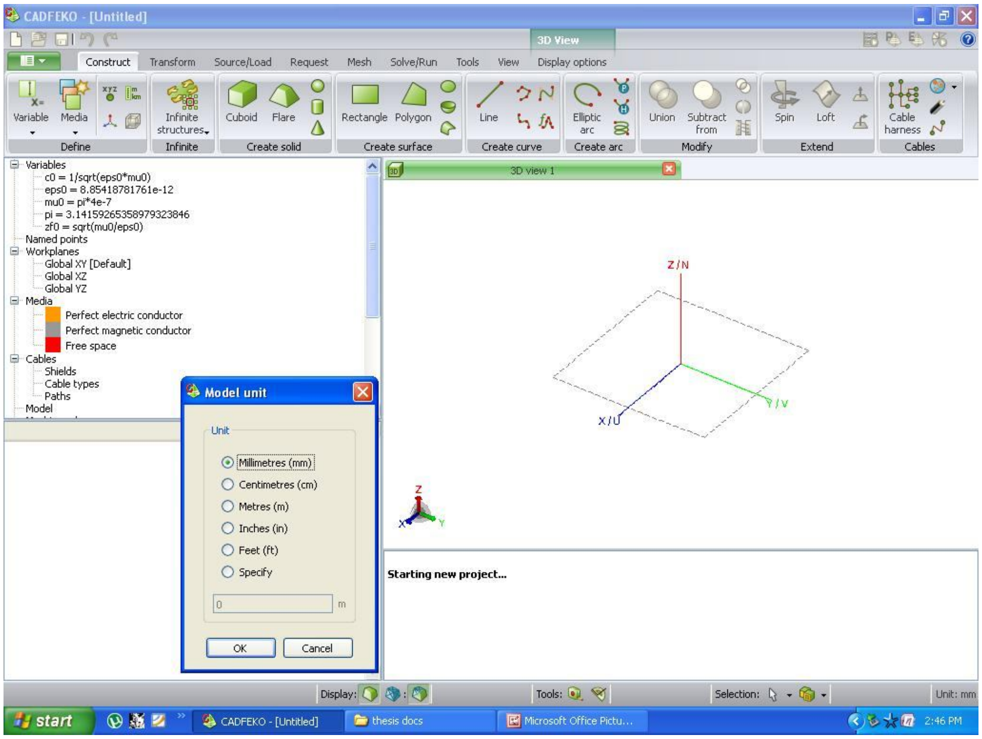
f) Design Window: This window is the workspace to create the required design. The design can be rotated in 3 dimensions with proper scaling features.

4.2.1.2 Design steps

Following are the design steps for creating the metal strip dipole antenna on CADFEKO v 6.1

1. Change the model unit

From the 'Construct' tab, select the model unit option and change the units to 'Millimeters (mm)'.



Variables
c0 = 1/sqrt(eps0*mu0)
eps0 = 8.85418781761e-12
mu0 = pi*4e-7
pi = 3.14159265358979323846
zf0 = sqrt(mu0/eps0)
Named points
Workplanes
Global XY [Default]
Global XZ
Global YZ
Media
Perfect electric conductor
Perfect magnetic conductor
Free space
Cables
Shields
Cable types
Paths
Model

Model unit

Unit
● Millimetres (mm)
○ Centimetres (cm)
○ Metres (m)
○ Inches (in)
○ Feet (ft)
○ Specify
0 m

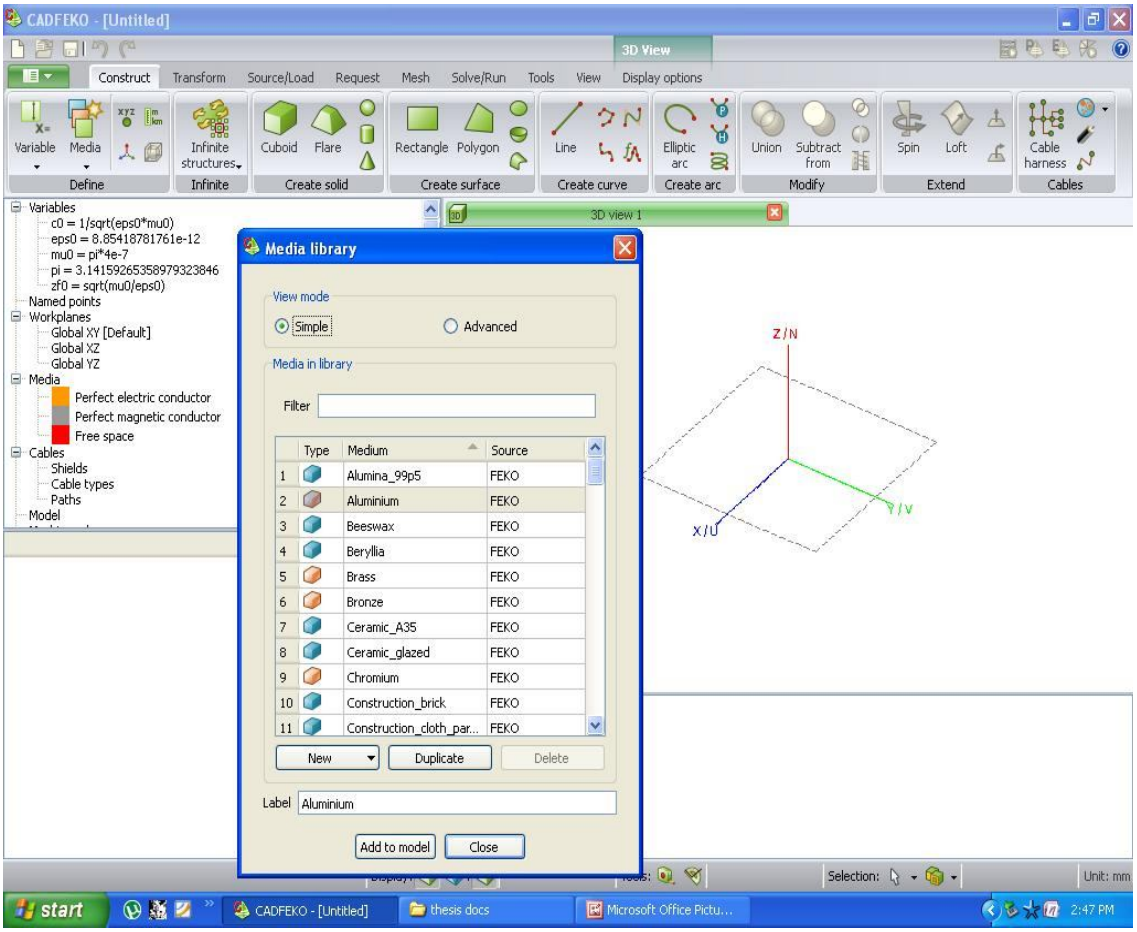
Starting new project...

Unit: mm

Fig. 4.2: Screenshot of EMSS FEKO with model unit options

2. Select material

From the media library, select the required medium and add it to the model



Variables
- c0 = 1/sqrt(eps0*mu0)
- eps0 = 8.85418781761e-12
- mu0 = pi*4e-7
- pi = 3.14159265358979323846
- zf0 = sqrt(mu0/eps0)

