DESIGN AND ANALYSIS OF FRACTAL ANTENNAS

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CERTIFICATE

This is to certify that the thesis entitled, "**Design and Analysis of Fractal Antennas**" submitted by **Mr. Shakti Prasad Badajena** in partial fulfilment of the requirements for the award of Master of Technology Dual Degree in Electronics and Communication Engineering with specialization in **"Communication Networks and Signal Processing"** during session 2010-15 at the National Institute of Technology, Rourkela (Deemed University) is an authentic work carried out by him 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.

Dr S K Behera

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Abstract

This report contains design proposals of three antennas with completely different functionalities. All of the three employ the concept of fractal geometry is designing compact antennas with better performance than Microstrip Patch antennas (MPAs). Fractals are one of the ripest fields of research for antenna design, their greatest merit being their ability to enhance electrical length while having virtually unaltered area and better performance.

The first proposal is that of a hybrid fractal employing, two distinct categories of fractals, namely Sierpinski Carpet and Giuseppe Peanu, superimposed with each other to give Narrow-band functionality to the antenna. Resonating in the S-band it comes with a possibility to be employed for WiMAX applications.

The second proposal is that of a multi-band fractal which again employs a self-similar iterative design. Carving circles out of squares while maintaining electrical conductivity throughout, the antenna results is multi-band functionality. Resonating at five distinct frequencies within the range of 3 GHz to 12 GHz, it has great scope of being employed for the applications that are possible within this range.

The third proposal is that of an Ultra Wide band antenna whose fabrication gas also been carried out. Designed by carving hexagonal slots out of a circular patch this is the smallest of the three and optimisation is done using parametric analysis.

All simulations are done in CST Microwave Studio. All of them are implemented on the readily available & low cost FR4 substrate of $\mathcal{E}_r$= 4.4.Antenna characteristics like radiation pattern and gain are analysed through simulations.

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Chapter 1

Thesis Overview

1.1 Introduction

“The World has become a small place”

One of the elementary grounds legitimising the above statement is the revolution that the communications field has gone through. Alluding to transfer of information between two or more points, not connected by an electrical conductor [1], wireless communication is one of the most exploding sectors of the aforementioned field. It provides a solution to many demanding and impractical to implement situations, for instance, applying wires at hilly regions or over large distances. It has freed one from the onerous task of holding onto a corded device at home or at office, through the usage of Mobile (cell) phones and also made it possible to communicate at any point of time from any place. WLAN (Wireless local area network) technology provides one the access to the internet sans the need to suffer from redundant and expensive high-speed cable and is being recognised universally as not only high-speed data connectivity solution but also as a flexible and economic solution. Information, in form of large chunks of data can now be transmitted and received over large as well as short distances with unprecedented ease. The basic principle behind these wireless devices is the usage of radio and other forms of EM waves.

It all started at around the end of the nineteenth century with James Maxwell laying the initial foundations of Electro-Magnetic (EM) Radiation with the compilation of the four equations that unified the erstwhile separate fields of Electricity and Magnetism. He proclaimed, “The energy, by the engagement of electric and magnetic waves could be transported through materials and space at a finite velocity.”[*2*] In 1888, the experiments conducted by Heinrich Hertz supported Maxwell’s theory. Proving that light and EM waves travel with the same speed, his experiments with these waves led to the advancement of wireless telegraph and the radio. [*3*] In 1908, when Marconi conducted his Trans-Atlantic Experiment transmitting the letter S in Morse Code over a distance of 4.5 kilometre (via 3 dots), the era of wireless communication dawned. [4] Owing to the efforts and initial success of these marvellous scientific experiments, further explorations were carried out, rendering wireless communications a reality, and born was thus, a revolutionary era in the personal communication segment.

Since the 1960s, a lot of research has been done into it but the late nineties have seen a hefty amount of explorations. An amalgamation of numerous factors can be attributed to the same. At the outset, the aforesaid advantages have clearly outweighed those of the landlines and cabled instruments. Secondly, low-power implementation of complex signal processing algorithms and compact coding techniques has been made possible by the dramatic advancement in VLSI technology. The incessant demand for pocket-sized and accessible communication systems has also been one of the major impetuses behind this, not to forget the ease of design and fabrication. [5]

It’s widely believed that the wireless networks of future would essentially have as an integral part, short-range high-speed wireless services, thanks to the ever increasing demand for a smooth integration of cellular networks such as 3G and GSM and WPAN & WLAN. The swiftness of such progress in the Wireless Comm. has been responsible for an upsurge in new devices and systems meant to cater to the growing necessities of multimedia applications. Primarily because the small and multi-purpose antennas have to bear the burden to provide for the cellular phones and WLAN’s musts, they need to be of high gain, wide bandwidth, embedded installation, etc. and thus, the deciding factors affecting the application of antennas in both present as well as future wireless communication systems are becoming nothing but the diverse constraints on parameters such as axial or polarization ratio, gain and radiation patterns and the impedance bandwidths. [6].

