Design and Analysis of Fractal Antennas for Wideband Applications

A thesis submitted in partial fulfilment of the requirements for the degree of

Bachelor of technology

in

Electronics and communication engineering

by

OMBENI KANZE KENNEDY
Roll no. 110EC0648

Under the supervision of

Prof. SANTANU KUMAR BEHERA

Department of Electronics and Communication Engineering
National Institute of Technology
Rourkela -769008, India

May-2014

Design and Analysis of Fractal Antennas for Wideband Applications

A thesis submitted in partial fulfilment of the requirements for the degree of

Bachelor of technology

in

Electronics and communication engineering

by

OMBENI KANZE KENNEDY
Roll no. 110EC0648

Under the supervision of

Prof. SANTANU KUMAR BEHERA

Department of Electronics and Communication Engineering
National Institute of Technology
Rourkela -769008, India

May-2014

DEPARTMENT OF ELECTRONICS AND COMMUNICATION ENGINEERING

NATIONAL INSTITUTE OF TECHNOLOGY
ROURKELA -769008, INDIA

CERTIFICATE

This is to certify that the thesis entitled "**Design and Analysis of Fractal Antenna for Wideband Applications**" submitted by **Mr Ombeni Kanze Kennedy, 110EC0648** in partial fulfilment of the requirements for the Award of a degree of Bachelor of Technology in Electronics and Communication Engineering during session 2013-2014 at National Institute of Technology, Rourkela is an authentic work he carried out under my supervision and guidance. To the best of my knowledge, the matter embodied in the thesis has not been submitted to any other University/Institute for the award of any degree or diploma. In my opinion, the thesis is of the standard required for the award of a Bachelor of Technology degree in Electronics and Communication Engineering.

Prof. SK BEHERA

ACKNOWLEDGEMENTS

I would like to express my gratitude and appreciation to all those who gave me the possibility to complete this Project. Many thanks go to my supervisor, **Prof. Santanu Kumar Behera**, who has given his full effort in guiding me in achieving the goal as well as his encouragement to maintain my progress in track.

I acknowledge the guidance given by other supervisors as well as the panel, especially in our project presentation that has improved our presentation skills by their comments and tips.

A special thanks to the PhD scholar **Mr Yogesh Kumar**, whose help, stimulating suggestions and encouragement, helped me to coordinate my project.

I would also like to acknowledge with much appreciation the crucial role of the staff and all **M.Tech students** in Microwave and antenna Laboratory, for their regular suggestions and encouragements during my entire work.

Finally, but by no means least, thanks go to my **Mum, Dad** and my entire **Family** for their unbelievable support and encouragements. They are the most important people in my world and I dedicate this thesis to them.

Ombeni Kanze Kennedy

ABSTRACT

The use of fractal geometries has significantly impacted many areas of science and engineering; one of which is antennas. Antennas using some of these geometries for various telecommunications applications are already available commercially. The use of fractal geometries has been shown to improve several antenna features to varying extents.

Wide band fractal antennas geometry has been proposed in this thesis. Fractal shapes and their properties are discussed. The proposed antennas are microstrip line fed and their structure are based on fractal geometry where the resonance frequency of antenna is lowered by applying iteration techniques. The bandwidth was optimized by combining different geometries resulting in a hybrid Fractal Antenna. Analysis of fractal antenna was done by using the Software named CST Microwave Studio Suite 12. This antenna has low profile, lightweight and easy to be fabricated and has successfully demonstrated wideband characteristics. The first Fractal antenna is based on the Koch curve geometry. It is operating in a wideband frequency range of **3.31-7.84GHZ** hence giving a bandwidth of **81.26%** and achieves an efficiency of **83.2%** with a peak Gain of **3.66 dB.** The second proposed Fractal antenna is a modified version of the 1st one and has a wide operating bandwidth of **85.37%** from **3.31-8.4GHz**.The antenna achieves an efficiency of **87.6%** with a peak Gain of **3.05dB.**The third proposed antenna is a Hybrid Fractal antenna that achieves an efficiency of **86.7%** and has a peak gain of **3.4dB.** It has a bandwidth of **85.05%** from **3.3-8.18GHZ**.The proposed antennas exhibit omnidirectional radiation behaviour. The measured bandwidth meets the requirements of many commercial bands such as WI-FI 802.11y (3.6-3.7GHZ), WiMAX (3.4-3.6 GHZ and 3.7-4.2 GHZ) and WLAN 802.11(5.31-6.32GHZ).

Content

List of Figures-- vi

List Tables -- vii

1. Introduction ---1
   - 1.1 Background ---1
   - 1.2 Thesis Motivation ---3
   - 1.3 Scope of the project ---3
   - 1.4 Thesis organization ---4
2. Antenna theory ---5
   - 2.1 Antenna properties --5
   - 2.2 Microstrip antenna --8
   - 2.3 Feeding techniques --10
3. Fractal Antenna --14
   - 3.1 Introduction --14
   - 3.2 Fractal theory ---14
   - 3.3 Fractal Geometries ---16
4. Proposed Wideband Antenna Design --22
   - 4.1 Koch curve Monopole Fractal antenna ---------------------------------------22
     - 4.1.1 Antenna Geometry --22
     - 4.1.2 Simulation Results --23
   - 4.2 Modified Koch curve Monopole Fractal antenna ----------------------------27
     - 4.3.1 Antenna Geometry --28
     - 4.3.2 Simulation Results --29
   - 4.3 Hybrid Fractal Antenna ---32
     - 4.4.1 Antenna Geometry --32
     - 4.4.2 Simulation Results ---34
   - 4.4 Inscribed circular Fractal Antenna --37
     - 4.4.1 Antenna Geometry --37
     - 4.4.2 Simulation Results --38

5. Conclusion and Future work --42

5.1 Conclusion ---42
5.2 Future work ---42

References ---43

List of Figures

2.1	Radiation pattern	6
2.2	Microstrip Antenna structure	9
2.3	Microstrip line feed	11
2.4	Coaxial probe feeding	11
2.5	Aperture coupling feeding	12
2.6	Proximity coupling	13
3.1	Some common examples of Fractal geometries	17
3.2	Steps for the construction of Sierpinski Gasket geometry	18
3.3	Steps for the construction of Sierpinski Carpet geometry	19
3.4	Steps for the construction of Koch curve geometry	20
3.5	Steps for the construction of the Cantor set geometry	20
4.1	Geometry of the proposed Koch Fractal antenna	22
4.2	Return loss graph for the Koch fractal antenna	24
	(a) With the ground plane width (W=12.9mm)	
	(b) With the ground plane width (W=13.9mm)	
4.3	Radiation pattern plots (a) at 3.72GHZ (b) At 5 GHZ (c) At 6.72GHZ	25
4.4	Surface current distribution (a) At 5GHZ (b) At 6.72GHZ	26
4.5	Geometry of the modified Koch Fractal antenna	28
4.6	Return loss graph for the modified Koch fractal antenna	29
	(a) With the ground plane width (W=12.9mm)	
	(b) With the ground plane width (W=13.9mm)	
4.7	Radiation pattern plots (a) at 3.72GHZ (b) At 5 GHZ (c) At 6.72GHZ	31
4.8	Surface current distribution (a) At 5GHZ (b) At 6.72GHZ	31
4.9	Geometry of the proposed Hybrid Fractal antenna	32
4.10	Iteration stages of the Sierpinski geometry used in the design	33
4.11	Return loss graph for the proposed Hybrid fractal antenna	34
4.12	Radiation pattern plots (a) at 3.72GHZ (b) At 5 GHZ (c) At 6.72GHZ	35
4.13	Surface current distribution (a) At 5GHZ (b) At 6.72GHZ	36
4.14	Geometry of the proposed inscribed triangle circular Fractal antenna	37

4.15 Return loss graph for the proposed Inscribed triangle circular fractal antenna 38
4.16 Radiation pattern plots (a) at 3.89GHZ (b) At 4.82 GHZ (c) At 5.8GHZ 40
4.17 Surface current distribution (a) At 3.89GHZ (b) At 5.8GHZ 40

List of Tables

4.1 Design parameters for the proposed Koch curve Fractal Antenna 23
4.2 Measured Gain, Return loss and total Efficiency of the Koch Antenna 27
4.3 Design parameters for the modified Koch curve Fractal Antenna 28
4.4 Measured Gain, Return loss and total Efficiency of modified version 32
4.5 Design parameters of the Sierpinski geometry used in the design 33
4.6 Measured Gain, Return loss and total Efficiency of the Hybrid antenna 36
4.7 Design parameters for the Inscribed triangle circular Fractal Antenna 38
4.8 Measured Gain, Return loss and total simulated Efficiency 41
4.9 Comparison study of the different Fractal Antennas proposed 41

Chapter1

INTRODUCTION

1.1 Background

Modern telecommunication systems require antennas with wider bandwidths and smaller dimensions than conventionally possible. This has initiated antenna research in various directions, one of which is by using fractal shaped antenna elements. In recent years several fractal geometries have been introduced for antenna applications with varying degrees of success in improving antenna characteristics. Some of these geometries have been particularly useful in reducing the size of the antenna, while other designs aim at incorporating multi-band characteristics. Yet no significant progress has been made in corroborating fractal properties of these geometries with characteristics of antennas. The research work presented here is primarily intended to analyse geometrical features of fractals that influence the performance of antennas using them. Several antenna configurations based on fractal geometries have been reported in recent years [1] – [4]. These are low profile antennas with moderate gain and can be made operative at multiple frequency bands and hence are multi-functional. In this work the multi-band (multifunctional) aspect of antenna designs are explored further with special emphasis on identifying fractal properties that impact antenna multi-band characteristics.
Antennas with reduced size have been obtained using Hilbert curve fractal geometry. Furthermore, design equations for these antennas are obtained in terms of its geometrical parameters such as fractal dimension. Antenna properties have also been linked to fractal dimension of the geometry. To lay foundations for the understanding of the behaviour of such antennas, the nature of fractal geometries is explained first, before presenting the status of literature on antennas using such geometries.

1.1.1 Engineering Applications of Fractals

Ever since they were mathematically re-invented by Mandelbrot, fractals have found widespread applications in several branches of science and engineering. Disciplines such as geology, atmospheric sciences, forest sciences, physiology have benefited significantly by fractal modelling of naturally occurring phenomena. Several books and monographs are available on the use of fractals in physical sciences. Fracture mechanics is one of the areas of engineering that has benefited significantly from the application of fractals [9]. The space filling nature of fractal geometries has invited several innovative applications. Fractal mesh generation has been shown to reduce memory requirements and CPU time for finite element analysis of vibration problems [10]. One area of application that has impacted modern technology most is image compression using fractal image coding [11] - [13]. Fractal image rendering and image compression schemes have led to significant reduction in memory requirements and processing time. In electromagnetics, scattering and diffraction from fractal screens have been studied extensively. Diffracted fields from self-similar Sierpinski gasket in the Franhauffer zone have been shown to be self-similar [14]. The study of wave interactions with such self-similar structures has later been termed fractal electrodynamics [15] - [17]. Some of these studies indicate that scattering patterns from fractal geometries have features of those geometries imprinted on these. More recently fractal geometries have also been used in frequency selective screens [18] - [20]. The self-similarity of the fractal geometry has been attributed to the dual band nature of their frequency response. Surface impedance of metallic patterns of fractal geometries on a dielectric slab has also been characterized [20]. Fractal antenna arrays and fractal shaped antenna elements have evolved in 1990's. An overview of the literature on the use of fractals in antenna engineering is given next.

1.1.2 Fractals in Antenna Engineering

The primary motivation of fractal antenna engineering is to extend antenna design and synthesis concepts beyond Euclidean geometry [12] - [13]. In this context, the use of fractals in antenna array synthesis and fractal shaped antenna elements have been studied. Obtaining special antenna characteristics by using a fractal distribution of elements is the main objective of the study on fractal antenna arrays. It is widely known that properties of antenna arrays are determined by their distribution rather than the properties of individual elements. Since the array spacing (distance between elements) depends on the frequency of operation, most of the conventional antenna array designs are band-limited. Self-similar arrays have frequency independent multi-band characteristics [16]. Fractal and random fractal arrays have been found to have several novel features [17]. Variation in fractal dimension of the array distribution has been found to have effects on radiation characteristics of such antenna arrays. The use of

Random fractals reduce the fractal dimension, which leads to a better control of side lobes [14]. Synthesizing fractal radiation patterns has also been explored [18]. It has been found that the current distribution on the array affects the fractal dimension of the radiation pattern. It may be concluded that fractal properties such as self-similarity and dimension play a key role in the design of such arrays.

1.2 Thesis Motivation

In modern wireless communication systems and increasing of other wireless applications, wider bandwidth, multiband [7-8] and low profile antennas are in great demand for both commercial and military applications. This has initiated antenna research in various directions; one of them is using fractal shaped antenna elements. Traditionally, each antenna operates at a single or dual frequency bands [7-8], where different antenna is needed for different applications. This will cause a limited space and place problem. In order to overcome this problem, multiband antenna can be used where a single antenna can operate at many frequency bands. One technique to construct a multiband antenna is by applying fractal shape into antenna geometry [9]. This project presents the Koch and Sierpinski Gasket patch antenna where this famous shape, the antenna behaviour is investigated. In addition to the theoretical design procedure, numerical simulation was performed using software (CST) to obtain design parameters such as size of patch and feeding location. The antennas have been analysed and designed by using the software CST Microwave Studio Suite [11].

1.3 Scope of the project

The scopes defined for this project are as follows:

- Understanding the antenna concept.
- Perform numerical solutions using CST Microwave Studio software
- Study of the antenna properties.
- Comparison of measurement and simulation results.

1.4 Thesis organization

Chapter 1: In the first chapter basic overview of the thesis is given. This chapter provides the background as well as the scope of the project.

Chapter 2: This chapter presents the basic theory of Antennas, including the basic microstrip patch geometry, features and different feeding techniques describing their characteristics, the advantages and disadvantages of MSAs.

Chapter 3: This chapter deals with fractal geometry. The chapter presents basic theory of fractals describing its features and different Fractal geometries. The performance of the fractal antenna with respect to conventional Euclidean geometry has also been discussed.

Chapter 4: This chapter describes the design of wideband antennas using CST Microwave Studio Suite 12. The simulated results are presented in terms of different antenna parameters such as return loss, gain, radiation patterns and efficiency. The effect of slots in the partial ground plane are analysed. Different parametric studies have also been shown.

Chapter 5: This chapter contains conclusion and scope of future work

Chapter 2

ANTENA THEORY

2.1 Antenna properties

The performance of the antenna is determined by several factors. Properties of those factors are as follows:

Input Impedance

Generally, input impedance is important to determine maximum power transfer between transmission line and the antenna. This transfer only happen when input impedance of antenna and input impedance of the transmission line matches. If they do not match, reflected wave will be generated at the antenna terminal and travel back towards the energy source. This reflection of energy results causes a reduction in the overall system efficiency.

Gain

The gain of an antenna is essentially a measure of the antenna's overall efficiency. If an antenna is 100% efficient, it would have a gain equal to its directivity. There are many factors that affect and reduce at the overall efficiency of an antenna. Some of the most significant factors that impact antenna gain include impedance matching, network losses, material losses and random losses. By considering all factors, it would appear that the antenna must overcome a lot of adversity in order to achieve acceptable gain performance.