Named points

Workplanes
- Global XY [Default]
- Global XZ
- Global YZ

Media
- Perfect electric conductor
- Perfect magnetic conductor
- Free space

Cables
- Shields
- Cable types
- Paths

Model

Media library

View mode

● Simple ○ Advanced

Media in library

Filter

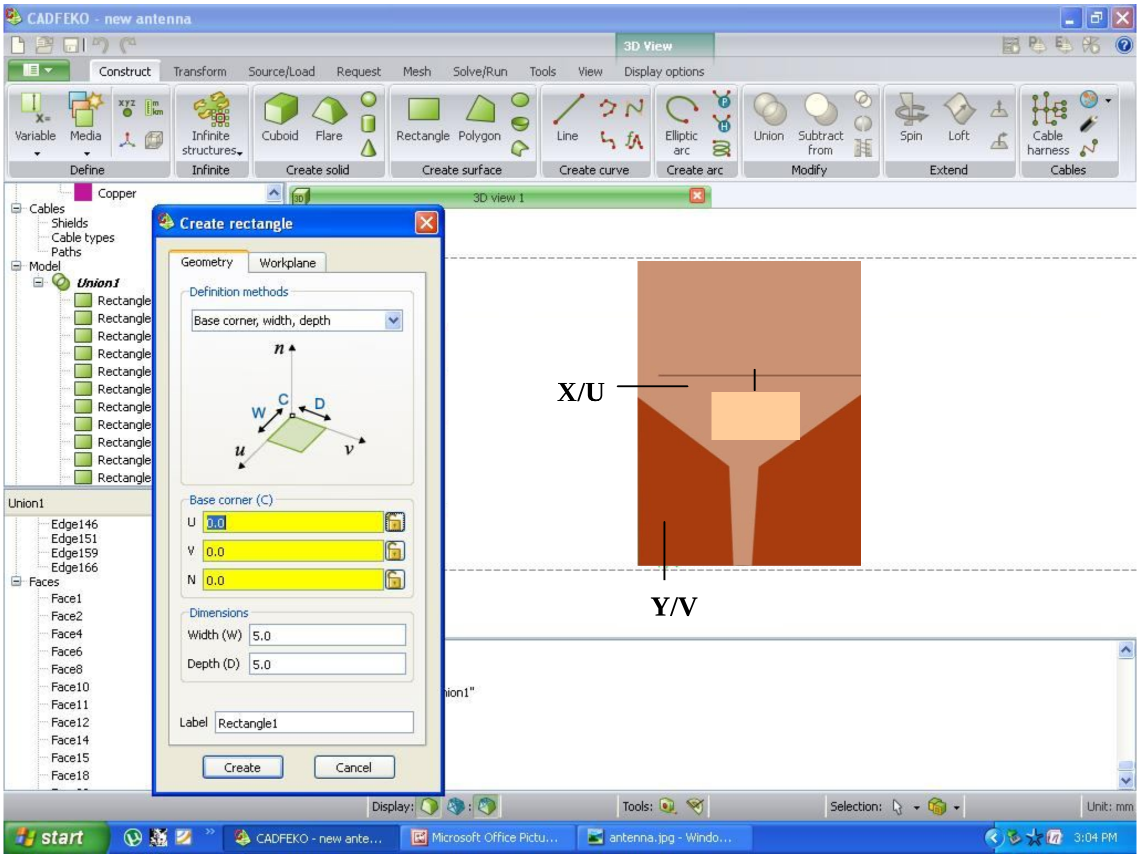
	Type	Medium	Source
1	■	Alumina_99p5	FEKO
2	■	Aluminium	FEKO
3	■	Beeswax	FEKO
4	■	Beryllia	FEKO
5	■	Brass	FEKO
6	■	Bronze	FEKO
7	■	Ceramic_A35	FEKO
8	■	Ceramic_glazed	FEKO
9	■	Chromium	FEKO
10	■	Construction_brick	FEKO
11	■	Construction_cloth_par...	FEKO

Label: Aluminium

Fig. 4.3: Screenshot of EMSS FEKO with Media library

3. Create design

The antenna is then designed using various surface blocks available in the ‘Construct’ tab.



Definition methods: Base corner, width, depth

Base corner (C)
U 0.0
V 0.0
N 0.0

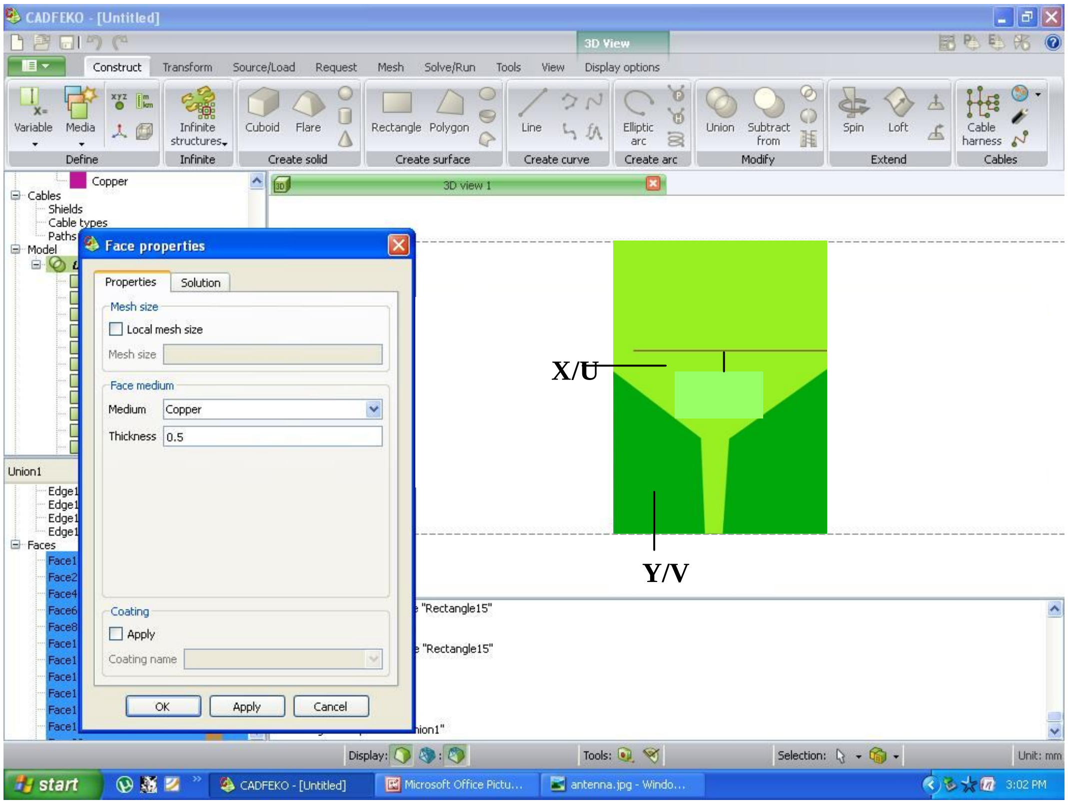
Dimensions
Width (W) 5.0
Depth (D) 5.0

Label Rectangle1

Fig. 4.4: Screenshot of EMSS FEKO with surface creation option.

4. Assign medium to design

From the side pane, all the surfaces of the antenna design are selected and a medium is assigned to them through their property window.



☐ Local mesh size

Mesh size:

Medium: Copper

Thickness: 0.5

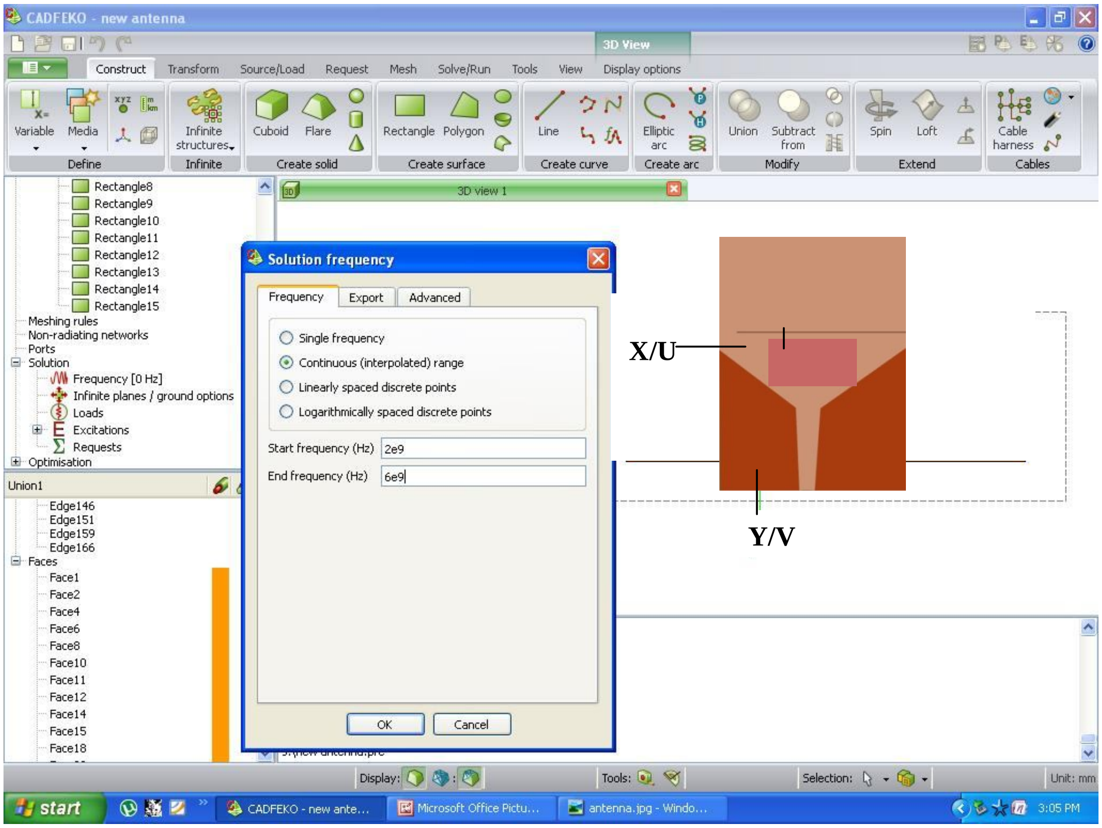
☐ Apply

Coating name:

Fig. 4.5: Screenshot of EMSS FEKO showing Face properties

5. Select frequency

In the left pane, right click on the Frequency option under the Solution option and Assign frequency to the model.