Owing to the steady evolution in the segment of wireless communication in recent years, antenna design has generated a substantial interest. Precisely speaking, the design of small antennas is currently receiving its quota of consideration, thanks to the increasing market demand for new mobile terminals. However, tough specifications can render the entire process of designing and fabrication to be an arduous undertaking. Orthodoxly, design of small handheld antennas require among others, specialisations like flexibility, low profile and sturdiness. [4]

Operative frequencies of some of the most regularly used wireless communication systems are shown in Table 1.1 (page 4). Varying between 7% and 13% for commercial mobile comm. systems, the bandwidths may reach up to 109% for UWB applications. Some of the essential requirements for an antenna to be used for the required purpose include proper execution over the applicable frequency range and near-perfect impedance matching. They need to have high gain and stable emission coverage over the operating range for applications like wireless access points and cellular base-stations. For portable devices like PDAs and headphones and laptop computers, the antennas need to be omnidirectional, embedded and efficient radiators. [6]

On top of it, since operation at multiple standards has become an indivisible obligation for latest mobile handsets, multi-band or broadband operations is what their antennas are expected to perform. [7] Regrettably, the lack of any meticulous formulation to analyse and examine the complicated antenna geometries necessitates the usage of numerical methods. [8-10] As a result, even before a physical archetype is even fabricated, antenna performance needs to be evaluated and thus, the design heavily banks on the use of commercial electromagnetic simulators, such as IE3D [11], FEKO [12], CST MW Studio [13], HFSS [14], etc or numerical coding techniques. [4]

Notwithstanding the presence of the aforesaid simulating soft-wares, the instincts and former experiences that the designer has undergone, dictates the realisation of the final design. In maximum cases, as a matter of fact, trial and error methods are employed to achieve requisite final optimisation levels. [4]

Alternatively speaking, optimization techniques based on pseudo-random search algorithms such as Particle Swarm Optimization (PSO) [15], Artificial Neural Networks (ANN) [16,17] Genetic Algorithms (GA) [18,19], Bees Algorithms [20], etc are indubitably a pervasive approach of modelling antennas. [21] The fact that due to self-regulating procedures, once the optimized algorithm is coded and upgraded, a little intercession of the designer is necessitated is predictably a key plus.

The major challenge that the present antenna designers face is in the fabrication and design of antennas which deliver high performance, are capable of meeting multi-standards and are handy enough to be used in small hand-held devices. The interest thus generated has initiated research on several fronts including the most promising field of fractal shaped antennas. While some have been helpful in reducing antenna size significantly, some other designs have been aimed to accommodate wideband and ultra-wideband features.

Table 1.1

System	Operating frequency	Overall bandwidth
Advanced Mobile Phone Service (AMPS)	Tx: 824–849MHz Rx: 869–894MHz	70 MHz (8.1 %)
Global System for Mobile Communications (GSM)	Tx: 880–915MHz Rx: 925–960MHz	80MHz (8.7 %)
Personal Communications Service (PCS)	Tx: 1710–1785MHz Rx: 1805–1880MHz	170MHz (9.5 %)
Global System for Mobile Communications (GSM)	Tx: 1850–1910MHz Rx: 1930–1990MHz	140MHz (7.3 %)
Wideband Code Division Multiple Access (WCDMA)	Tx: 1920–1980MHz Rx: 2110–2170MHz	250MHz (12.2 %)
Universal Mobile Telecommunication Systems (UMTS)	Tx: 1920–1980MHz Rx: 2110–2170MHz	250MHz (10.2 %)
Ultra-wideband (UWB) communications and measurement	3100–10 600MHz	7500MHz (109 %)

In all, introduction of fractal geometry into antenna design, which does not go back much, has shown significant potential, aimed at bettering antenna characteristics, with varying degrees of success.

The research work that is presented here is an attempt at analysing and understanding the impact of fractal geometries on antenna characteristics. In recent years, several reports of such attempts have been made [22-25]. Attempts have been made at understanding the effects of antenna parameters on antenna performances through parametric studies and analysis. Finally, with proper effort, an antenna with CPW fed hexagonal fractal structure with UWB$^{@}$ characteristics is reported.

1.2 Thesis Motivation

Over the last few years, communication systems have undergone a sea change. AWS (Advanced Wireless Services) offering a variety of wire-less services has been licensed. Mobile phones have ceased to be just phones with the leading players more bent on integrating applications like TV than ever. As a matter of fact, the scope has transcended the limits and even research has grown manifolds for high-scale military applications. Ultrathin, high performance and convenient devices capable to meet the multiple specifications have become the need of the hour. This, in turn, has warranted a growing need for more efficacies in antenna design and therein lays the origin of the next big thing in the field of antenna engineering. To confront these inevitabilities, investigations into various novel shaped fractal antennas is carried out.