Directivity gain: $G_D(\vartheta, \phi) = \dfrac{4\pi U(\theta,\phi)}{P_r} = \dfrac{4\pi\left|\vec{E}(\theta,\phi)\right|^2}{\int_0^{2\pi}\int_0^{\pi}\left|\vec{E}(\theta,\phi)\right|^2 \sin\theta d\theta d\phi}$, $\therefore D = (G_D)_{max}$

Power gain: $G_P = \dfrac{4\pi U_{max}}{P_i}$, where $P_i = P_r + P_l$, P_i: total input power, P_l: loss

Radiation efficiency: $\eta_r = G_P/D = P_r/P_i$

Radiation Pattern

The radiation patterns of an antenna provide the information that describes how the antenna directs the energy it radiates. If an antennas is100% efficient, it will radiate the same total energy for equal input power regardless of the pattern shape. Radiation patterns are generally presented on a relative power dB scale.

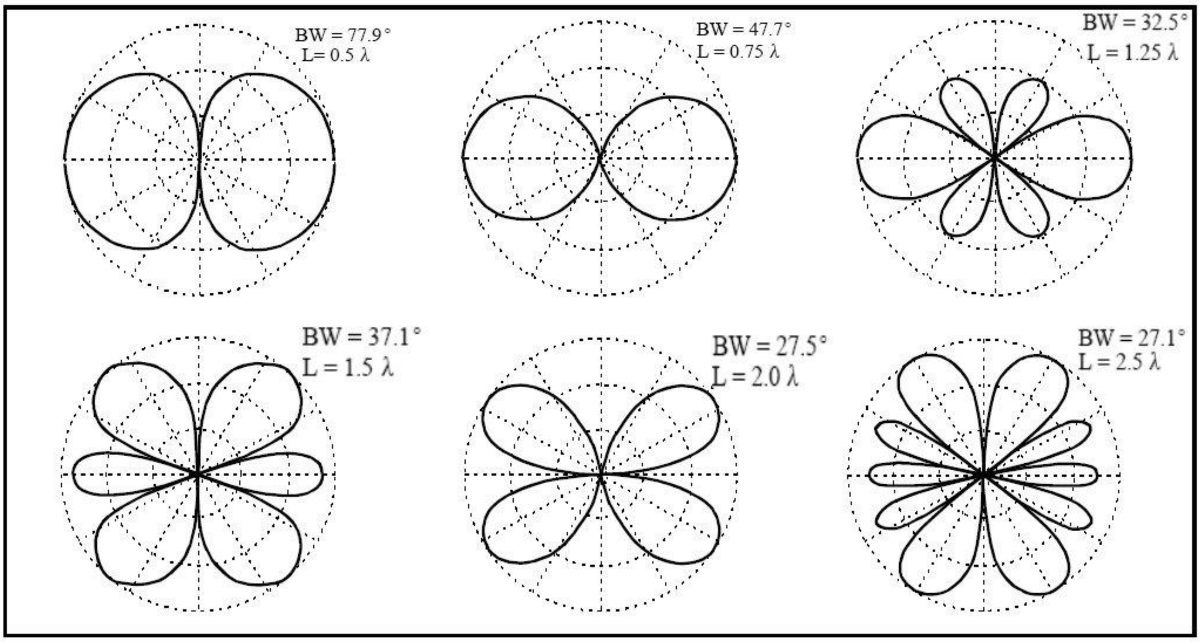


Figure 2.1 Radiation pattern

Half-power beam width: Angular width of main beam between the half-power (-3dB) points

Side lobe level: ($|E_{max}|$ in one side lobe)/ ($|E_{max}|$ in main beam)

Null positions: Directions which have no radiations in the far-field zone.

Directivity

Directivity, D is important parameter that shows the ability of the antenna focusing radiated energy. Directivity is the ratio of maximum radiated to radiate reference antenna. Reference antenna usually is an isotropic radiator where the radiated energy is same in all direction and has directivity of unity. Directivity is defined as the following equation:

D = F_{max} /F_0

Where

F_{max} = Maximum radiated energy

F_0 = Isotropic radiator radiated energy

Directivity: $D=\frac{4\pi U_{max}}{P_r}=\frac{4\pi\left|\vec{E}_{max}\right|^2}{\int_0^{2\pi}\int_0^{\pi}\left|\vec{E}(\theta,\phi)\right|^2\sin\theta d\theta d\phi}$, where $U=R^2P_{av}\propto R^2\left|\vec{E}\right|^2$

And $P_r=\oint P_{av}dS=\oint Ud\Omega\propto R^2\int_0^{2\pi}\int_0^{\pi}\left|\vec{E}\right|^2\sin\theta d\theta d\phi$ is the time-average radiated power

Polarization

The polarization of an antenna describes the orientation and sense of the radiated wave's electric field vector. There are three types of basic polarization:

- Linear polarization
- Elliptical polarization
- Circular polarization

Generally most antennas radiate with linear or circular polarization. Antennas with linear polarization radiate at the same plane with the direction of the wave propagate. For circular polarization the antenna radiate in circular form.

Bandwidth

The term bandwidth simply defines the frequency range over which an antenna meets a certain set of specification performance criteria. The important issue to consider regarding bandwidth is the performance trade-offs between all of its performance properties described above. There are two methods for computing an antenna bandwidth.

An antenna is considered broadband if $f_h/f_l \geq 2$

Narrowband by % age

BW_P = **(f_h-f_l)/f_c** ×100**%**

Broadband by ratio BWb= f_h/f_l

Where

f_c= center frequency

f_h = Higher cut-off frequency

f_l = Lower cut-off frequency

2.2 Basic Microstrip Antenna

Microstrip antenna have been of the most innovative topic in antenna theory and design in recent years. And are increasingly finding application in a wide range of modern microwave system. In 1960's microwave semiconductor device were developed. These device were fabricated on semiconductor chips of very small volume and mounted in suitably designed packages.

Basic configuration of a microstrip antenna is a metallic path printed on a thin, grounded dielectric substrate. The micro strip antenna radiates relatively broad beam broad side to the plane of the substrate. Thus the micro strip antenna has a very low profile and can be fabricated using printed circuit or photolithography technique. Other advantage include the fabrication into linear or planes arrays and easy integration with microwave integrated circuit. To a large extent the development of a micro strip antenna have been driven by system requirement for antennas with low weight, low cost, last integeablitiy into array or with microwave integrated circuits for polarization diversity. Among the several configuration, there are four basic forms which are widely used in microwave integrated circuits.

There are,

1. Strip line
2. Slot line
3. Coplanar wave guide
4. Microstrip line

In this forms the microstrip line is widely used.

Microstrip line

Microstrip line consist of a dielectric substrate with strip conductor on one side baked by ground plane on the other side. This is most commonly used transmission line structure for

Microwave integrated circuit and is shown in the figure. The characteristic impedance of the microstrip line is determined by the strip width, substrate thickness and dielectric constant.

Microstrip structure

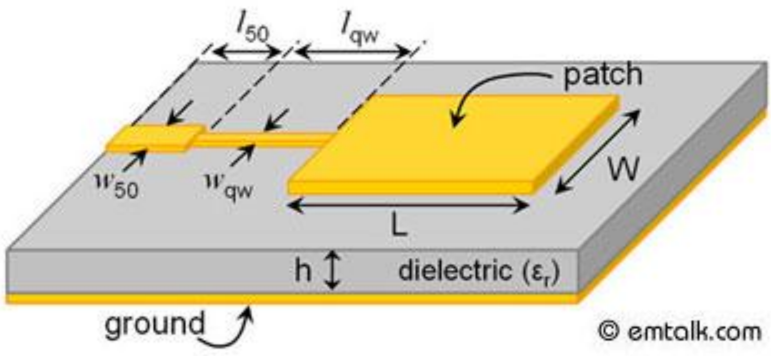


Figure 2.2 Microstrip Antenna structure

Basic characteristics

In this section we will summarize the basic operation an electrical characteristics of microstrip antenna consider the basic microstrip antenna with rectangular with probe feed. When operating in the transmitting mode the antenna is driven with a voltage between feed probe and ground plane. This exits current on the patch and the ground plane. The dielectric substance is usually electrically thin. So the dielectric field components paralleled to the ground plane must very small throughout the substrate. The patch element resonates when its length is near ½, leading to relatively large field and current amplitudes.

The magnetic pole approximation of the cavity model and the open and approximation of the transmission line model become more realistic as the substrate becomes thin. This implies that the Q of the patch antenna on a thin substrate is large and that the bandwidth is small from an alternative point. The current on the patch element is in very close proximity to its reimage caused by the presence of the ground plane. This causes near cancellation of radiation field and relatively large stored energy below the patch impedance bandwidth of a microstrip element. It is seen that the bandwidth increases with substrate thickness and decreased with an increased in substrate permittivity.

Principle of operation

Using a bank like model the electric field lines at the edge of the patch can be resolved into normal and tangential components. Only the next field radiate and from the far back pattern for the antenna. The microstip antenna when operating in the transmitting mode is driven with a voltage source between the feed probe and ground plane. The electric field component parallel to the ground plane are small at the dialectic substrate is electrically very thin. As the length of the patch is nearly 0 there are large currents and field components at resonance. The resulting radiation is due to the magnetic current radiating in the presence of ground plane and induced surface current density on the patch conductor in the conductor in the presence of the ground dialectic substrate surface.

2.3 Feeding techniques

Feeding techniques [1-2-13] are important in designing the antenna to make antenna structure so that it can operate at full power of transmission. Designing the feeding techniques for high frequency, need more difficult process. This is because the input loss of feeding increases depending on frequency and finally give huge effect on overall design. There are a few techniques that can be used.

1. Microstrip Line feeding
2. Coaxial Probe feeding
3. Aperture Coupled feeding
4. Proximity Coupled feeding
5. CPW feeding

a. Microstrip Line feeding

It has more substrate thickness i.e. directly proportional to the surface wave. Radiation bandwidth limit is 2-5%.It is easy to fabricate and model. Microstrip line feed is one of the easier methods to fabricate as it is a just conducting strip connecting to the patch and therefore can be consider as extension of patch. It is simple to model and easy to match by controlling the inset position. However the disadvantage of this method is that as substrate thickness increases, surface wave and spurious feed radiation increases which limit the bandwidth.

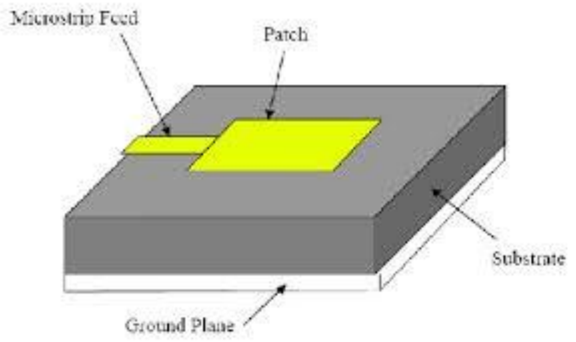


Figure 2.3 Microstrip line feed

2.4.2 COAXIAL PROBE FEEDING

It has low spurious radiation and narrow bandwidth. Coaxial feeding is feeding method in which that the inner conductor of the coaxial is attached to the radiation patch of the antenna while the outer conductor is connected to the ground plane difficult to model.

Advantages

- Easy to fabricate
- Easy to match
- Has low spurious radiation

Disadvantages

- Has narrow bandwidth
- It is difficult to model specially for thick substrate
- .It is easy to fabricate but it possesses inherent asymmetries which generate higher order modes which produce cross-polarization radiation.

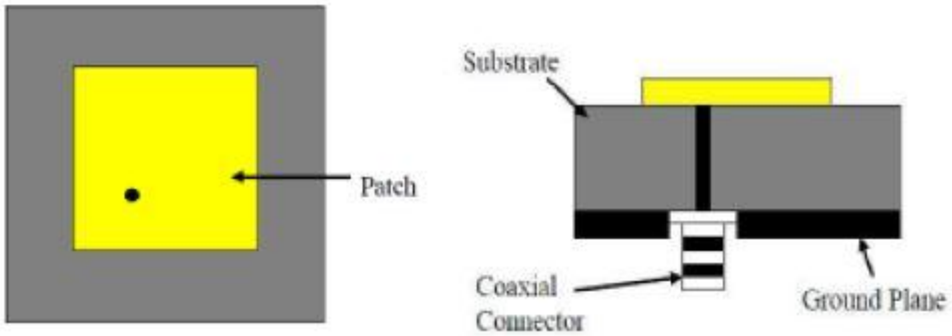


Figure 2.4 Coaxial Probe feeding

2.4.3 APERTURE COUPLED FEEDING

It has a narrow bandwidth and moderate spurious radiation. It consists of two different substrates separated by a ground plane. Below the lower substrate, there is a microstrip feed line whose energy is coupled to the patch through a slot on the ground plane separating two substrates. Such arrangement allows independent optimization of the feed mechanism and the radiating element. Normally, the top substrate uses a thick low dielectric constant substrate while the bottom substrate has high dielectric permittivity. The ground plane isolates the feed from radiation element and minimizes interference of spurious radiation for pattern format ion and pure polarization.

Advantages:

It allows optimization of feed mechanism element.

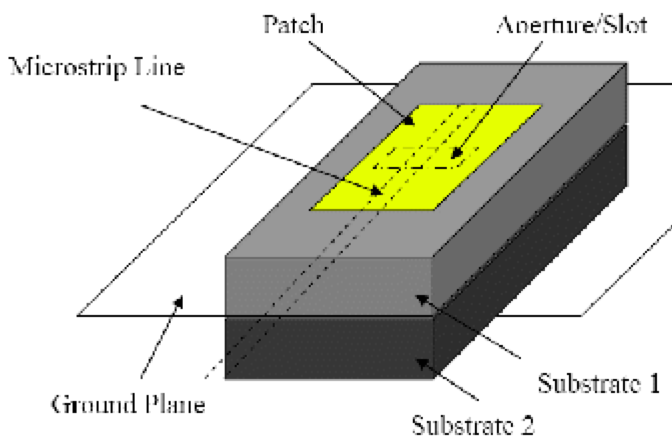


Figure 2.5 Aperture coupling feeding

2.4.4 Proximity Coupled feed

Proximity coupling has the largest bandwidth, has low spurious radiation. However fabrication is difficult. Length of feeding stub and width-to-length ratio of patch is used to control the match.

Advantage

- It has largest band width.

- It is easy to model.
- It has low spurious radiation and is difficult to fabricate.

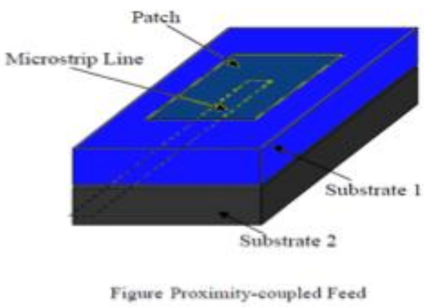


Figure 2.6 proximity coupled feed

Chapter 3

FRACTAL ANTENNA

3.1 Introduction

The use of fractal geometries has significantly impacted many areas of science and engineering; one of which is antennas. Antennas using some of these geometries for various telecommunications applications are already available commercially. The use of fractal geometries has been shown to improve several antenna features to varying extents. Yet a direct corroboration between antenna characteristics and geometrical properties of underlying fractals has been missing. This research work is intended as a first step to fill this gap.