Solution frequency

Frequency | Export | Advanced

○ Single frequency
● Continuous (interpolated) range
○ Linearly spaced discrete points
○ Logarithmically spaced discrete points

Start frequency (Hz) 2e9
End frequency (Hz) 6e9

Fig. 4.6: Screenshot of EMSS FEKO with solution frequency selection window

6. Create mesh

Under the „Mesh" tab, select the „Create mesh" option. Specify the Mesh size as „Standard" and click on the „Mesh" button.

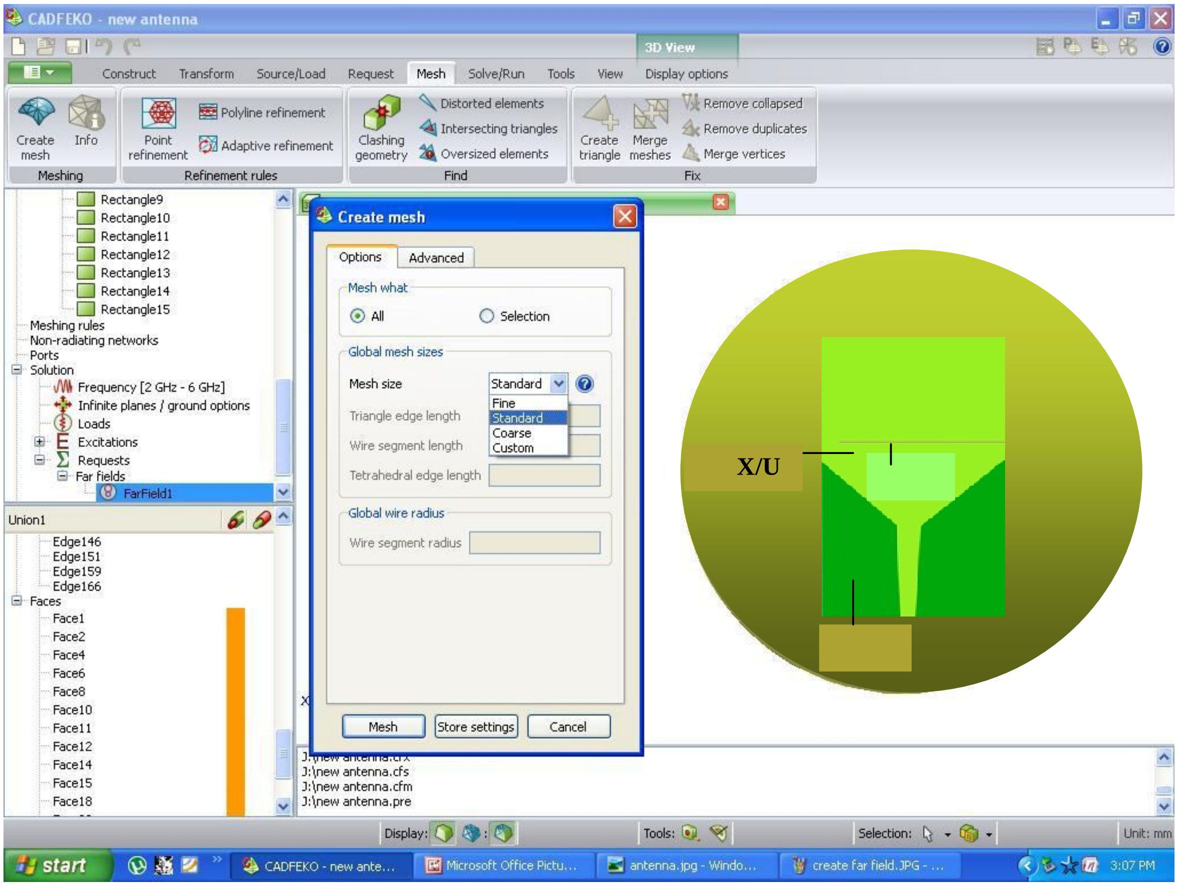
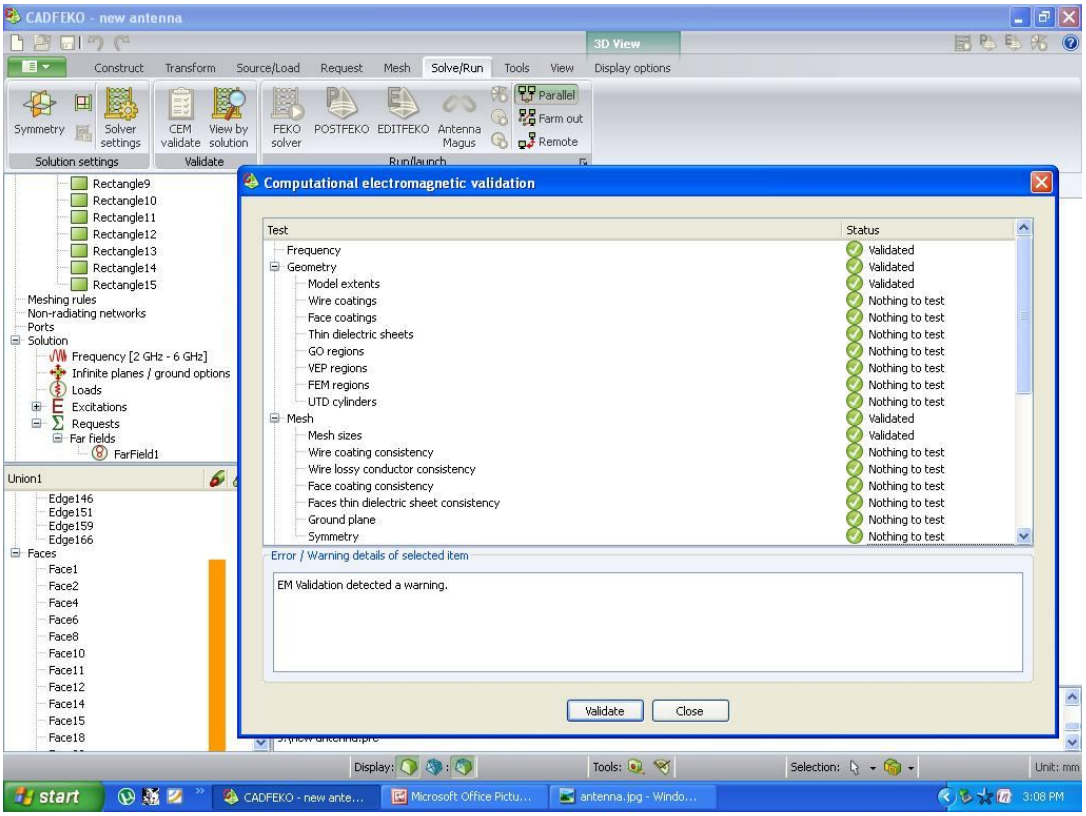


Fig. 4.7: Screenshot of EMSS FEKO with meshing options selection window selection window

7. CEM validate

Under the Solve/Run tab,click on the ‘CEM validate’ button. It will validate the model for final simulation.



Test	Status
Frequency	Validated
Geometry	Validated
Model extents	Validated
Wire coatings	Nothing to test
Face coatings	Nothing to test
Thin dielectric sheets	Nothing to test
GO regions	Nothing to test
VEP regions	Nothing to test
FEM regions	Nothing to test
UTD cylinders	Nothing to test
Mesh	Validated
Mesh sizes	Validated
Wire coating consistency	Nothing to test
Wire lossy conductor consistency	Nothing to test
Face coating consistency	Nothing to test
Faces thin dielectric sheet consistency	Nothing to test
Ground plane	Nothing to test
Symmetry	Nothing to test