This is a great technique of creating small volume and low-profile antennas. Antenna efficiencies can be greatly improved by fractalising planar antennas. Besides resulting in reduction in antenna dimensions, it is quite fruitful in bandwidth expansion. [26] This is greatly compounded by the fact that Fractals tend to increase the antenna’s electrical length without altering the total area. Antennas can thus be miniaturised. Without compromising with the performance and functioning, sizes are reducible up to four times. As a matter of fact, the performance gets significantly improved as well.

The aim and motivation of this thesis is, thus, to comprehend the behaviour of antennas with fractal characteristics of self-similarity and space.

1.3 Literature Review

Although the creation of microstrip patch antennas (MPA) has been ascribed to a number of creators, notably being Greig and Engleman, Lewin and Deschamps, who among themselves distributed the initial works starting in the 1960s. [5] In the seventies, design equations started to be formulated along with the arrival of the numerous publications carried out by keen researchers and authors like James Hall and David Pozar. Theirs and contribution of others in the initial investigations set the pace for further works. In fields as demanding as those of space research, satellite or military applications including missile and high performance aircraft manufacturing, where every inch counted, the constraints such as size, weight, performance, ease of integration and most importantly, cost, had created the need for a highly efficient yet low profile antenna. The new microstrip antennas were just tailor made for the same. The existing antennas were, as aforesaid, cumbersome and needed space to be deployed. With their appealing highlights, such as simplicity in incorporation in clusters, compact-ness, highly cost-effective nature and light weighted-ness MPAs were hard to resist and it wasn't long before they began to be considered as perfect candidates to be used in the communication systems of the modern era, especially in WLAN and cellular applications. [5] However, times have changed and even more efficient methods of radiation and antennas have risen over MPAs. To have preferred attributes over the microstrip antennas, an idea which is being actualized is Fractal. From a quantitative point of view, the space filling properties and the self-symmetry property are invariably linked to the frequency characteristics of fractals. The innate property of fractals to rehash themselves at distinctive scales, i.e., the fact that they are self-similar repetitive geometrical structures is important as what it essentially does is enhance the electrical length of the antennas without altering the area.

Coined by Benoit B. Mandelbrot [27] these may be found naturally in the various patterns observable in the environment and can be generated by mathematical methods as well. Successively, one-step feedback systems were used to create the whole fractal concept [28] Ramsey, a scientist of great repute, established the basic tenet of frequency independence of antennas. He established that an absence of characteristics size that can be scaled by the wave's wavelength would render an antenna frequency-free. In other words, an antenna definable by angles only, would be independent of any relation with frequency. Apparently the “father of Fractal geometry”, took inspiration from the Latin ‘Fractus’ which is an adjective which stands for uneven or broken. It also signified anything of extremely irregular shapes or curves or any geometry that repeats itself on any scale that it’s inspected. [4]

Usage of fractal geometry in the radiating patch or ground of an antenna maximises the effective electrical length. It also results in an increment of the perimeter or the boundary on any side of the structure of material thereby enabling the reception and transmittance of EM radiation within a given volume or total surface area. [5] Another interesting attribute is that the more one zooms in at finer and finer scales more does one encounter self-recurring structures, so much so it becomes virtually impossible to comprehend the level one is at.

1.4 Chapter Outline

The FIRST chapter of this thesis is dedicated to offer a brief insight into the historical context of how wireless systems came into existence and the way demands of our day to day lives and unforgiving experiences with nature inspired and necessitated invention and innovation and enabled the modern communication systems to reach the stage they are at present. Also, provided is the motivation behind undertaking such a task and the literature review. Finally the chapter is summarised and a brief overview of the subsequent chapters is given.

The SECOND chapter starts with providing a brief introduction about antennas through terms and lexicons and their definitions. Supplementing this, an introduction about Microstrip Patch Antennas (MPAs) is provided. Description about their features, feeding methods and their associated advantages and disadvantages is also given. It goes on to provide different calculations and formulations for the calculation of feed-line width and other dimensions of the MPAs and introduces the Fractal geometry and the possibility of its usage in antenna engineering. Fractal antenna engineering is a booming new field of research that essentially brings together the attributes of antenna design and fractal geometry. Basic theory providing details of characteristics and classes and dimensions is given. It also provides for a comparison of fractals used as antennas vis-à-vis conventional Euclidean ones. Discussing the pros and cons of the fractal antennas, the chapter concludes

The THIRD chapter carries on from where the previous one left, dealing with fractals. It carries the details of the very first design, a narrowband fractal antenna that’s been realised by using a hybrid of Giuseppe Peanu Fractal and Sierpinski fractal. It deals briefly with the applications of Narrow-band antennas before concluding with the possible applicability of the proposed design.