In terms of antenna performance, fractal shaped geometries are believed to result in multi-band characteristics and reduction of antenna size. Although the utility of different fractal geometries varies in these aspects, nevertheless they are primary motives for fractal antenna design. For example, monopole and dipole antennas using fractal Sierpinski gaskets have been widely reported and their multiband characteristics have been associated with the self-similarity of the geometry. However this qualitative explanation may not always be realized, especially with other fractal geometries. A quantitative link between multiband characteristics of the antenna and a mathematically expressible feature of the fractal geometry is needed for design optimization. To explore this, a Koch curve is chosen as a candidate geometry, primarily because its similarity dimension can be varied from 1 to 2 by changing a geometrical parameter (indentation angle). Extensive numerical simulations presented here indicate that this variation has a direct impact on the primary resonant frequency of the antenna, its input resistance at this frequency, and the ratio of the first two resonant frequencies. In other words, these antenna features can now be quantitatively linked to the fractal dimension of the geometry. This finding can lead to increased flexibility in designing antennas using these geometries.

3.2 Fractal theory

In modern wireless communication systems wider bandwidth, multiband and low profile antennas are in great demand for both commercial and military applications. This has initiated antenna research in various directions; one of them is using fractal shaped antenna elements. Traditionally, each antenna operates at a single or dual frequency bands, where different antennas are needed for different applications. Fractal shaped antennas have already been proved to have some unique characteristics that are linked to the various geometry and properties of fractals. Fractals were first defined by Benoit Mandelbrot in 1975 as a way of classifying structures whose dimensions were not whole numbers. Fractal geometry has unique geometrical features occurring in nature. It can be used to describe the branching of tree leaves and plants, rough terrain, jaggedness of coastline, and many more examples in nature. Fractals have been applied in various field like image compression, analysis of high altitude lightning phenomena, and rapid studies are apply to creating new type of antennas.. Fractals are geometric forms that can be found in nature, being obtained after millions of years of evolution, selection and optimization.

There are many benefits when we applied these fractals to develop various antenna elements. By application of fractals to antenna elements:

- We can create smaller antenna size.
- We achieve resonating frequencies that are multiband.
- Optimize for gain.
- Achieve wideband frequency band or multiband frequencies.

Most fractals have infinite complexity and detail that can be used to reduce antenna size and develop low profile antennas. Self-similarity concept can achieve multiple frequency bands because of different parts of the antenna are similar to each other at different scales Combination of infinite complexity and self-similarity makes it possible to design antennas with various wideband performances.

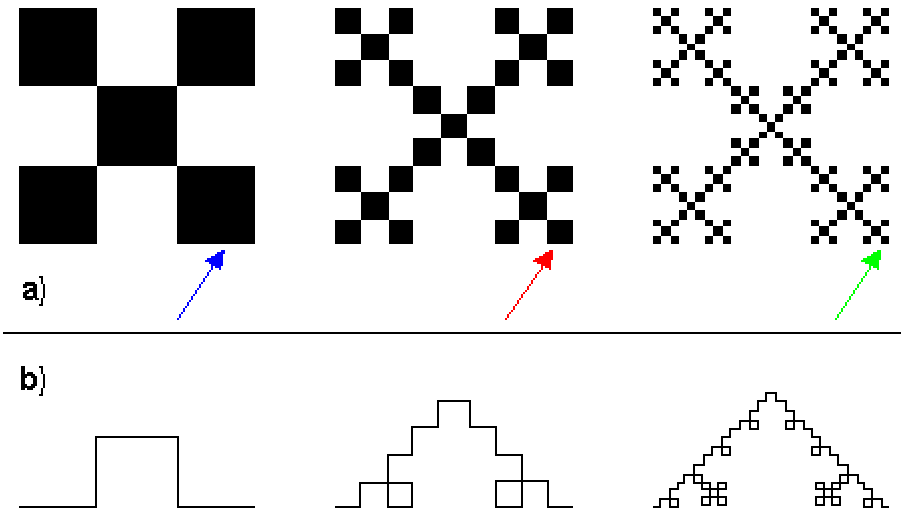
We need fractal antenna for following reasons:

- They have broadband and multi-band frequency response
- Compact size compared to conventional antennas.
- Mechanical simplicity and robustness.
- Characteristics of the fractal antennas are due to its geometry and not because of the addition of discrete components.
- Design to suit particular multi-frequency characteristics containing specified stop bands as well as specific multiple pass bands as required.

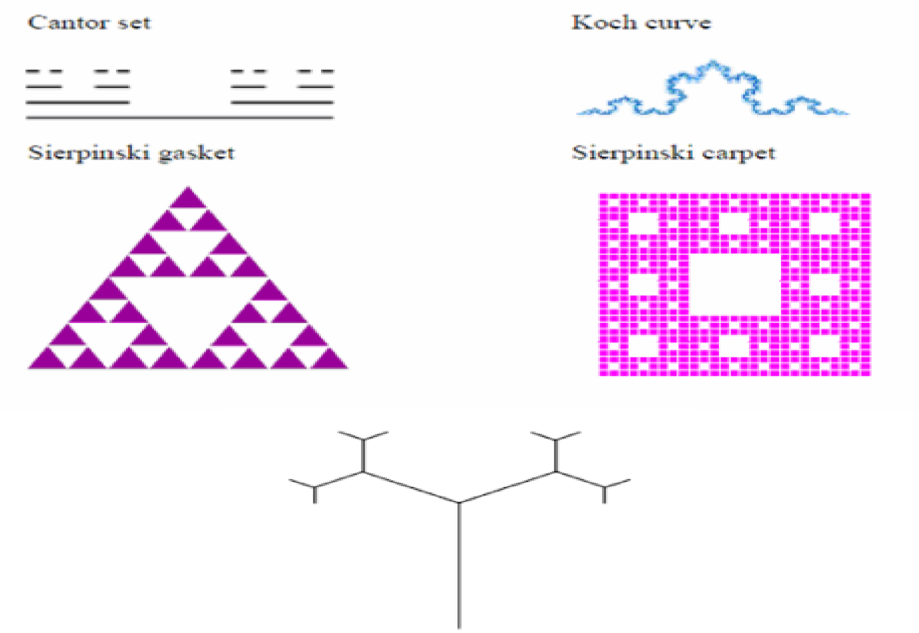
3.3 Fractal Geometries

The term *fractal* was coined by the French mathematician B.B. Mandelbrot during 1970's after his pioneering research on several naturally occurring irregular and fragmented geometries not contained within the realms of conventional Euclidian geometry. The term has its roots in the Latin word *fractus* which is related to the verb *fangere* (meaning: to break). These geometries were generally discarded as formless, but Mandelbrot discovered that certain special features can be associated with them. Many of these curves were recognized well before him, and were often associated with mathematicians of yesteryears. But Mandelbrot's research was path-breaking: he discovered a common element in many of these seemingly irregular geometries and formulated theories based on his findings.

Two examples of naturally occurring fractal geometries are snow-flakes and boundary of geographic continents. Several naturally occurring phenomena such as lightning are better analysed with the aid of fractals. One significant property of all these fractals is indeed their irregular nature. Some examples of fractals are given in Fig. 1.1. Most of these geometries are infinitely sub-divisible, with each division a copy of the parent. This special nature of these geometries has led to several interesting features uncommon with Euclidean geometry.



(a)



(b)

Figure 3.1 (a) and (b) some common examples of Fractal Geometries

Mandelbrot defines the term fractal in several ways. These rely primarily on the definition of their dimension. *A fractal is a set for which the Hausdorff Besicovich* dimension *strictly exceeds its topological dimension*. Every set having non-integer dimension is a fractal. *But fractals can have integer dimension*. Alternately, fractal is defined as set F such that:

F has a fine structure with details on arbitrarily small scales,

F is too irregular to be described by traditional geometry

F having some form of self-similarity (not necessarily geometric, can be statistical)

F can be described in a simple way, recursively, and Fractal dimension of F greater than its topological dimension of a geometry can be defined in several ways, most of these often lead to the same number, albeit not necessarily. Some examples are topological dimension, Euclidean dimension, self-similarity dimension and Hausdorff dimension. Some of these are special forms of Mandelbrot's definition of the fractal dimension. However the most easily understood definition is for self-similarity dimension. To obtain this value, the geometry is divided into scaled down, but identical copies of itself.

a. Sierpinski Gasket Geometry

Sierpinski gasket geometry [1] is the most widely studied fractal geometry for antenna applications. The steps for constructing this fractal are described.1st a triangle is taken in a plane. Then in next step a central triangle is removed with vertices that are located at the midpoint of the sides of the triangle as shown in the figure. The process is then repeated for remaining triangles as shown in figure. The Sierpinski gasket fractal is formed by doing this iterative process infinite number of times. Black triangular areas represent a metallic conductor and the white triangular areas represent the region from where metals are removed.

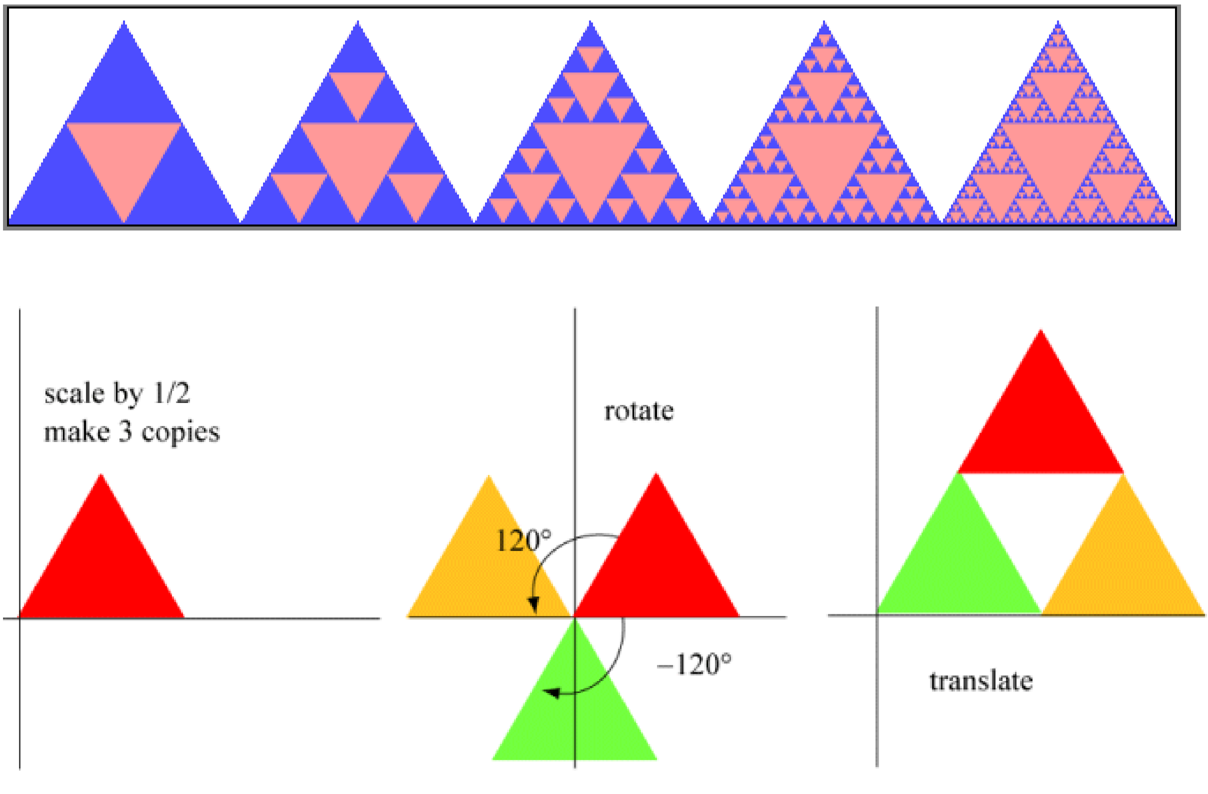


Figure 3.2 Steps of construction of Sierpinski Gasket Geometry

b. Sierpinski Carpet Geometry

The Sierpinski carpet [1] is constructed similar to the Sierpinski gasket, but it use squares instead of triangles. In order to start this type of fractal antenna, it begins with a square in the plane, and then divides it into nine smaller congruent squares where the open central square is dropped. The remaining eight squares are divided into nine smaller congruent squares.

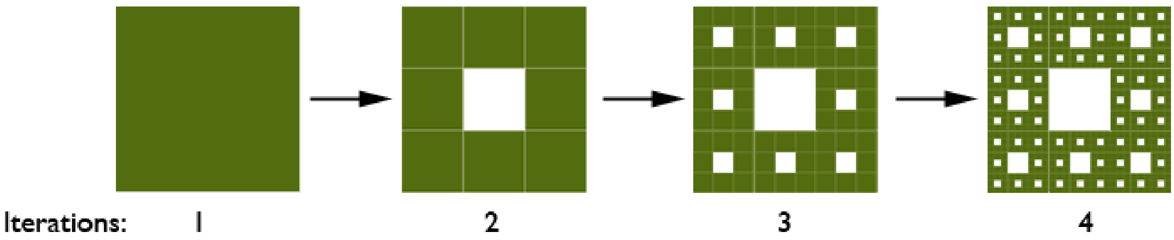
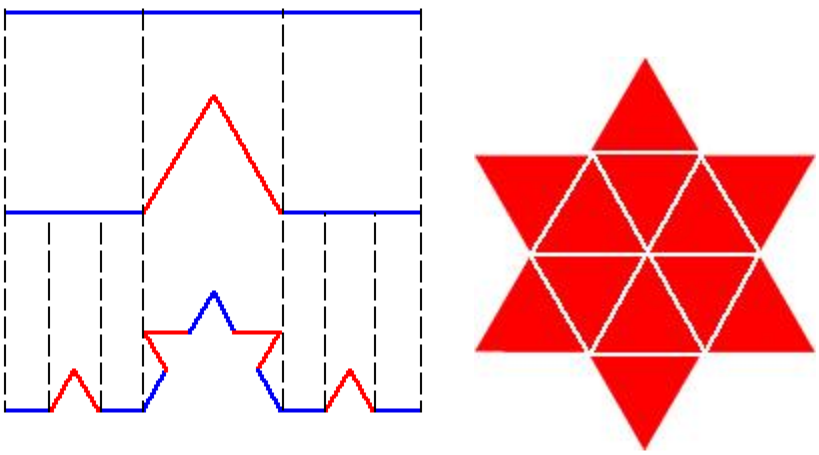


Figure 3.3 Steps for the construction of the Sierpinski Carpet geometry

c. Koch Curves

The geometric construction of the standard Koch curve [1] is fairly simple. It starts with a straight line as an initiator. This is partitioned into three equal parts, and the segment at the middle is replaced with two others of the same length. This is the first iterated version of the geometry and is called the generator. The process is reused in the generation of higher iterations.