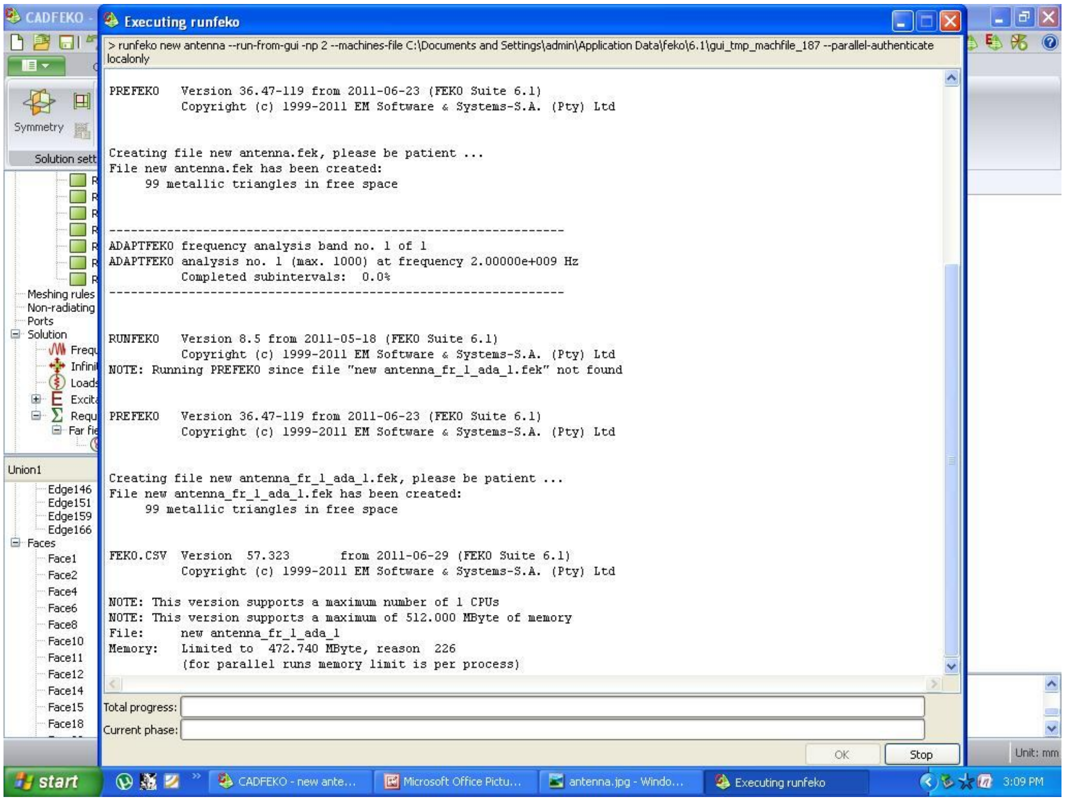
Error / Warning details of selected item

EM Validation detected a warning.

Fig. 4.8: Screenshot of EMSS FEKO while validating a design.

8. Solve

Click on FEKO solver button under ‘Solve/Run’ tab.



```
> runfeko new antenna --run-from-gui -np 2 --machines-file C:\Documents and Settings\admin\Application Data\feko\6.1\gui_tmp_machfile_187 --parallel-authenticate localonly

PREFEKO   Version 36.47-119 from 2011-06-23 (FEKO Suite 6.1)
          Copyright (c) 1999-2011 EM Software & Systems-S.A. (Pty) Ltd


Creating file new antenna.fek, please be patient ...
File new antenna.fek has been created:
     99 metallic triangles in free space


----------------------------------------------------------------
ADAPTFEKO frequency analysis band no. 1 of 1
ADAPTFEKO analysis no. 1 (max. 1000) at frequency 2.00000e+009 Hz
          Completed subintervals:  0.0%
----------------------------------------------------------------


RUNFEKO   Version 8.5 from 2011-05-18 (FEKO Suite 6.1)
          Copyright (c) 1999-2011 EM Software & Systems-S.A. (Pty) Ltd
NOTE: Running PREFEKO since file "new antenna_fr_1_ada_1.fek" not found


PREFEKO   Version 36.47-119 from 2011-06-23 (FEKO Suite 6.1)
          Copyright (c) 1999-2011 EM Software & Systems-S.A. (Pty) Ltd


Creating file new antenna_fr_1_ada_1.fek, please be patient ...
File new antenna_fr_1_ada_1.fek has been created:
     99 metallic triangles in free space


FEKO.CSV  Version  57.323      from 2011-06-29 (FEKO Suite 6.1)
          Copyright (c) 1999-2011 EM Software & Systems-S.A. (Pty) Ltd

NOTE: This version supports a maximum number of 1 CPUs
NOTE: This version supports a maximum of 512.000 MByte of memory
File:     new antenna_fr_1_ada_1
Memory:   Limited to  472.740 MByte, reason  226
          (for parallel runs memory limit is per process)
```

Fig. 4.9: Screenshot of EMSS FEKO with FEKO solver.

The antenna design is solved by CADFEKO using Method of Moments (MoM) numerical method. The module which solves the antenna design is called FEKO solver. After the FEKO solver has completed its processing. POSTFEKO is used to view the results.