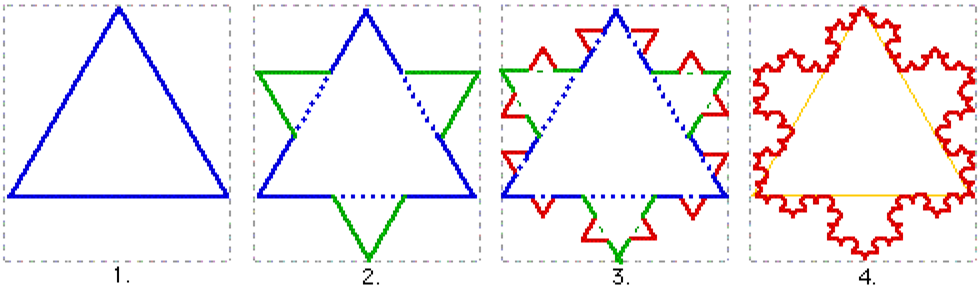


Figure 3.4 Steps for construction of the Koch curve geometry

d. The Cantor Set Geometry

The Cantor Set [1] is created by the following algorithm. It starts with the closed interval [0, 1].

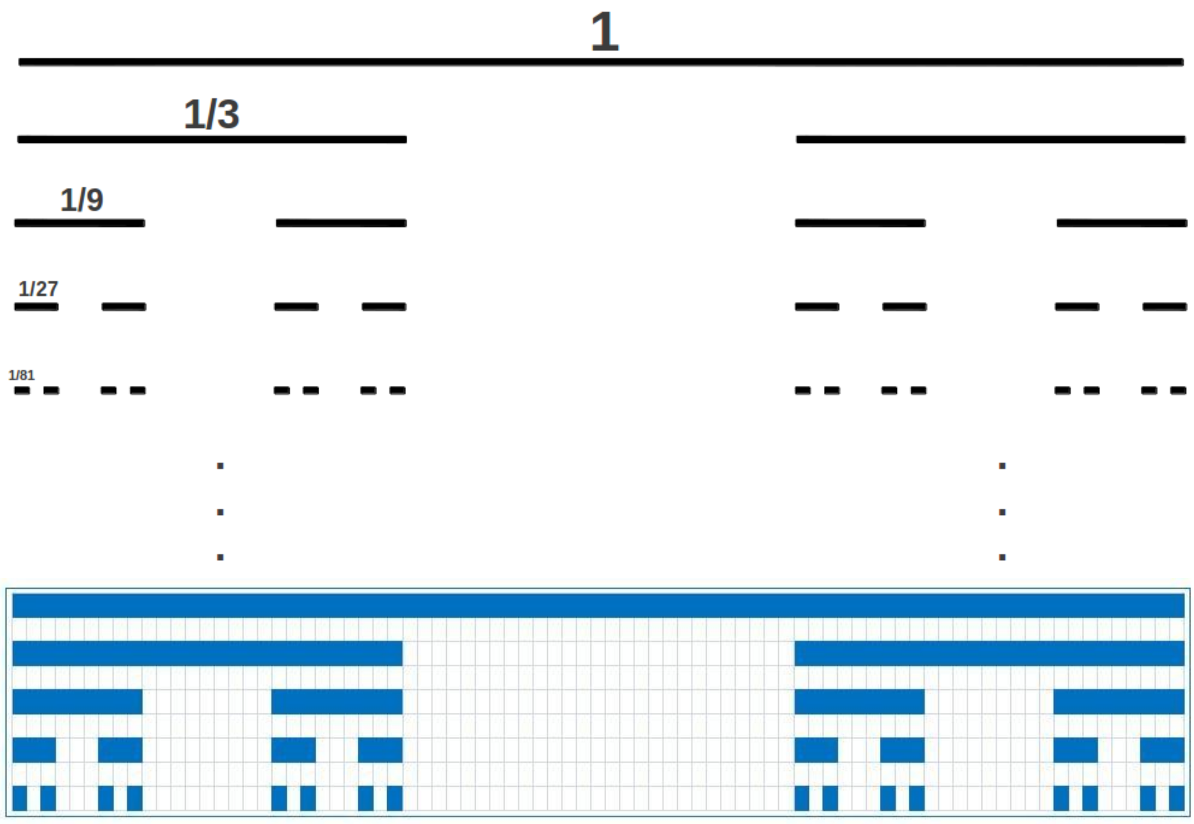


Figure 3.5 steps for construction of the Cantor set

Say it as set A1 or the 0th (initial) set. Delete the middle open third. This leaves a new set, called A2 [0, 1/3] U [2/3, 1]. Each iteration through the algorithm removes the open middle third from each segment of the previous iteration. Thus, the next two sets would be A3[0,1/9]U[2/9,1/3]U[2/3,7/9]U[8/9,1] and according to the previous one A4 set will be A4 [0,1/27]U[2/27,1/9]U[2/9,7/27]U[8/27,1/3]U[2/3,19/27]U[20/27,7/9]U[8/9,25/27]U[26/27,1]. We can see that the set becomes sparser as the number of iteration increases. The Cantor Set is defined to be the set of the points that remain as the number of iterations tends to infinity.

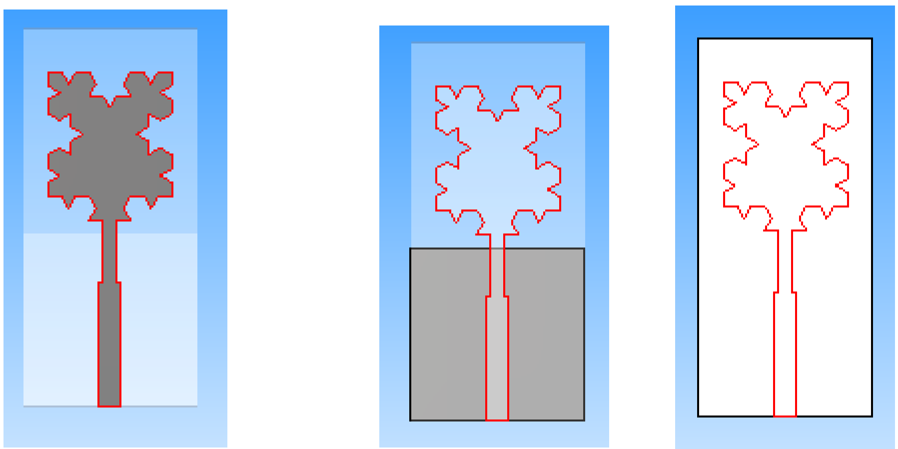
Chapter 4

FRACTAL MONOPOLE WIDEBAND ANTENNAS

4.1 Koch Fractal Curve Monopole Antenna

An antenna based on Koch Fractal geometry and Microstrip line feeding technique for wideband wireless application is studied in this section .The Koch curve structure is applied to the upper, bottom, left and right side of a rectangular patch. The impedance bandwidth of the proposed model is **81.26%** from **3.31-7.84 GHZ** (2:1 VSWR BW).

4.1.1 Antenna Geometry



(a) (b) (c)

Figure 4.1 Geometry of the proposed Koch fractal antenna I (a) Front view (b) Back view (c) substrate

The graphical representation of Koch curve is shown in Figure 4.1. The Geometry of the proposed antenna is illustrated in Figure 4.3 with corresponding optimized parameters listed in Table 4.1.Here, the Koch Fractal is considered in simple rectangular patch edges to expand the antenna bandwidth. The proposed antenna is built on one side of FR-4 dielectric substrate (thickness **t_s=1**.6mm and relative permittivity **ε_r=4.4**) of **14×30.4×1.6mm^3.** It is fed by 50Ω Microstrip line feeding technique of **1.8×10×0.05mm^3** for the transmission line portion and

1.1×5×0.05mm^3 for the quarter wave transformer portion. A first iteration of Koch Fractal Geometry of iteration factor of 3 is applied to the rectangular patch of dimensions **10×10×0.05mm^3**. The proposed antenna uses a partial ground plane of dimensions **14×12.9×0.05mm^3.**

Table 4.1 Design parameters of the proposed Koch fractal Antenna

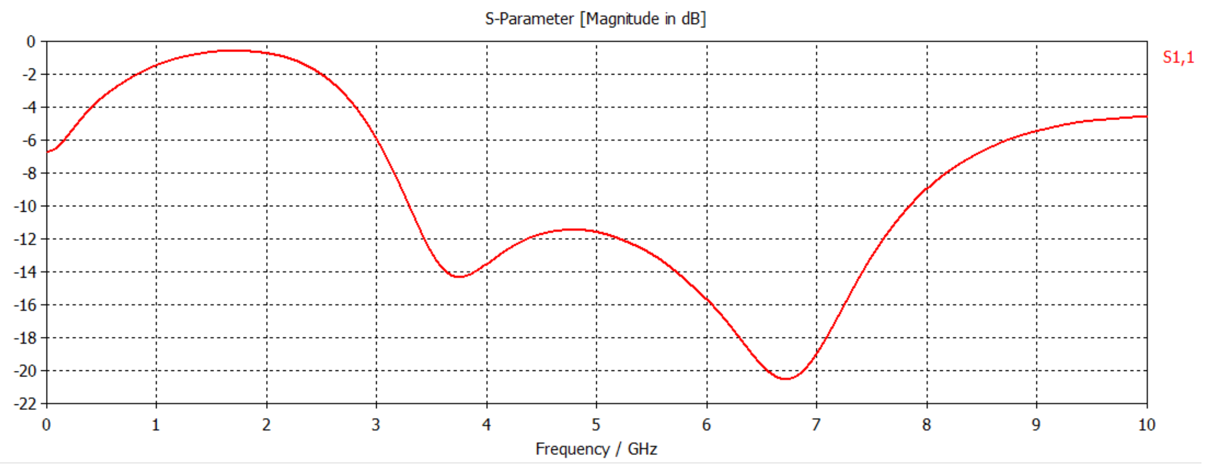
	Length (L)	Width (W)	Height (H)
Ground plane	14 mm	12.9 mm	0.05 mm
Feed line	Lq=1.1 mm 1.8 mm	Wq=5 mm 10 mm	0.05 mm
Patch	10 mm	10 mm	0.05 mm
Substrate	14 mm	30.4 mm	1.6 mm

Lq= Length of the quarter wave Transformer and

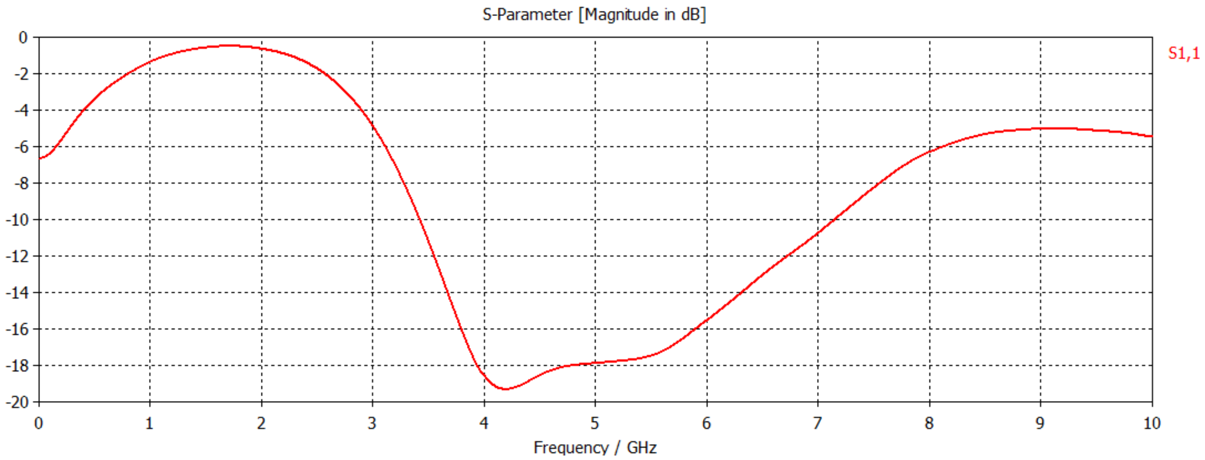
Wq=width of the quarter wave transformer

4.1.2 Simulation Results

1. Return loss



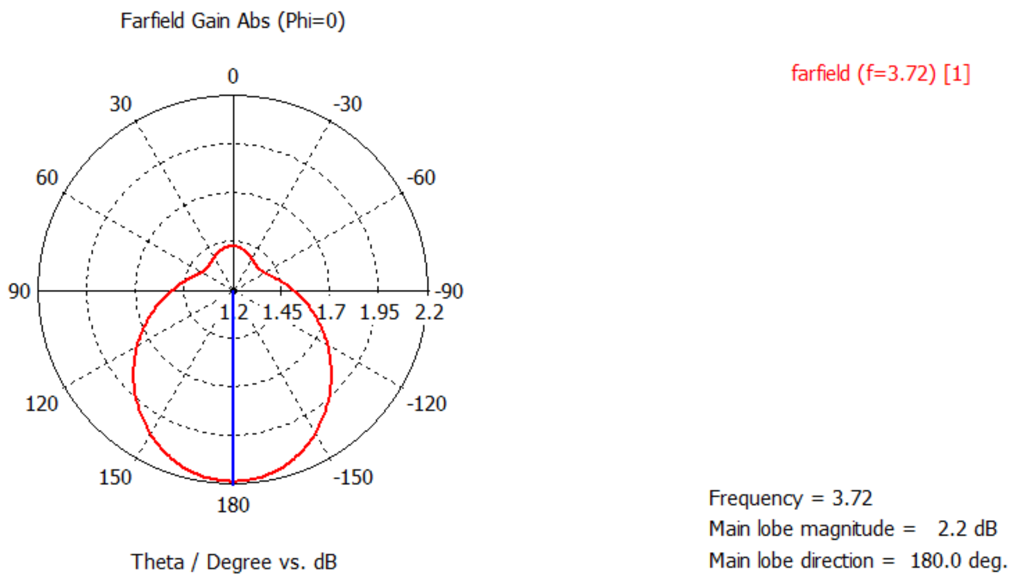
(a)



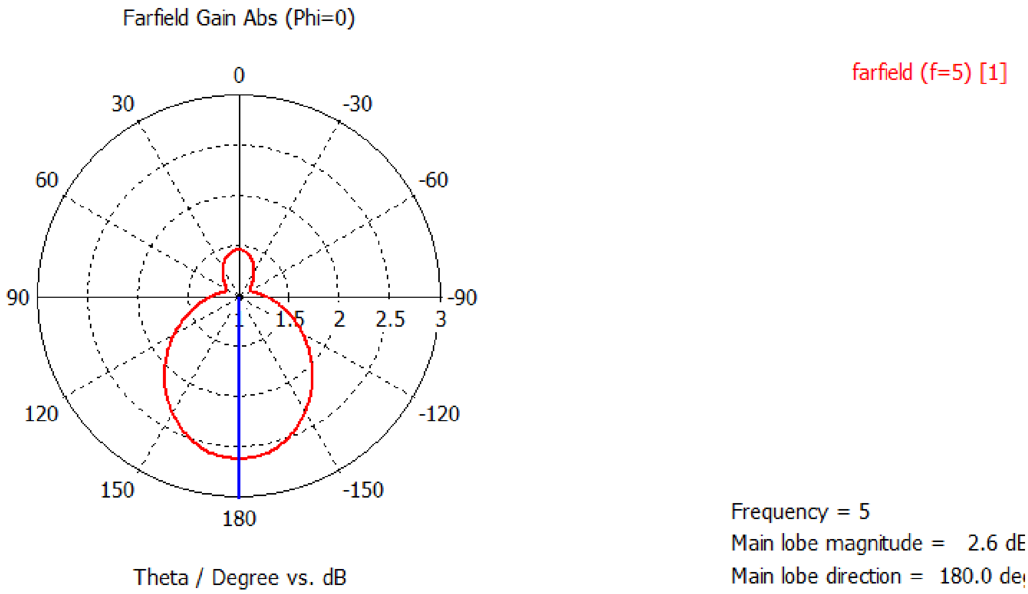
(b)

Figure 4.2 Return loss (a) width of the ground plane (W=12.9mm) (b) W=13.9mm

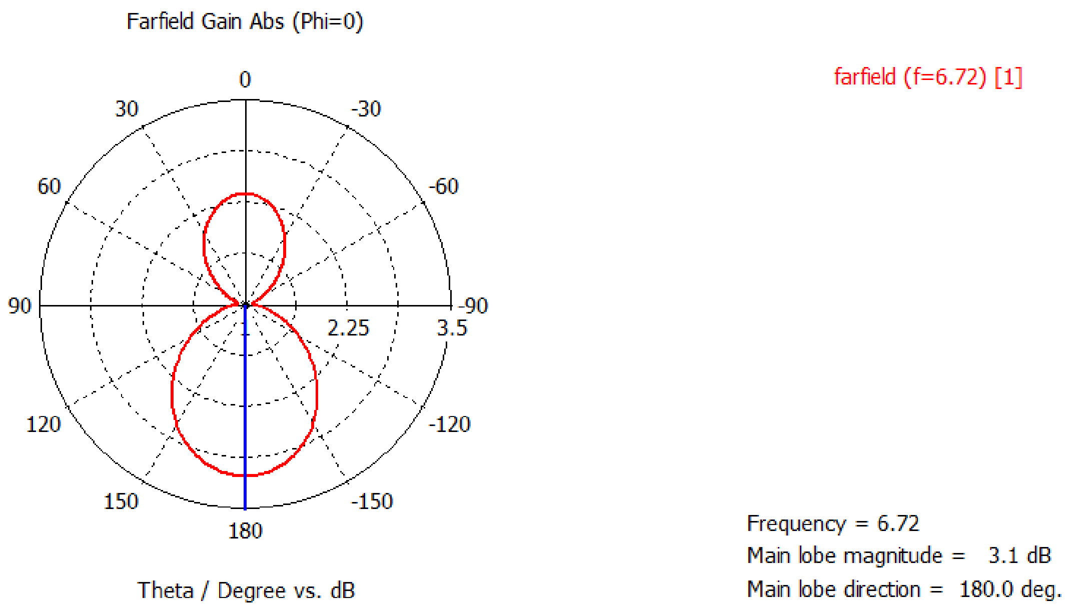
2. Radiation pattern



(a)



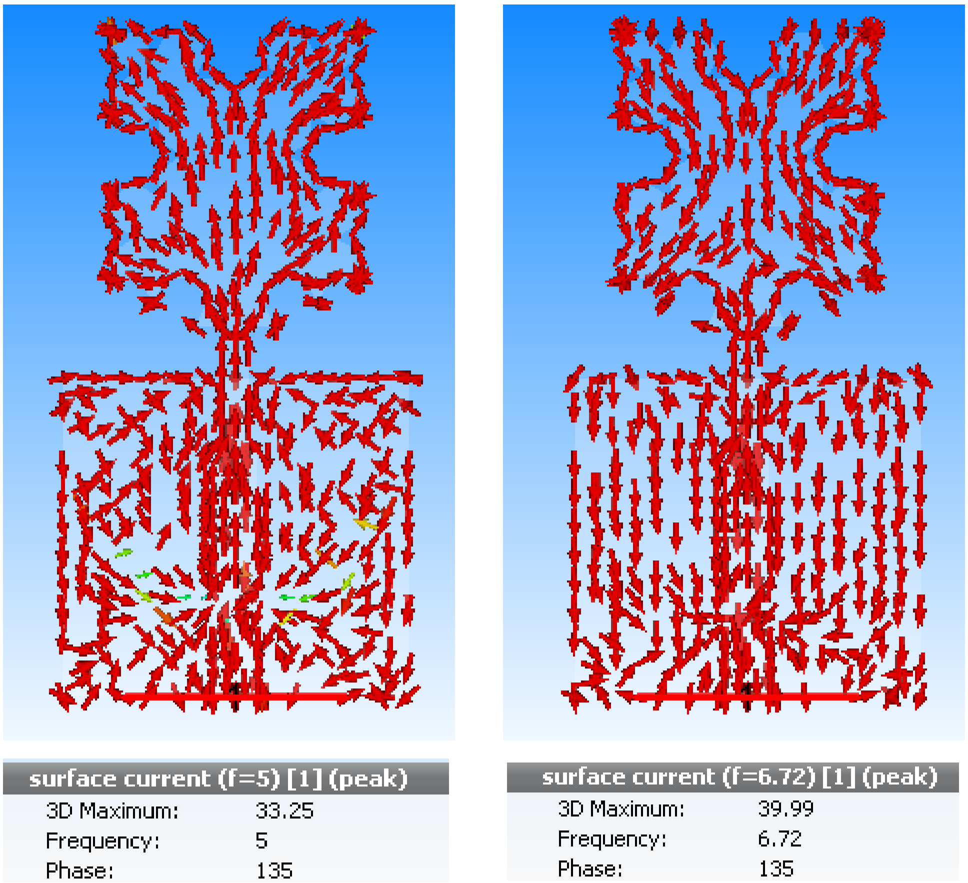
(b)



(c)

Figure 4.3 Radiation pattern (a) at 3.72 GHZ (b) at 5 GHZ (c) at 6.72 GHZ

3. Surface Current distribution



(a) (b)

Figure 4.4. Current distribution (a) at 5GHZ (b) at 6.72GHZ

Figure 4.2 (a) shows the simulated reflection coefficients of the proposed antenna. Figure 4.2 (b) shows the simulated results due to change of the ground plane width (W).The width has a prominent effect on the wideband operation of the proposed Fractal antenna. Although the length of the ground plane has negligible effect, it is fixed in this case. It is observed that the resonant frequency decreases with the increase in ground plane width for example, for W=13.9 mm, the frequency range shifts from (3.31-7.84 GHZ) 8.26% to (3.43-7.14 GHZ)

70.2%.When w=12.9 mm, the impedance bandwidth is well matched bellow -10Db and covers the desired operating bandwidth.

Figure 4.3 and Figure 4.4 illustrate the simulated 2D radiation patterns and surface current distribution of the proposed antenna at 3.72 GHZ, 5GHZ and 7GHZ. It shows that the patterns are omnidirectional in nature for wideband frequency.

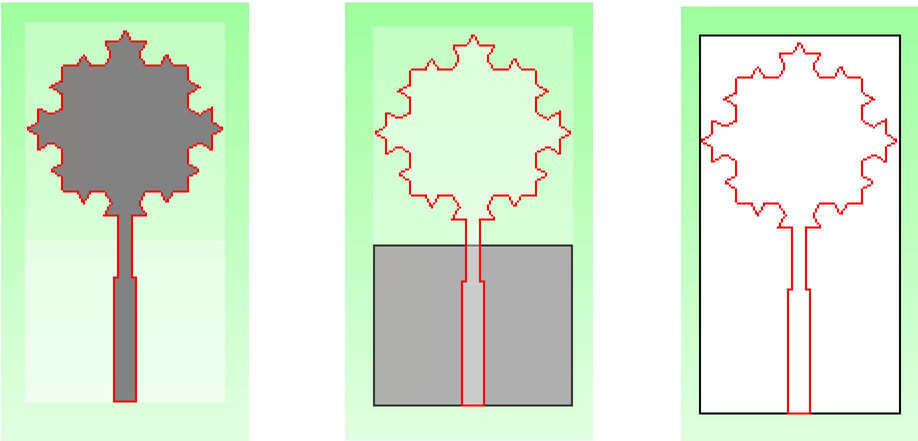
Frequency	3.72 GHZ	4.2 GHZ	5 GHZ	6 GHZ	6.72 GHZ	7 GHZ
Return loss (dB)	-14.68	-19.33	-17.9	-15.53	-12.02	-10.75
Gain (dB)	2.58	2.80	3.17	3.58	3.76	3.66
Efficiency	87.61%	**88.34%**	86.94%	85.94%	82.9%	80.37%

Table 4.2 Measured Gain, Return loss and total simulated Efficiency

4.2 Modified Koch Fractal Curve Monopole Antenna

A modified version of the previous fractal antenna based on Koch Fractal geometry and Microstrip line feeding technique for wideband wireless application is presented here .The Koch curve structure is added on the rectangular patch. The impedance bandwidth of the proposed model is improved from **81.26% (3.31-7.84 GHZ**) to **85.37%** from **3.31-8.24 GHZ** (2:1 VSWR BW).

4.2.1 Antenna Geometry



(a) (b) (c)

Figure 4.5 Geometry of the modified Koch antenna (a) Front view (b) Back view (c) substrate

The graphical representation of the Koch curve is shown in Figure 4.5. The designed and optimized parameters are listed in Table 4.1. The proposed antenna is built on one side of FR-4 dielectric substrate (thickness **ts=1**.6mm and relative permittivity **εr=4.4**) of **16×30.4×1.6mm^3.** It is fed by 50Ω Microstrip line feeding technique of **1.8×10×0.05mm^3** for the transmission line portion and **1.1×5×0.05mm^3** for the quarter wave transformer portion. A first iteration of Koch Fractal Geometry of iteration factor of 3 is applied to the rectangular patch of dimension **10×10×0.05mm^3.** The proposed antenna uses a partial ground plane of dimensions **16×12.9×0.05mm^3.**

Table 4.3 design parameters of the modified Koch fractal Antenna

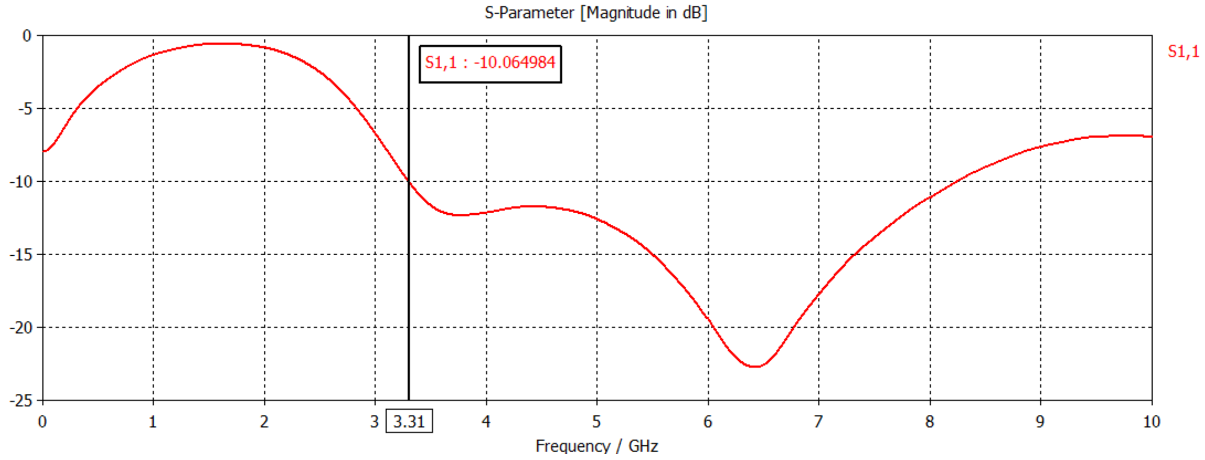
	Length (L)	Width (W)	Height (H)
Ground plane	16 mm	12.9 mm	0.05 mm
Feed line	Lq=1.1 mm 1.8 mm	Wq=5 mm 10 mm	0.05 mm
Patch	10mm	10mm	0.05mm
Substrate	16 mm	30.4 mm	1.6 mm

Lq= Length of the quarter wave Transformer and

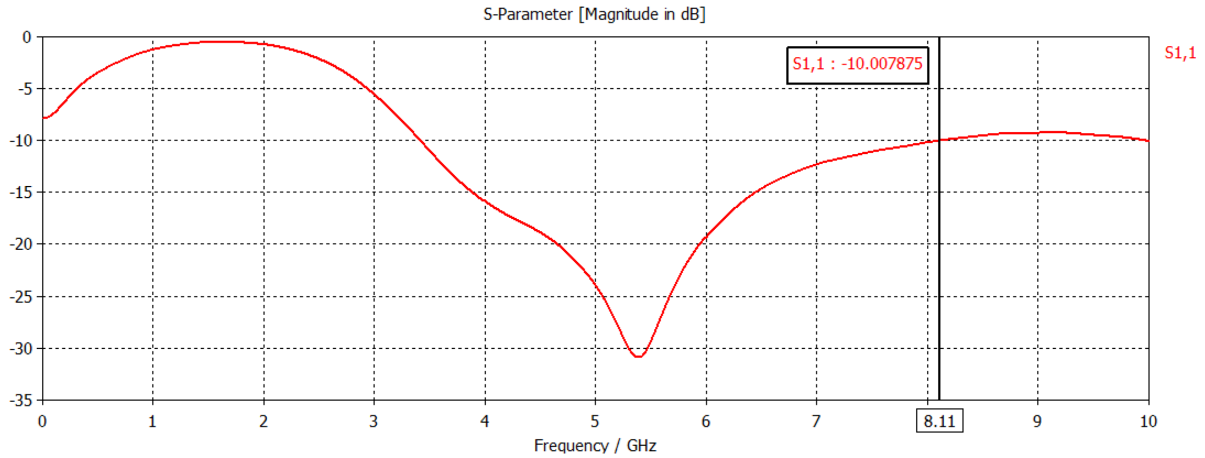
Wq=width of the quarter wave transformer