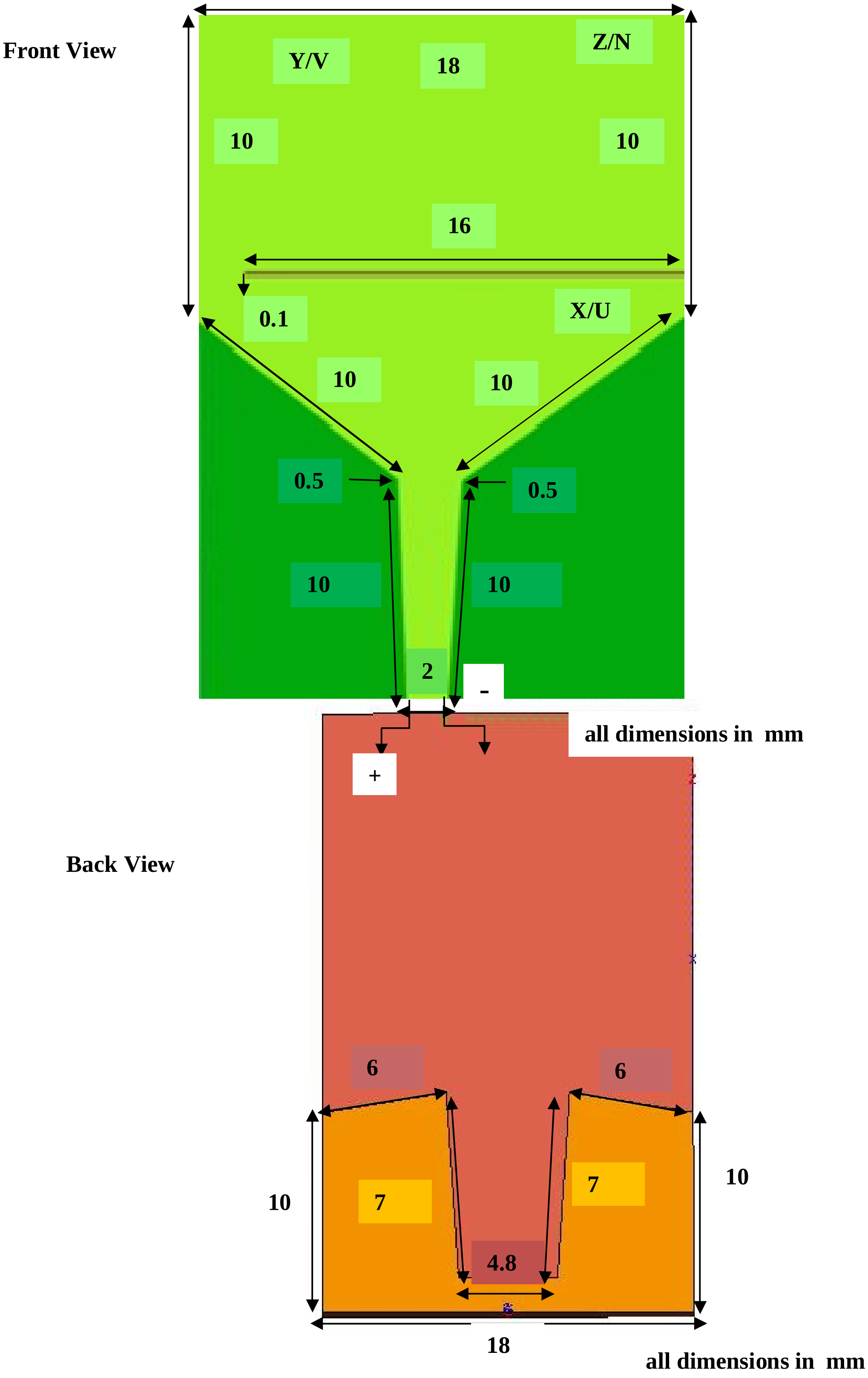


Fig . 4.10 Proposed Antenna Design

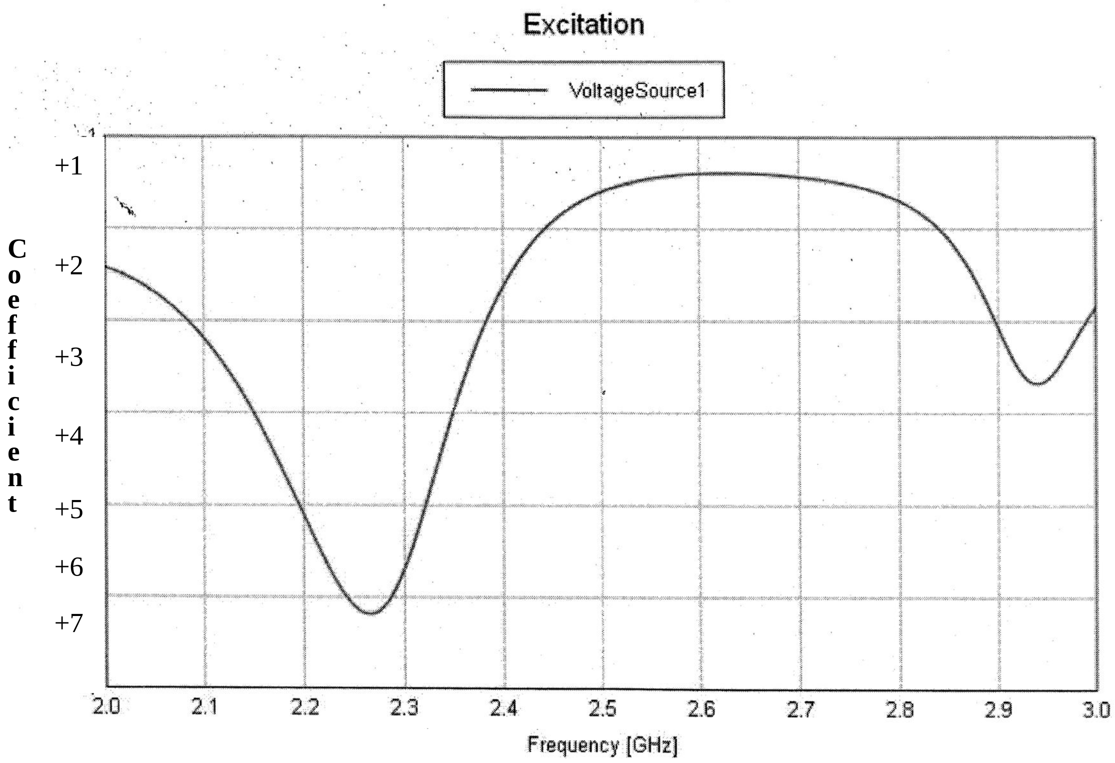


Fig. 4.11 Return Loss vs. Frequency

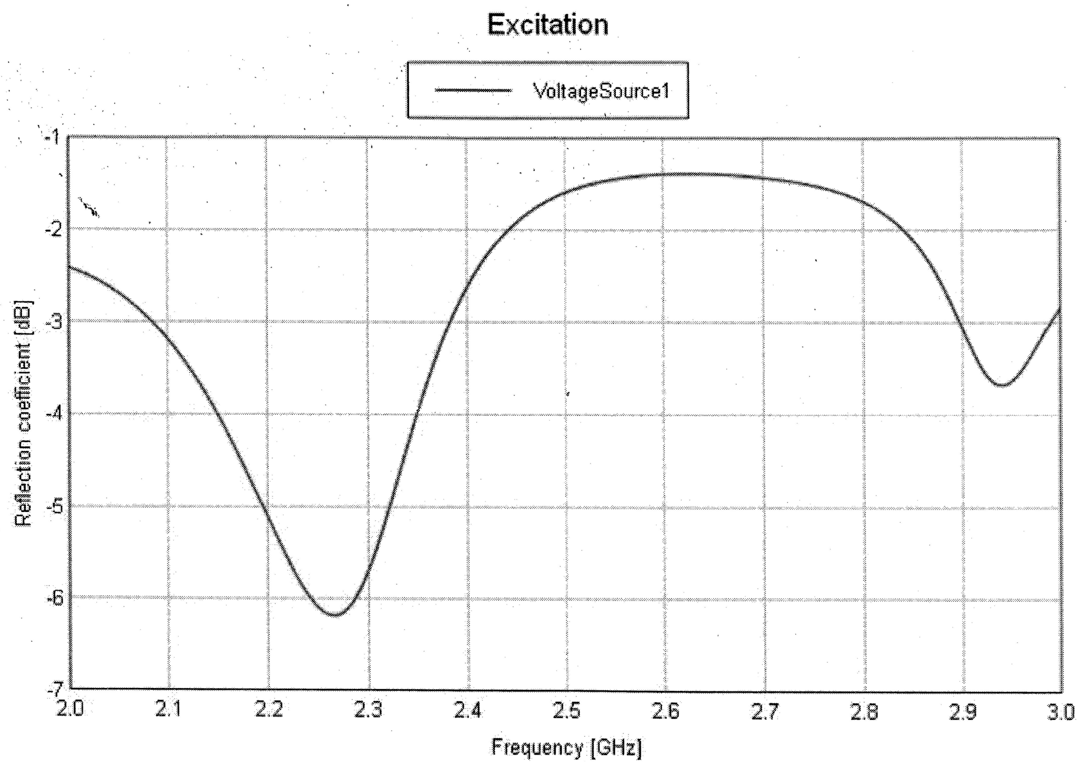


Fig. 4.12 Reflection coefficient vs. frequency

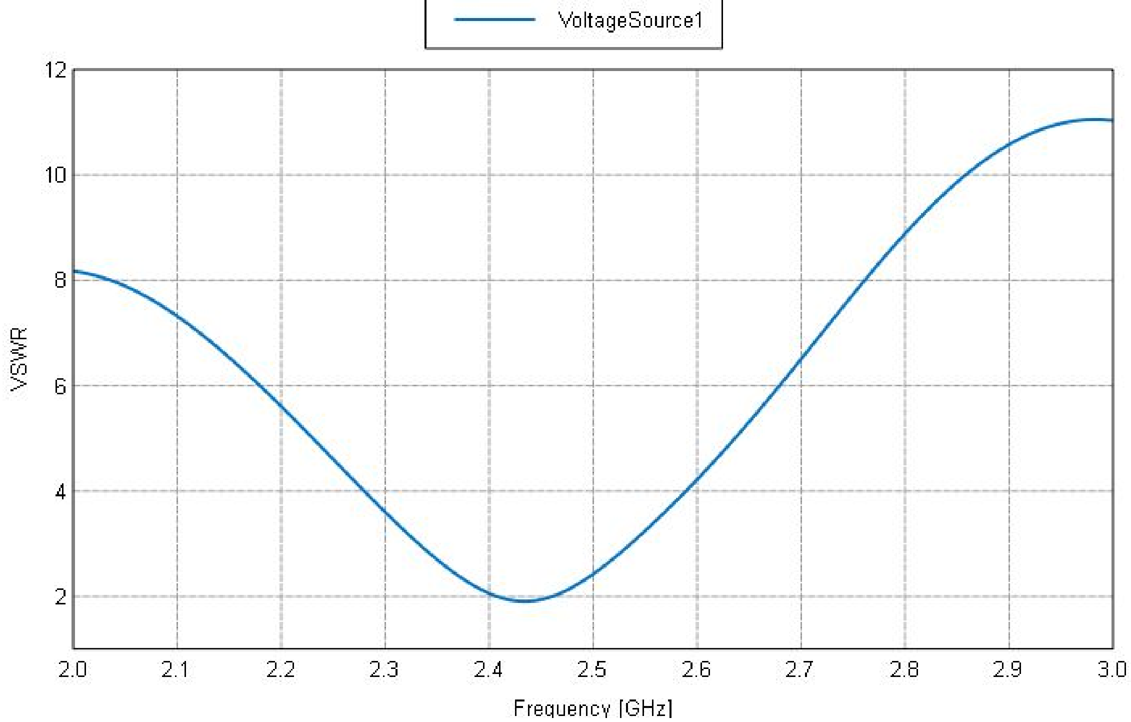


Fig. 4.13: VSWR vs. Frequency

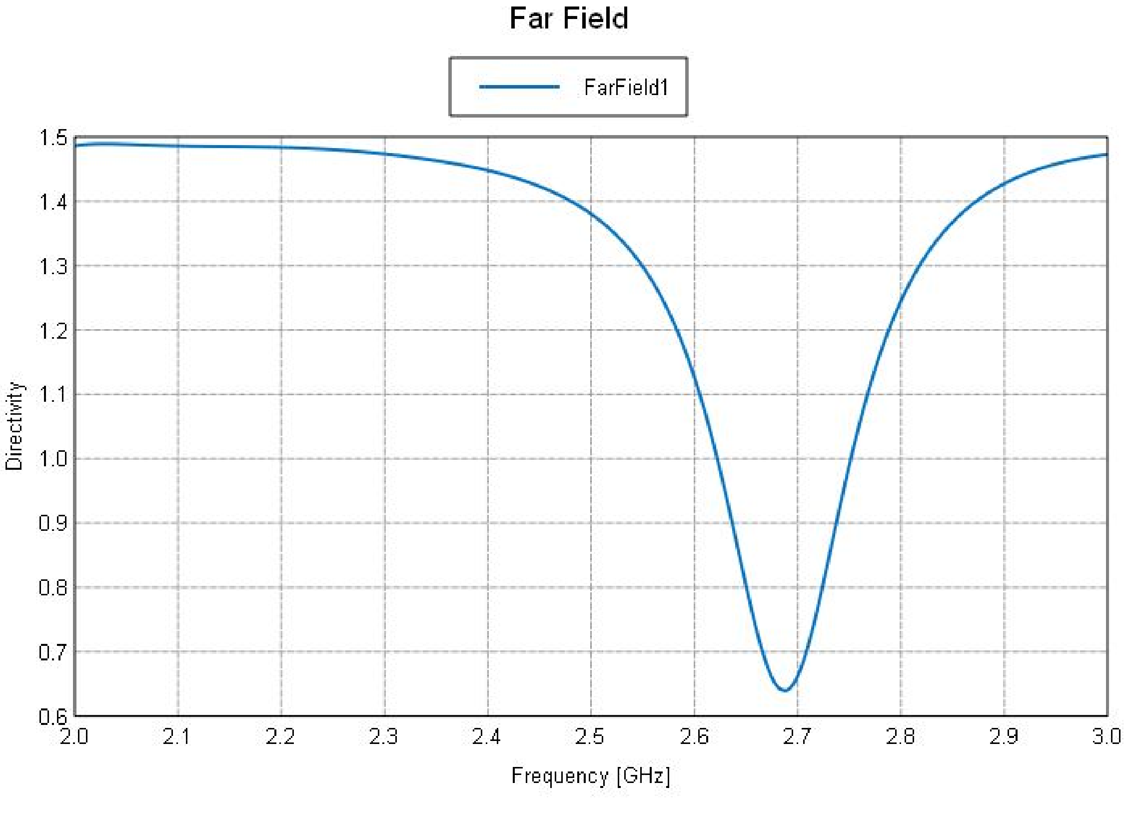
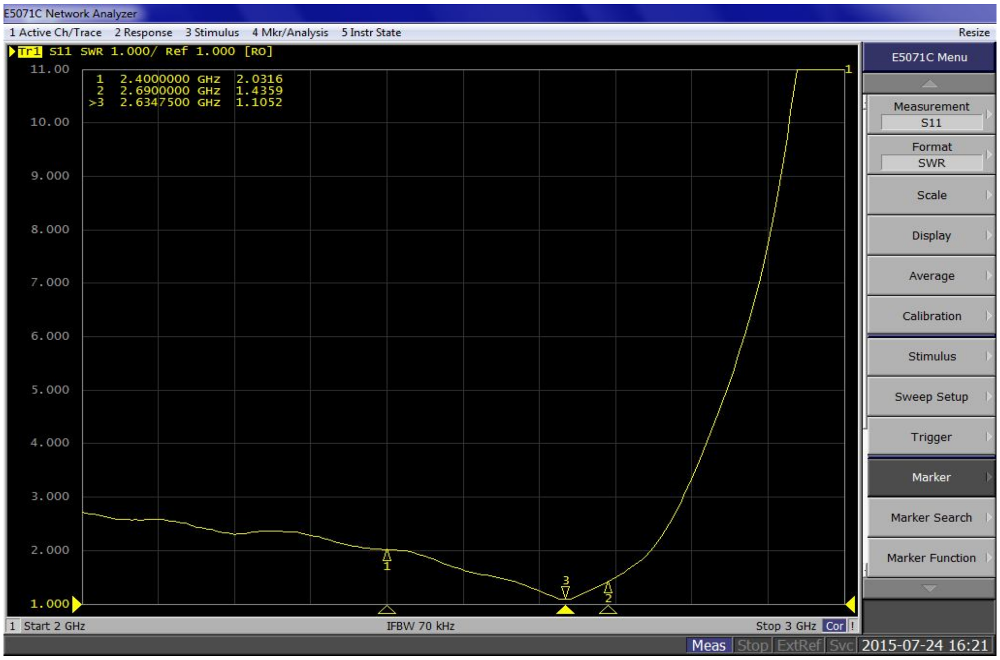


Fig. 4.14: Total directivity vs. frquency

Antenna Fabrication



```
 1   2.4000000 GHz  2.0316
 2   2.6900000 GHz  1.4359
>3   2.6347500 GHz  1.1052
```

Fig. 4.17: Measured VSWR vs. frequency curve on VNA

```
 1   2.4000000 GHz -9.2936 dB
 2   2.6900000 GHz -14.857 dB
>3   2.6347500 GHz -25.914 dB
```

Fig. 4.18: Measured return loss vs. frequency curve on VNA

Fig 4.17 and 4.18 shows the measured radiation pattern of the antenna on Virtual Network Analyzer. The VNA used for measurement is Anritsu make VNA Master MS2025B. The frequency range of VNA is 500 KHz – 6 GHz. The fig. reveals that the measured radiation pattern is in accordance with the simulated radiation pattern. Return loss of -10dB is obtained for both frequency bands. For lower band, the minimum value of return loss is -9.2936 dB at 2.400 GHz and for upper band, it is -25.914 dB at 2.488 GHz.

Chapter-5

RESULTS AND DISCUSSION