4.2.2 Simulation Results

1. Return loss



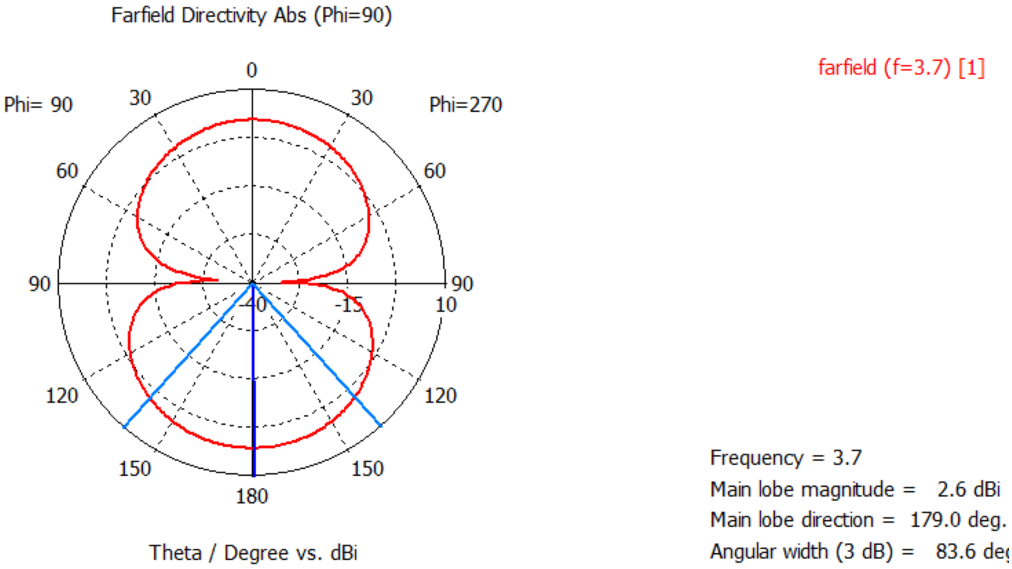
(a)



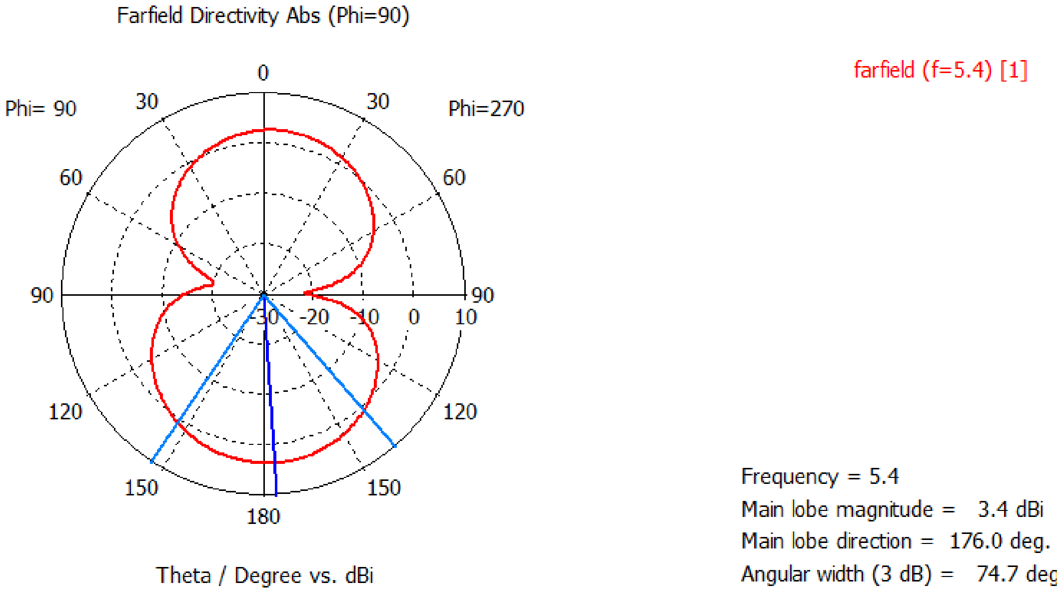
(b)

Figure 4.6 Return loss (a) width of the ground plane (W=12.9mm) (b) W=13.9mm

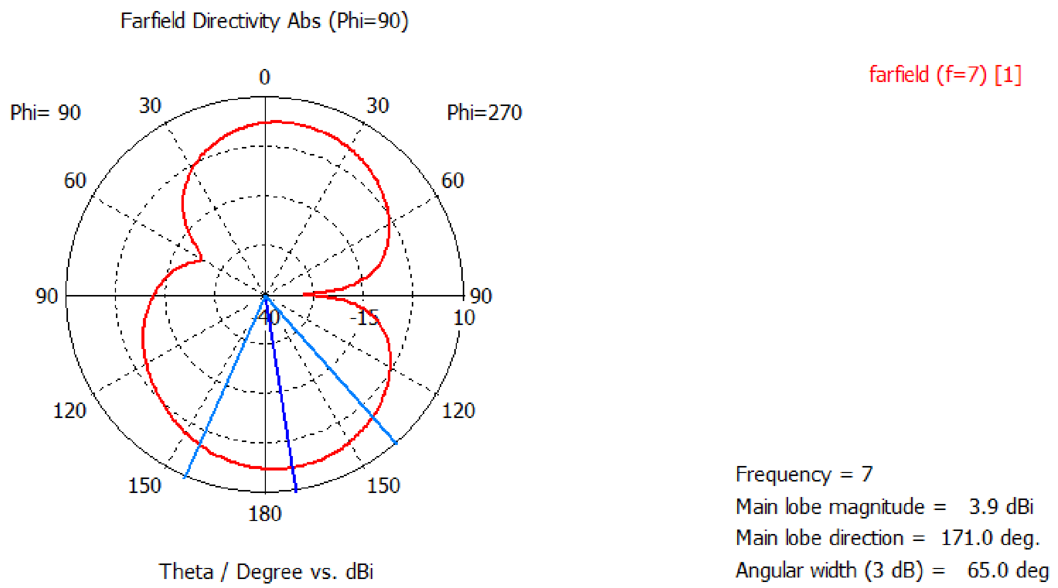
2. Radiation pattern



(a)



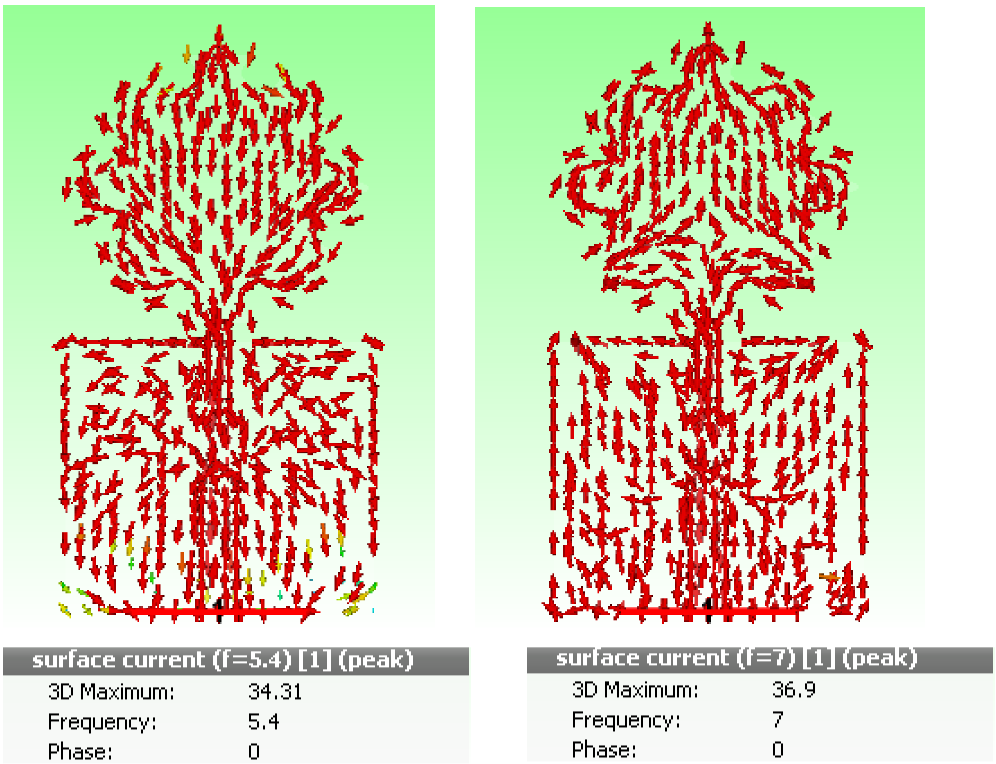
(b)



(c)

Figure 4.7 Radiation pattern (a) at 3.7 GHZ (b) at 5.4 GHZ (c) at 7 GHZ

3. Current distribution



(a) (b)

Figure 4.8 Current distribution (a) at 5.4GHZ (b) at 7GHZ

Frequency	3.7GHZ	4.5 GHZ	5.4 GHZ	6 GHZ	7 GHZ	7.5 GHZ
Return loss (dB)	-12.3	-11.76	-14.35	-19.44	-17.45	-13.88
Gain (dB)	1.96	2.22	2.75	3.1	**3.2**	3.05
Efficiency	87.4	85.14	87.57	**90**	89.38	85.6

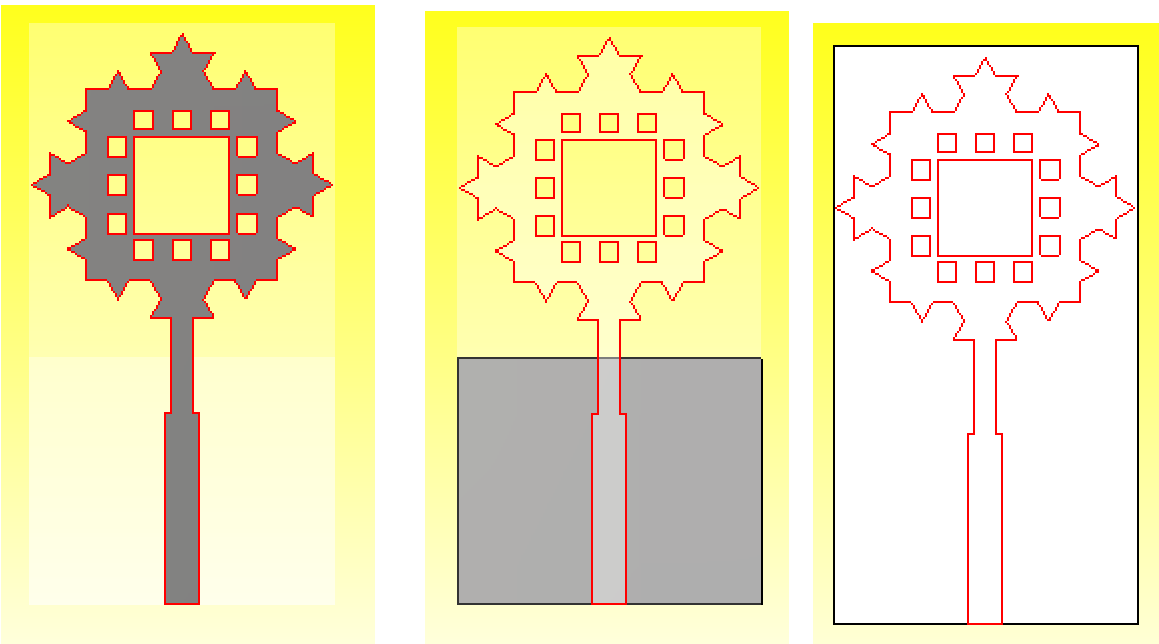
Table 4.4 Measured Gain, Return loss and total simulated Efficiency

4.3 Hybrid Fractal Monopole Antenna

This section presents a new antenna structure based on two fractal geometries for wideband wireless applications which is realised by the combination of Koch curve and the sierpinski carpet geometry. The basic antenna is a rectangular shape as described earlier. The proposed model exhibits a bandwidth **of 85.02%** in the range **3.3-8.18 GHZ** (2:1 VSWR BW).

The measured bandwidth meets the requirements of many commercial bands such as WI-FI 802.11y (3.6-3.7GHZ), WiMAX (3.4-3.6 GHZ and 3.7-4.2 GHZ) and WLAN 802.11(5.31-6.32 GHZ).

4.3.1 Antenna Geometry



(a) (b) (c)

Figure 4.9 Geometry of the Hybrid Fractal Antenna (a) Front view (b) Back view (c) substrate

The recursive procedure of the Koch curve and the sierpinski fractal is shown in Figure 4.9. The Koch curve is added to a rectangular patch is explained for the previous fractal antenna with the same dimensions. The Hybrid fractal antenna optimizes the size of the antenna and enhances the bandwidth as well.

The design is fabricated using FR-4 board with relative permittivity, $\varepsilon r = 4.4$, substrate thickness, $t = 1.6mm$ and tangent loss, $\tan \delta = 0.019$ where the radiating element is the cooper clad.

The iteration of the sierpinski fractal geometry from zero stage until second stage is shown below:

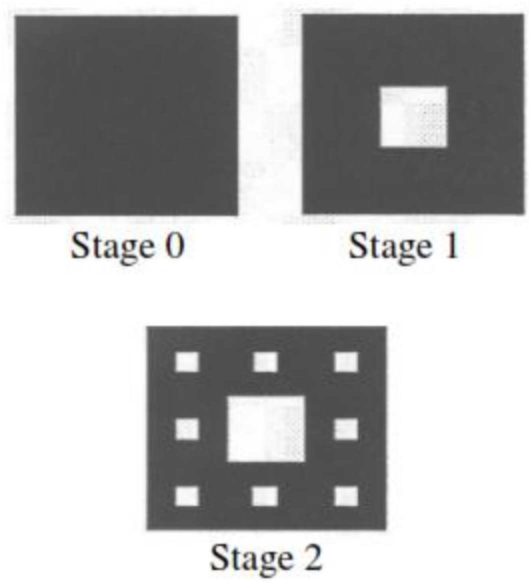


Figure 4.10 stages iteration of the sierpinski geometry used in the design

	Length (L)	Width (W)	Height(H)
Iteration 0	**10mm**	10mm	0.05mm
Iteration 1	**5mm**	5mm	0.05mm
Iteration 2	1.1mm	1.1mm	0.05mm

Table 4.5 design parameters of the sierpinski fractal geometry

4.3.2 Simulation Results

1. Return loss

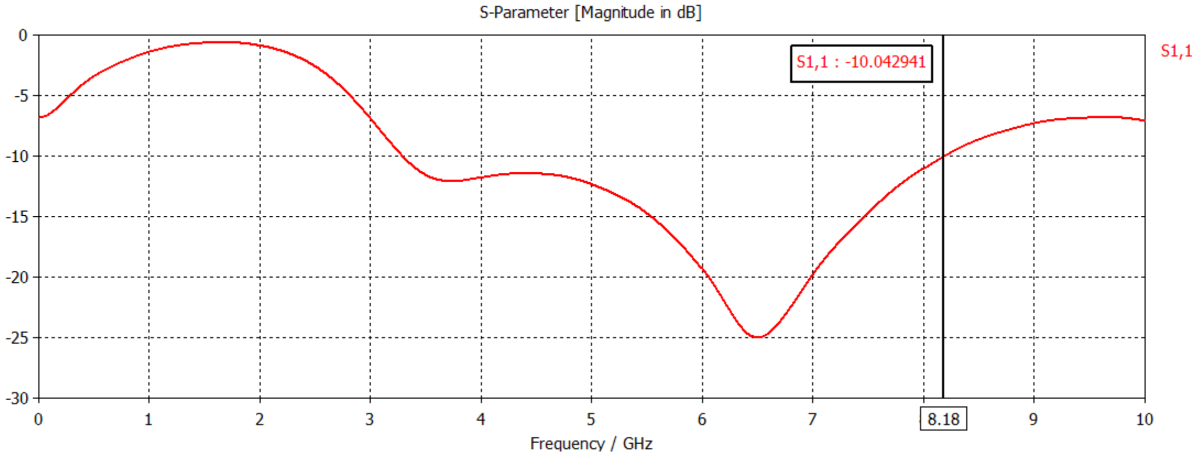
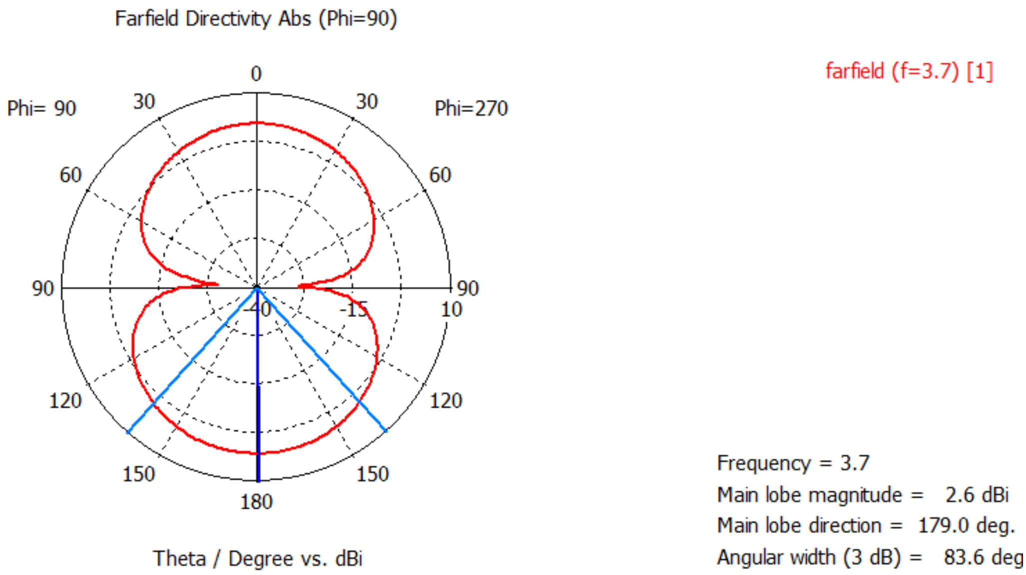
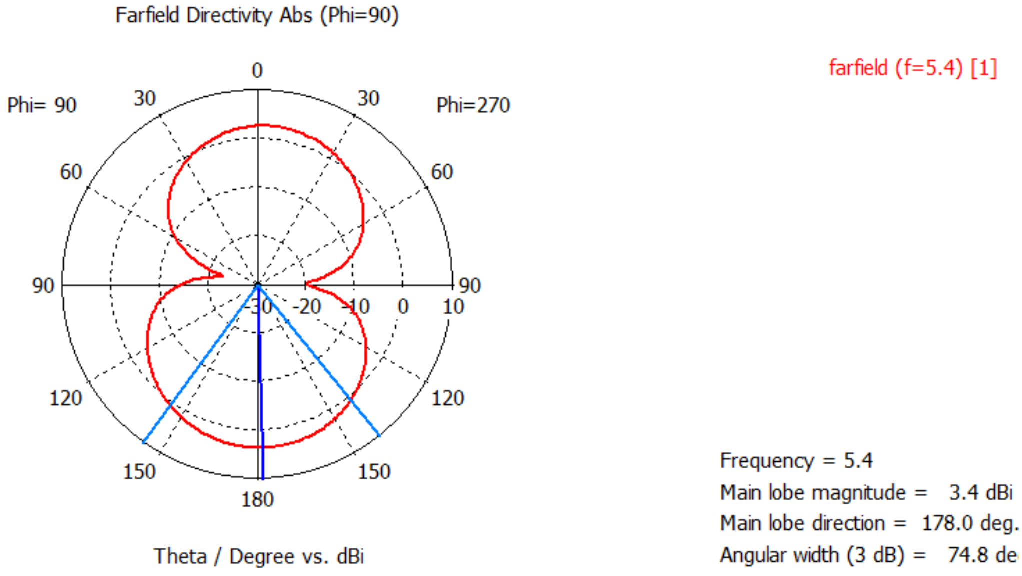


Figure 4.11 Return loss

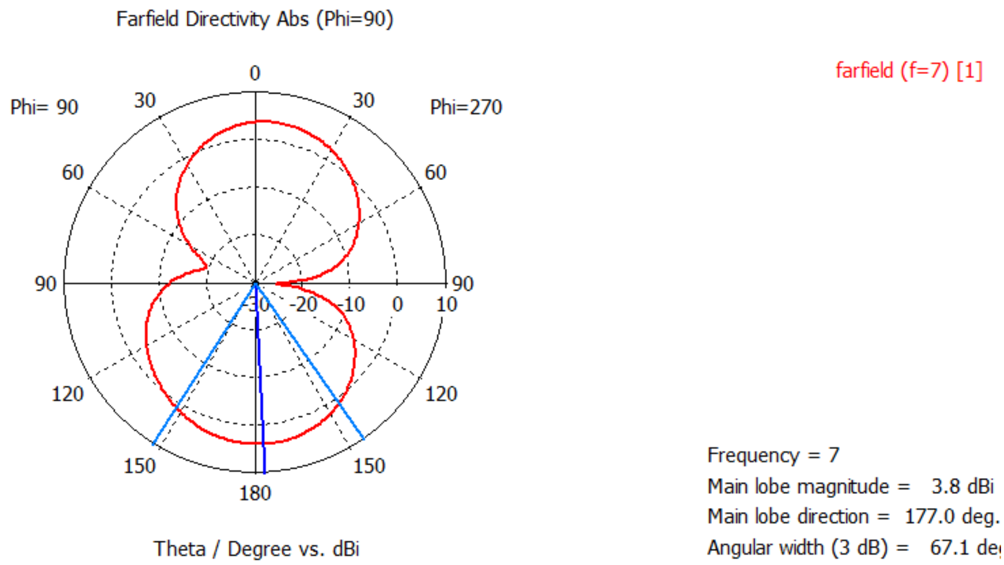
2. Radiation pattern



(a)



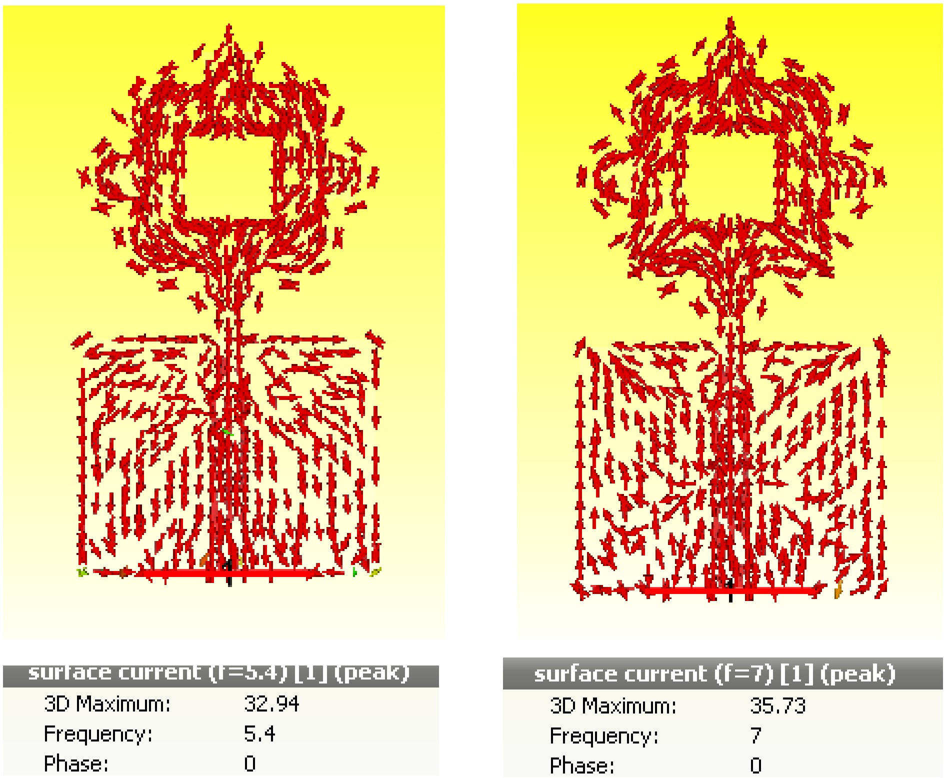
(b)



(c)

Figure 4.12 Radiation pattern (a) at 3.7 GHZ (b) at 5.4 GHZ (c) at 7 GHZ

4.3.2 Surface Current



(a) **(b)**

Figure 4.13 Current distribution (a) at 5.4GHZ (b) at 7GHZ

Figure 4.12 and Figure 4.13 illustrate the simulated 2D radiation patterns and surface current distribution of the proposed antenna at 3.72 GHZ, 5GHZ and 7GHZ. It shows that the patterns are omnidirectional in nature for wideband frequency. The patterns describes the behaviour of the antenna's direction and gain. The surface current distribution shows the different modes of propagation as well as the variation of the resonant frequency.

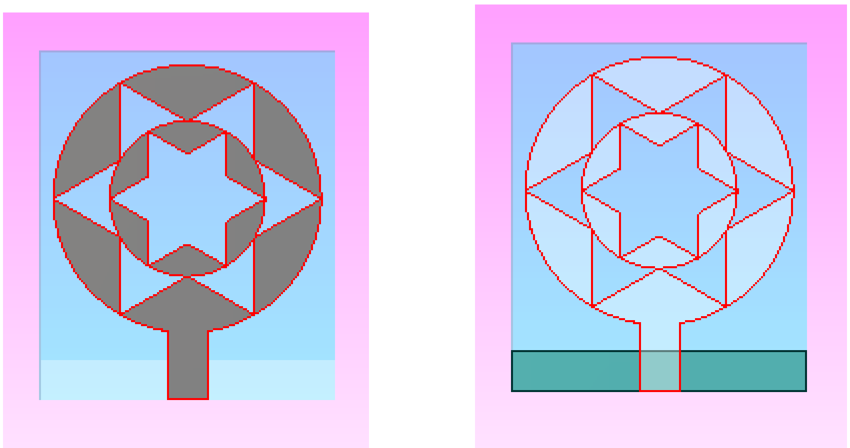
Frequency	3.7GHZ	4.2 GHZ	5.4 GHZ	6.5 GHZ	7 GHZ	7.9 GHZ
Return loss (dB)	-12.1	-11.54	-14.1	-25.0	-19.83	-11.65
Gain (dB)	1.97	2.1	2.77	3.34	3.27	3.4
Efficiency	86.72	84.76	86.94	**90.73**	89.64	80.72

Table 4.6 Measured Gain, Return loss and total simulated Efficiency

4.4 Inscribed triangle circular Fractal Antenna

An inscribed triangle Fractal antenna is presented here for wideband applications. The antenna has been designed on a substrate FR-4 with permittivity εr=4.4 and thickness ts=1.6mm with an initial diameter of 30mm.The antenna exhibits a bandwidth from **3.37-6.53 GHZ (63.8%)** Impendence bandwidth at VSWR 2:1.This wideband characteristic is achieved by using a Microstrip line feeding technique.

4.4.1 Antenna geometry



(a) (b)

Figure 4.14 Geometry of the inscribed triangle circular Fractal antenna

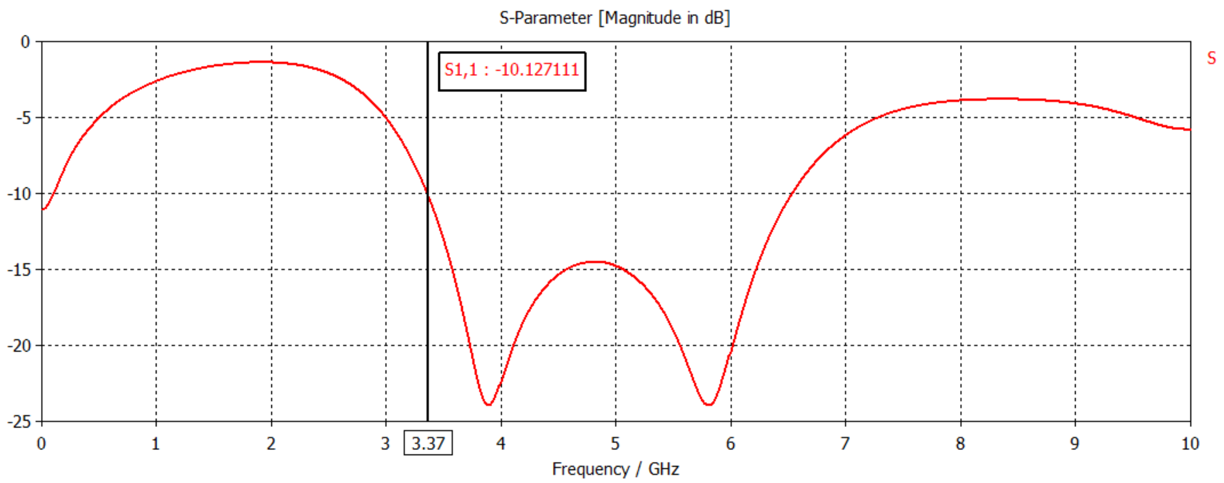
A Fractal Monopole antenna with a Microstrip feed of 10 mm radius is shown in Figure 4.14. Fractal Geometry with each iteration has been constructed from monopole circular disc of 10 mm radius. In the first iteration, four regular polyhedrons of size 2.856 mm has been taken inside the circle of radius 10mm and each polyhedron is rotated with an angle 30 degree. These four polyhedrons were subtracted from the 10 mm circle radius. This is called 1st iteration. In 2nd iteration, a circle of 5.8mm radius has been taken inside these four polyhedrons. In this 5.8 mm radius circle, four polyhedron of size 2.1 mm has been taken again and each polyhedron is rotated with an angle of 30 degree then this four polyhedrons were subtracted from 5.8 mm circle radius resulting in the second iteration.