To manufacture the required MIMO sector antenna, first of all an elementary metal plate dual band antenna is fabricated which radiates efficiently at required frequency bands of WLAN standard. Using this antenna, two designs of fractal antennas are created. Four sections of these fractal antenna designs are then placed inside a single radome to create the required 4 port MIMO fractal antenna.

Table 5.1 : Simulation results of the Microstrip antenna

PARAMETER	**SPECIFICATIONS**
	In 2.4GHz band
Frequency Range	2.400GHz-2.488GHz
Gain	-1.6 dBi at 2.4, -4.6 dBi at 2.488 GHz
VSWR	< 2.6
Polarization	Circular
Return Loss	>7dB
Impedance	50 Ohms
Size	180 mm X 160 mm X 100mm

The proposed antenna achieves return loss > 7dB for entire frequency range. This corresponds to VSWR < 2.6. the peak value for return loss is 10.2dB at 2434 MHz

The antenna achieves peak gain of -1.6 dBi at 2.4 GHz which falls to -4.6 dBi at 2.488 GHz.

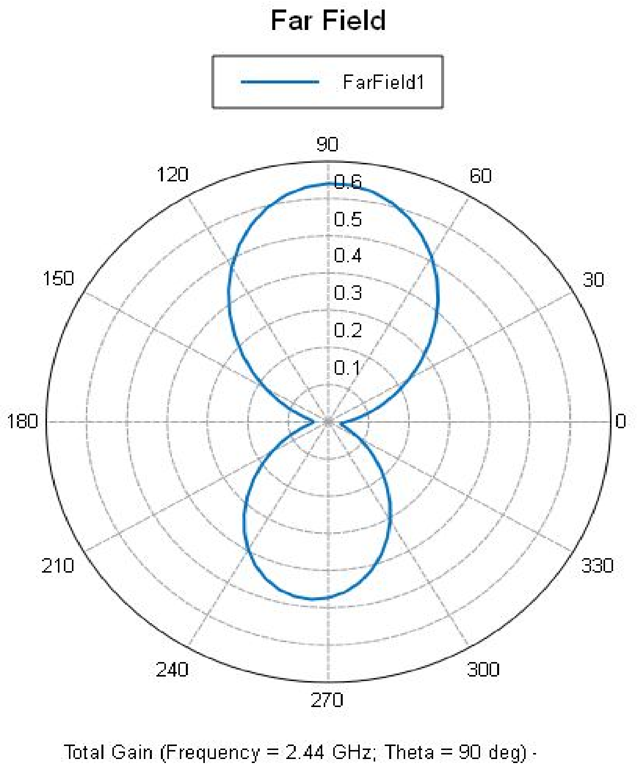


Fig 5.1 : XY plane radiation

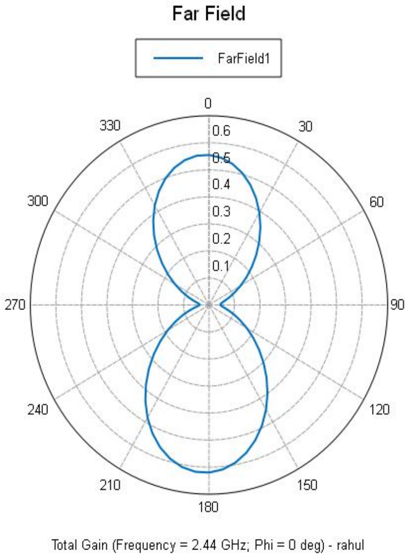


Fig. 5.2 : XZ plane radiation

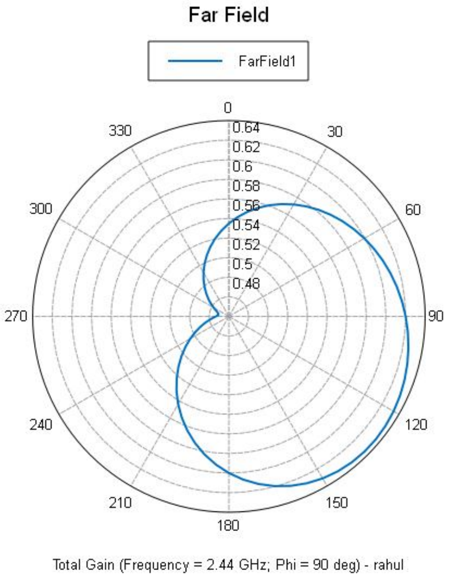


Fig 5.3: YZ plane radiation

Fig. 5.1-5.3 shows the radiation pattern of the proposed antenna at 2.444 GHz. It shows doughnut like pattern similar to a dipole antenna. The front lobe is slightly bigger than the back lobe which normally occurs that high frequencies. This may be attributed to uneven shape of the antenna which results in current flow variations.

Similarly fig 5.2 shows the XZ plane radiation pattern. Radiation pattern is still doughnut like similar to that of a dipole antenna.

Fig. 5.3 shows the YZ plane radiation patternof the antenna at 2444 MHz.

The radiation cover right half of the plane. The pattern corresponds to sectorial radiation pattern with beam width of about 120◦

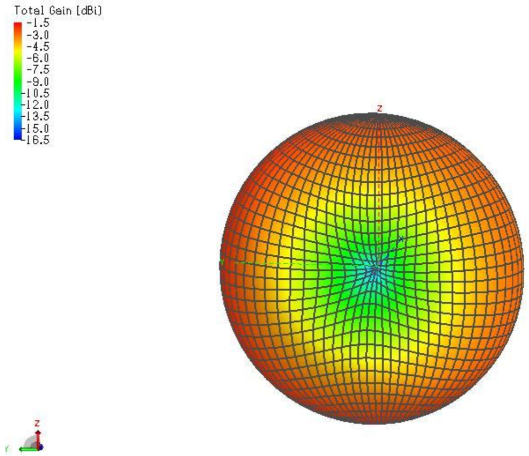


Fig. 5.4

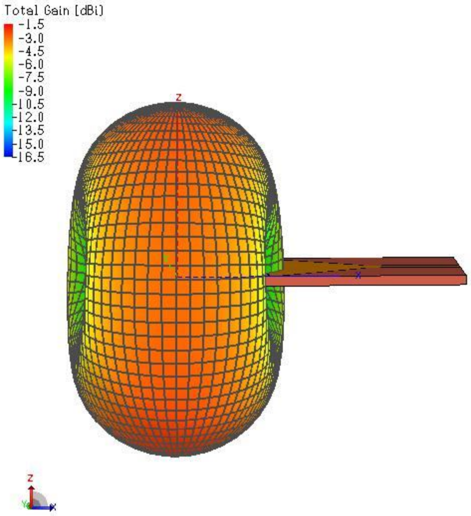


Fig. 5.5

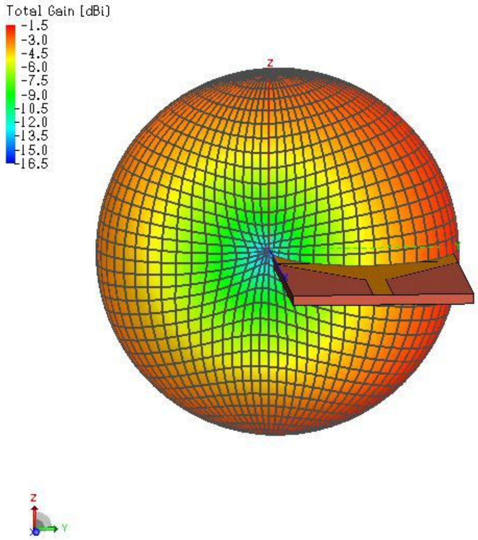


Fig. 5.6

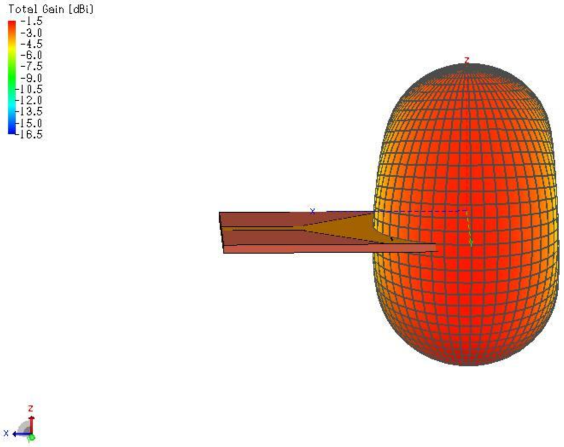
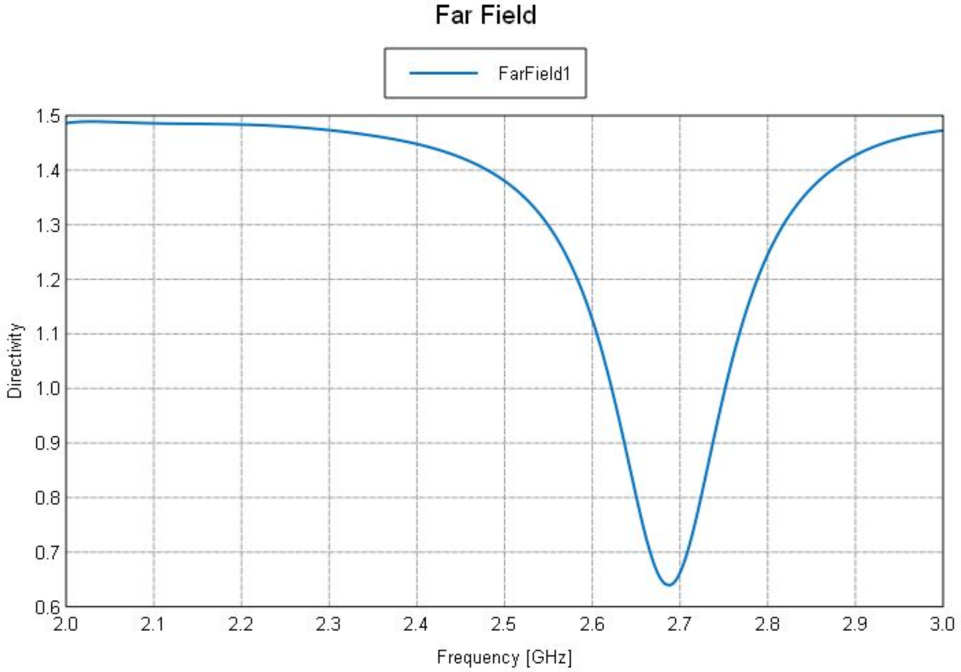


Fig. 5.7



Total Directivity (Theta = 0 deg; Phi = 0 deg.)

Fig. 5.8: Directivity XY plane vs. frequency

Fig 5.4 : (5.4) (5.5) (5.6) & (5.7)shows 3 dimensional radiation patterns

Fig. 5.8 shows directivity of antenna on XY plane. it shows that the antenna has directivity of 1.4 to 1.45 in the desired frequency range . This corresponds to the high power front lobe of XY plane. It depicts that antenna is not perfectly omnidirectional.

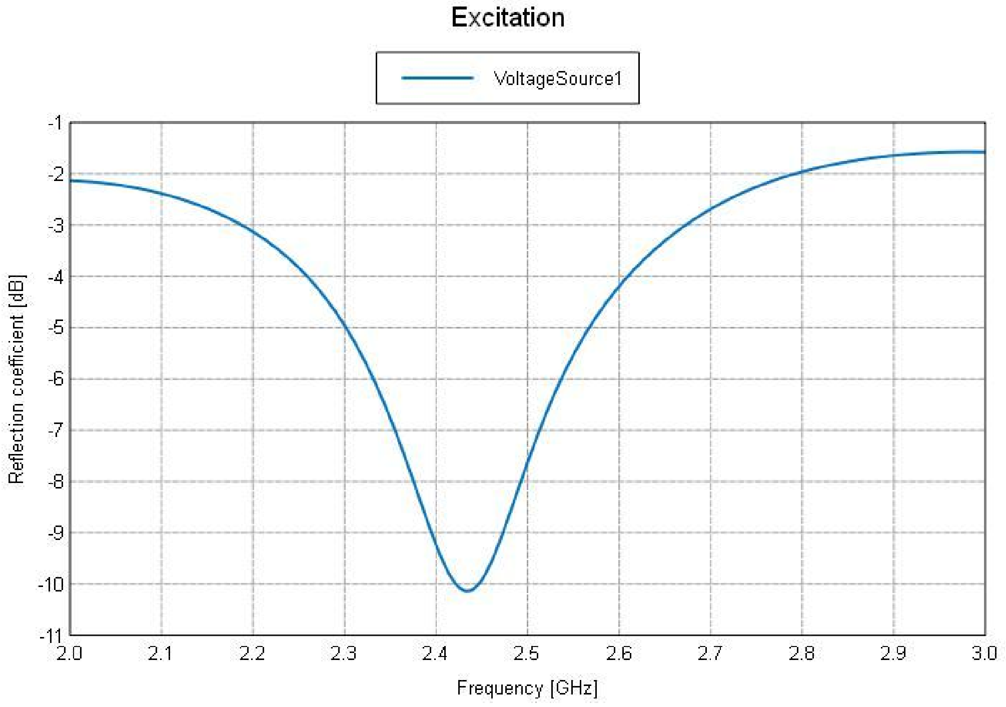


Fig. 5.9: Reflection coefficient (dB) vs. frequency

The proposed antenna achieves return loss >7dB for entire frequency range. This corresponds to VSWR <2.6. The Peak value of return lose is 10.2dB at 2434 MHz.