	Length (L)	Width (W)	Height(H)	Radius
Substrate	22mm	22mm	1.6mm	
Ground plane	22 mm	3mm	0.05mm	
Feed line	3mm	4.8mm	0.05mm	
Patch			0.05mm	10mm

Table 4.7 Design parameters of the inscribed triangle circular fractal antenna

4.4.2 Results

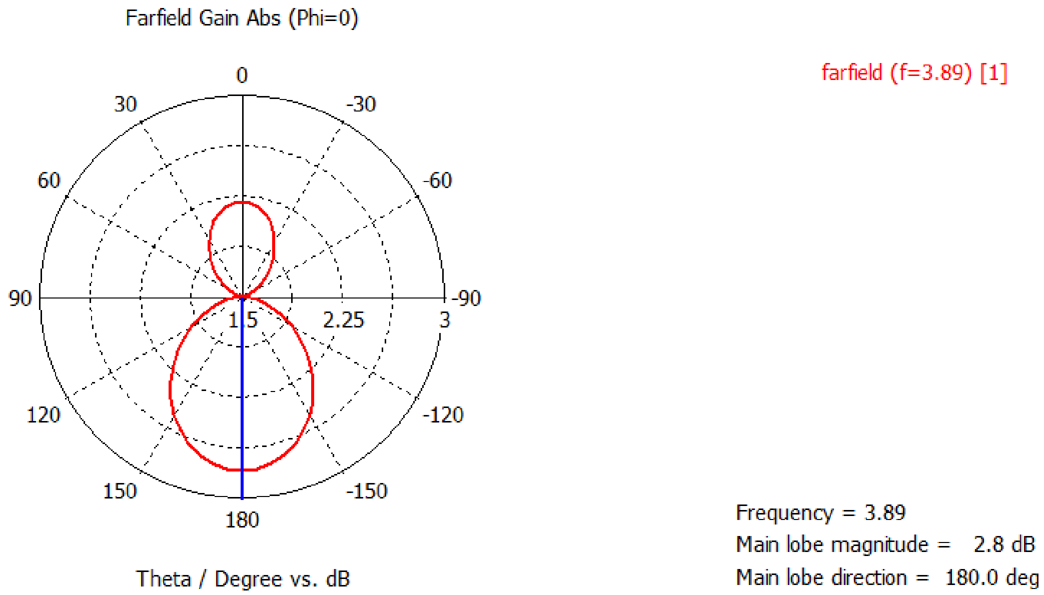
1. Return loss



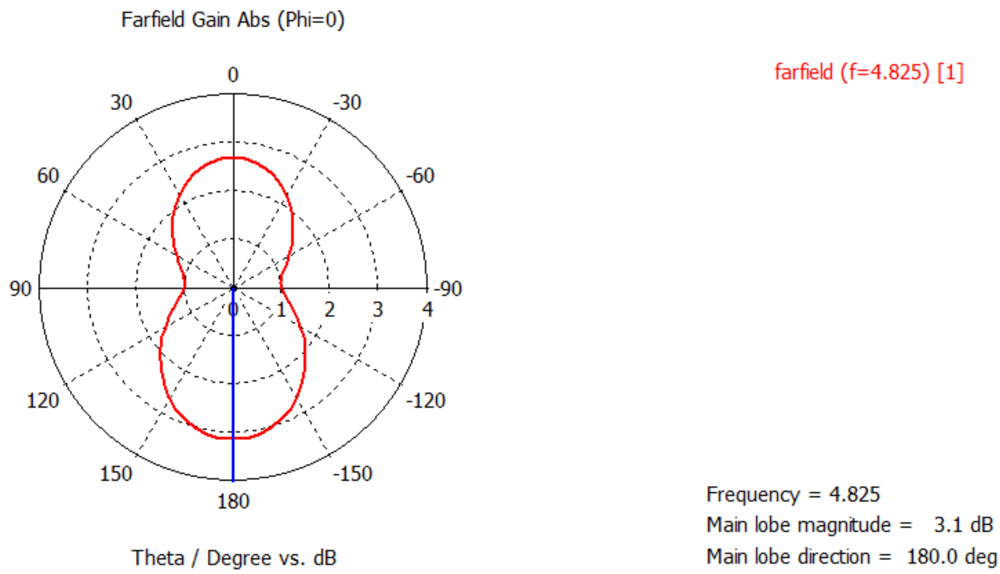
(a)

Figure 4.15 Return loss of the inscribed circular Fractal antenna

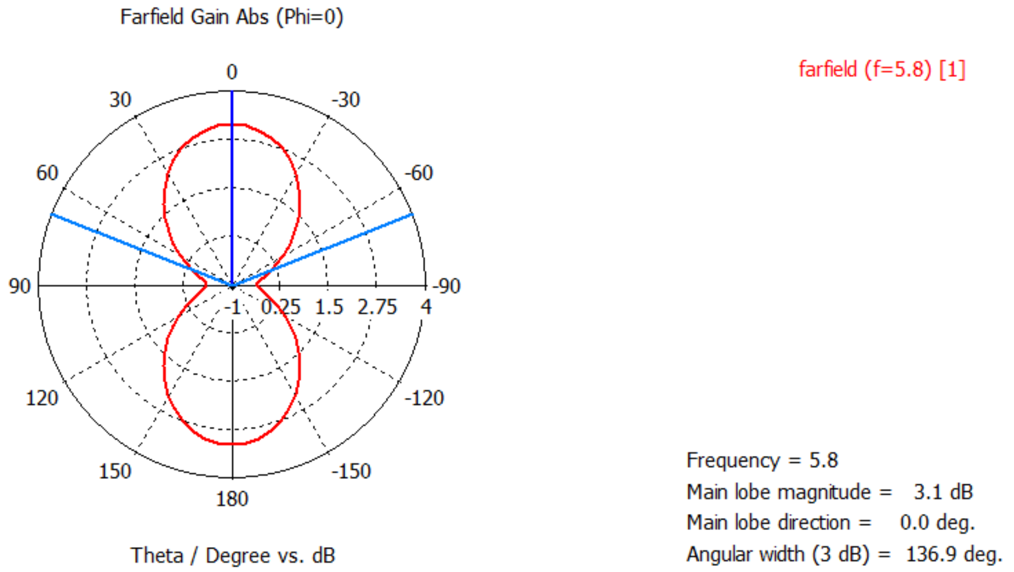
4.4.2 Radiation pattern



(a)



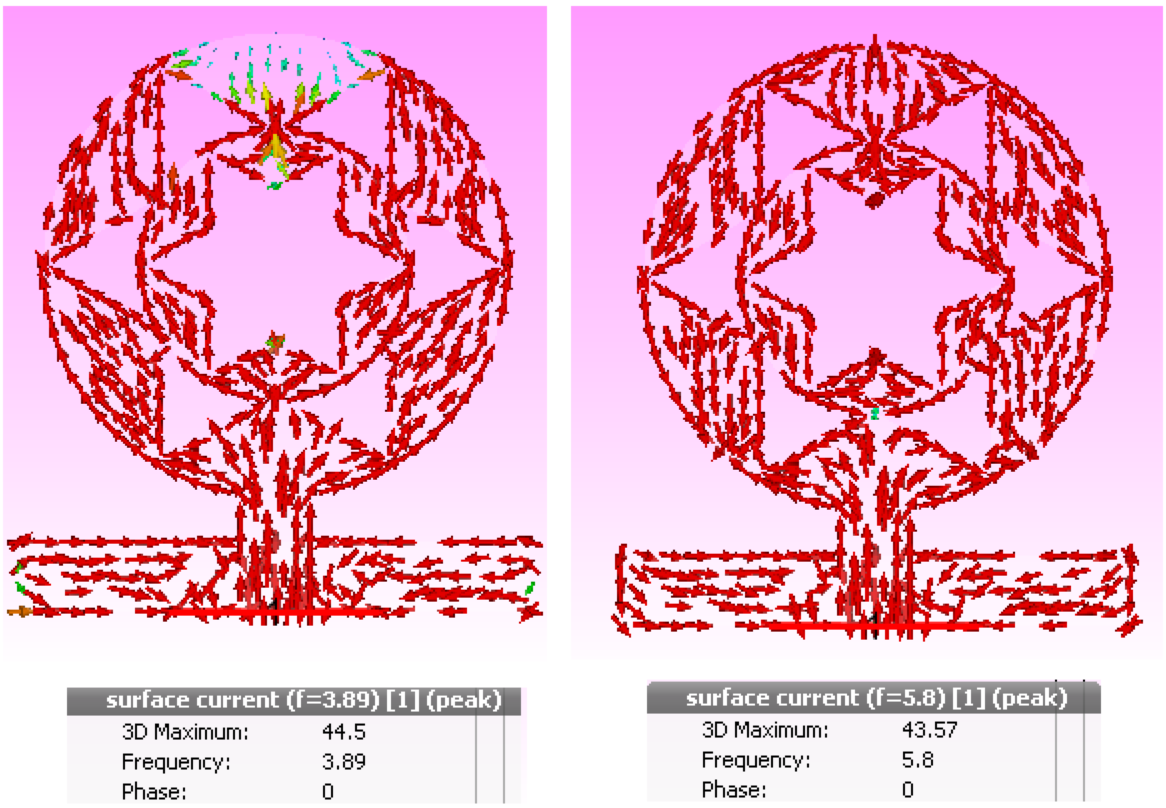
(b)



(c)

Figure 4.16 Radiation pattern (a) at 3.89 GHZ (b) at 4.82 GHZ (c) at 5.8 GHZ

4.4.3 Surface current



(a) **(b)**

Figure 4.17 Current distribution (a) at 3.89GHZ (b) at 5.8GHZ

Frequency	3.7GHZ	3.89 GHZ	4.83 GHZ	5 GHZ	5.8 GHZ	6.4 GHZ
Return loss (dB)	-18.73	-23.95	-14.53	-14.79	-23.97	-11.8
Gain (dB)	2.67	2.82	3.21	3.34	4.1	**4.25**
Efficiency	100.95	**102.45**	99.17	99.22	101.07	93.23

Table 4.8 Measured Gain, Return loss and total simulated Efficiency

	Koch Fractal antenna I	**Modified Koch Fractal antenna**	**Hybrid Fractal antenna**	**Inscribed circular Fractal antenna**
Dimensions(mm)	**14×30.4×1.6**	16×30.4×1.6	**16×30.4×1.6**	22×22×1.6
Impedance Bandwidth(GHZ)	3.31~7.84	**3.31 ~ 8.24**	3.3~8.18	**3.37~6.53**
Impedance Bandwidth (%)	81.26%	**85.5%**	85.01%	**63.8%**
Gain (dB)	2.58~3.66	1.96~3.05	1.97~3.4	**2.67~4.25**
Efficiency (%)	**~83.2%**	**~87.5%**	**~86.7%**	**~95.5%**

Table 4.9 comparison study of the different wideband Fractal antennas proposed.

Chapter 5
CONCLUSUION AND FUTURE WORK

5.1 Conclusion

This thesis describe the development of different wideband fractal Monpole antennas to achieve low profile and ease of integration. The aim of the design is to reduce the physical antenna size and increase the impedance bandwidth .The Koch curve fractal antenna is designed for wideband wireless application and covers an impedance bandwidth of 81.26% from 3.31-7.84 GHZ. The peak gain of 4.4 dB is achieved with a total efficiency of 80%.

The proposed Hybrid Fractal antenna model exhibits a bandwidth **of 85.02%** in the range **3.3-8.18 GHZ** (2:1 VSWR BW).The measured bandwidth meets the requirements of many commercial bands such as WI-FI 802.11y (3.6-3.7GHZ), WiMAX (3.4-3.6 GHZ and 3.7-4.2 GHZ) and WLAN 802.11(5.31-6.32 GHZ).
For further understanding of the behaviour of the proposed antennas, Surface current Distribution and 2D Radiation patterns are presented.

The Simulated results have confirmed wideband behaviour of the proposed antennas with a nearly omnidirectional radiation properties over the entire frequency band of interest. These features make them attractive for future communication systems.

5.2 Future work

In this thesis different types of compact fractal antennas are studied for wideband operation. Based on this, future work may be carried out such as

- The effect of material properties on Fractal antenna performance such as gain, efficiency, radiation patterns, etc. can be studied.
- Study of new techniques to reduce the size and enhance the bandwidth of fractal wideband antennas for use in mobile and portable devices.
- Fabrication of the proposed Fractal antennas and comparison of simulated Results with the measured Results.

References

1. C. Puente, J. Romeu, R. Bartoleme, and R. Pous, "Fractal multiband antenna based on Sierpinski gasket," *Electron. Lett.*, vol. 32, pp. 1-2, 1996.

2. C. Puente-Baliarda, J. Romeu, R. Pous, and A. Cardama, "On the behavior of the Sierpinski multiband fractal antenna," *IEEE Trans. Ant. Propagat.*, vol. 46, pp. 517524, 1998.

3. N. Cohen, "Fractal antenna applications in wireless telecommunications," in Professional Program Proc. of Electronics Industries Forum of New England, 1997, IEEE, pp. 43-49, 1997.

4. C. Puente-Baliarda, J. Romeu, R. Pous, J. Ramis, and A. Hijazo, "Small but long Koch fractal monopole," *Electron. Lett.*, vol. 34, pp. 9-10, 1998.

5. B.B. Madelbrot, *The Fractal Geometry of Nature*, New York: W.H. Freeman, 1983.

6. H.O. Peitgen, H. Jurgens, and D. Saupe, *Chaos and Fractals: New Frontiers of Science*, New York: Springer-Verlag, 1992.

7. K.J. Falconer, *Fractal Geometry: Mathematical Foundations and Applications*, New York: Wiley, 1990.

8. B.H. Kaye, *A Random walk through Fractal Dimensions*, New York: VCH, 1994.

9. G.P. Cherepanov, A.S. Balankin, and V.S. Ivanova, "Fractal fracture mechanics," *Engineering Fracture Mechanics*, vol. 51, pp. 997-1033, 1995.

10. J.H. Jeng, V.V. Varadan, and V.K. varadan, "Fractal finite element mesh generation for vibration problems," *J. Acous. Soc. Amer.*, vol. 82, pp. 1829-1833, 1987.

11. D.H. Werner, P.L. Werner K.H. Church, J.W. Culver, and S.D. Eason "Genetically Engineered dual-band fractal antennas," IEEE AP-S Inter. Symp. 2001, Vol. 3, pp.628-631, 2001.

12. K.J. Vinoy, K.A. Jose, and V.K. Varadan, "Multiband characteristics and fractal Dimension of dipole antennas with Koch curve geometry," IEEE 2002 AP-S Inter. Symp. 2002.

13. W.L. Stutzman and G.A. Thiele, *Antenna theory and Design*, New York: John Wiley, 1981.

14. R.T. Stevens, *Fractal Programming in C*, Redwood City, CA: M&T Books, 1989.

15. K.J. Vinoy, K.A. Jose, V.K. Varadan, and V.V. Varadan, "Hilbert curve fractal Antenna: a small resonant antenna for VHF/UHF applications," *Microwave &Optical Technology Letters*, vol. 29, pp. 215-219, 2001.

16. H.-O. Peitgen, J.M. Henriques, L.F. Penedo (Eds.), *Fractals in the Fundamental and Applied Sciences*, Amsterdam: North Holland, 1991.

17. C.T.P. Song, P.S. Hall, H. Ghafouri-Shiraz and D. Wake, "Sierpinski monopole Antenna with controlled band spacing and input impedance," *Electron. Lett.*, vol. 35, pp. 1036-1037, 1999.

18. J. Yeo and R. Mittra, "Modified Sierpinski gasket patch antnna for multi-band Applications," IEEE AP-S Inter. Conf. 2001, Vol. 3, pp. 134-147, 2001.

19. V.K. Varadan, K.A. Jose, V.V. Varadan, R. Hughes, and J.F. Kelley, "Novel Microwave planar phase shifter," *Microwave J.*, vol 38, 1995.

20. K.A. Jose, V.K. Varadan, and V.V. Varadan, "Electronically tunable microstripPatch antenna," *Microwave Opt. Technol. Lett.*, vol. 20, pp. 166-169, 199.