The antenna achieves peak gain of -1.6dBi at 2.4GHz which falls to -4.6dBi at 2.488 GHz.

CHAPTER 6
SUMMARY

In this thesis, a dual band MIMO antenna with 4 ports is designed, that works on IEEE 802.11a/b/g/n frequency bands. These bands are specified for WLAN applications and the frequency of operation in these bands is 2400MHz-2488MHz

To design such antenna, firstly a dual band microstrip antenna is designed which radiates efficiently in both the WLAN bands. This antenna is designed using a copper sheet of 0.5mm thickness. The dual band characteristics are achieved by cutting two slots in the sheet to create two dipoles, one for each frequency band.

To create the microstrip antenna, the microstrip antennas are then strategically placed in front of a reflector to generate the desired radiation pattern.

However, there is some disagreement in theoretical and practical VSWR values for both the microstrip antenna, which can be attributed to calibration mismatch between VNA and the antenna.

The desired 4 port MIMO microtsrtip antenna can be designed by arranging four units of the individual antenna sections inside one radome. Since the size of both types of sector antennas is reasonably small, it permits to place 4 such sections inside a single radome with sufficient gap. Also, the low vertical beamwidth prevents interference of radiations from individual antennas.

This type of antenna solves the problem of location constraint, which is faced when multiple antennas are to be placed at transmitter and receiver side in such a way, that they provide least interference with each other. The locations, at which the antennas are to be placed, are not always suitable to place multiple antennas at desired positions. To overcome this problem, high gain MIMO antennas can be used which are capable of accepting input from multiple sources without causing interference with each other. This solves the problem of placement of antennas to a great extent

LITERATURE CITED

A. Ismahayati, P.J. Soh, R. Hadibah, G.A.E Vandenbosch, “ Design and Analysis of a Multiband Koch Fractal Monopole Antenna.” IEEE International RF and Microwave Confrence. pp. 58-62, 12th -14th December 2011.

Ahn, J., Kim, S., Lee, M., and Kim, Y. A Compact Printed Dual-Band WLAN Antenna with a Shorted Coupling Strip for Mobile Terminals. *In :Proceedings of APMC 2012*, held at Kaohsiung, Taiwan during pp. 313-315, Dec. 4-7, 2012.

Alhaddad, A.G., Abd-Alhameed, R.A., Zhou, D., See, C.H., Elfergani, I.T.E., Excell, P.S. Low profile dual-band-balanced handset antenna with dual-arm structure for WLAN application. *In: Proceedings of International Conference on Communications, Propagation and Electronics (MIC-CPE2010)*.pp 1045 – 1053. 2011.

Amer Basim Shaalan, “Design of Fractal Quadratic Koch Antenna.” International Multi-Conference on Systems, Signals and Devices, 2010.

B.B. Mandelbrot, The fractal Geometry of Nature. W.H. Freeman and Company, New Yourk, 1983.

B.L. Ooi, “A modified contour integral analysis for Sierpinski fractal carpet antennas with and without electromagnetic band gap ground plane,” IEEE Trans. Antennas Propag., Vol.52, pp. 1286-1293, May 2004.

C. puente, j. Romeu, R. Bartoleme, and R. pous, "Fractal multiband antenna based on Sierpinski gasket," Electronics letters, vol.32, app. 1-2, 1996

C. Puente, j. Romeu, R. pous and A. Cardama, "On the behavior of the Sierpinski multiband fractal antenna," IEEE Transaction Antenna Propagation, vol. 46. pp. 517-524, 1998

C. Puente, J. Romeu, R. Pous, J. Ramis, and A. Hijazo, "Small but long koch fractal monoploe," Electronic. Letters, vol.34, pp. 9-10,1998.

Constantine A. Balanis, Antenna Theory Analysis & Design, John Wiley & Sons, 1997.

D.D. Krishna, M. Gopikrishna, C.K. Aanandan, P. Mohanan, and K. Vasudevan, “ Compact wideband Koac Fractal Printed slot antenna.” IET Micro waves, Antennas and Propagation, Vol3, No. 5, pp. 782-789, 2009.

D.H. Werner and S.Ganguly, "An overview of Fractal Antenna Engineering Research," IEEE Antennas and propagation Magazine, vol.45, No.1, PP. 38-57, Feb 2013.

H.O. peitgen, H. Jurgens, and D. Saupe, Chaos and fractals: New Frontiers of Science, Springer- Verlag, New York, 1992

Introduction to antenna and near-field simulation in CST Microwave Studio Software By Jorge R.Costa Jerzy Guterman.

M. Ahmed, A. Letif, M.A.Z. Habeeb, and H.S. Jaafer, "performance characteristics of Murkowski curve fractal antenna," Journal of Engineering and Applied Sciences, vol.1, No.4, PP. 323-328, 2006

N. A. Saidatul, A. A. H. Azremi, R. B. Ahmad, P. J. Soh, and F. Malek, "Multiband fractal planar inverted F antenna (F-PIFA) for mobile phone application," *Progress in lectromagnetic Research (PIER),* vol. 14, pp. 127-148, 2009.

N. Abdullah, M. A. Arshad, E. Mohd, S. A. Hamzah, “Design of Minskowsi Fractal for Dual Band Application.” IEEE, pp. 352-355, May 13-15, 2008.

N.Cohen, "Fractal antenna application in wireless telecommunications," In professional program proceedings of Electronics Industries Forum of New England, pp. 43-49, 1997.

N.Cohen, Fractal Antennas: part I Introduction and the fractal Quad. Communications Quarterly. vol. 43, no.2, pp. 7-22, 1995.

Neetu, Savina Bansal, R K Bansal, “Design and Analysis of Fractal Antennas based on Koch and Sierpinski Fractal Geometries.” IJAREEIE Vol. 2, Issue 6, pp. 2110-2116, June 2013.

P. J. Soh, G. A. E. Vandenbosch, S. L. Ooi, and M. R. N. Husna, "Wearable dual-band Sierpinski fractal PIFA using conductive fabric," *Electronics Letters,* vol. 47, pp. 365-367, 2011.

Raj Kumar, Yogesh B. Thakare and M. Bhattacharya, “Novel Design of Star Shaped Circular Fractal Antenna.” IEEE, pp. 239-241, 2008.

S. N. Shafie, I. Adam, and P. J. Soh, "Design and Simulation of a Modified Minkowski Fractal Antenna for Tri-Band Application," in *Mathematical/Analytical Modelling and Computer Simulation (AMS), 2010 Fourth Asia International Conference on*, 2010, pp. 567-570.

Vinoy, K. J., “Fractal shaped antenna elements for wide and multi-band wireless applications,” Thesis, Pennsylvania, Aug. 2002.

Yogesh Kumar Choukiker, S.K. Behera, “Design of Wideband Fractal Antenna with Combination of Fractal Geometries.” ICICS, 2011.

Yu, D., Zhang, Z., Liu, W., and Yang, B. Dual-Band Miniaturized Printed Antenna for WLAN Applications”, In : Proceedings of International Conference on Microwave and Millimeter Wave Technology. **3.** pp. 1–4, 2012.

Zhang, Z., Iskander, M. F., Langer, J. and Mathews, J. Dual-Band WLAN Dipole Antenna Using an Internal Matching Circuit. *In: IEEE Transactions On Antennas And Propagation***53** : 1813 – 1818, 2005.

Zhanmeng, L., Chunlan, L., Luqu, Y., Jianxin, J. and Jie, Y. A Novel Compact Dual-BandMIMO Antenna for WLAN Application”, *In : Proceedings of International Conference on Microwave and Millimeter Wave Technology (ICMMT)* **3:** 1 – 4, 2012

Neetu, Savina Bansal, R.K. Bansal, "Design and Analysis of Fractal Antennas basedon Koch and Sierpinski Fractal Geometries." IJAREEIE Vol. 2, Issue 6, pp. 2110-2116, June 2013.