The FOURTH chapter provides details of another design; a multi-band antenna that has been carried out by the author simulated using the CST Microwave Studio Suite 12.0, formed by carving out circular slots within squares. Various properties are studied and finally, the details of the dimensions of the CPW fed slotted fractal antenna are provided.

The FIFTH chapter gives the details of the final design presented in this thesis. It’s about a UWB antenna realised by carving out hexagonal slots in a circle in a continuous fashion. The details of its dimensions and the numerous parametric studies that have been performed also form a part of this chapter. Finally the simulated results are provided at one of the frequencies. .

The SIXTH chapter is the last one which includes conclusion, which is an inference gathered by the compilation of the overall work and observations and describe briefly about the scope of future work.

1.5 Summary

This chapter provides a brief account of the brief journey of modern communication systems and the evolution in antenna technology which was an essential by-product. Besides comprehensively outlining the motivation that provided the impetus for the investigation, and stating the gist of scholarly works that have been studied and drawn inspiration from, attempts are made to provide an overview of the rest of the thesis in a condensed manner.

Chapter 2

Antenna Theory

2.1 Antenna Fundamentals

Antenna: An antenna is a mean for “receiving and radiating radio waves”; an intermediate structure between a guiding device as shown in Fig 1.1 and free space. [29]

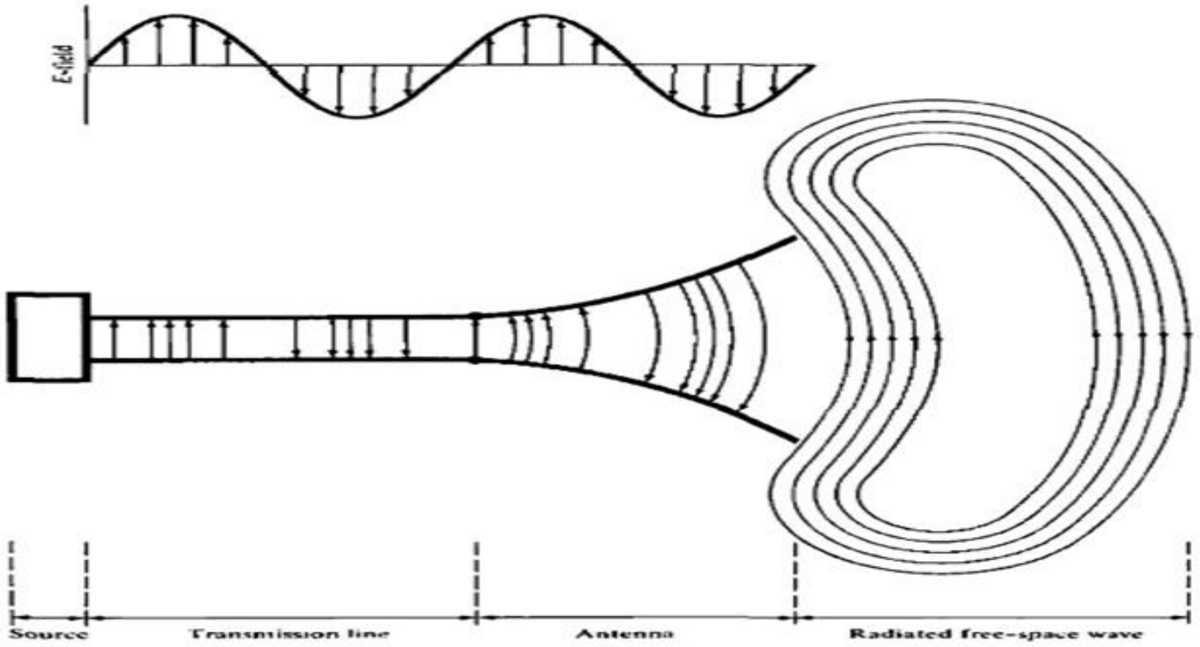


Figure 2.1: Antenna as a transition device [29]

“Besides transmitting or receiving energy, in an advanced wireless system, an antenna is required to subdue the radiation energy in some directions and give prominence to it in others; thus, rendering an important role of being a directional device to the antenna apart from the regular one.” [29] The pathway provides a route for the alternating EM variations, which tend to form a complete loop once they detach from the main transition segment thereby independent of all variations that occur in the antenna once they leave it.

Several parameters ordain the performance of an antenna. Some of those parameters and their properties are presented below.

Input Impedance:

Calculation of the input impedance plays an important role in determining and is responsible for maximum power transfer between transmission line and the antenna. Only when the matching of the respective input impedance of the transmission line and antenna occurs, does the transfer happen. In case the matching does not happen, reflected waves are generated at the antenna terminal. These waves then travel back towards the energy source thereby resulting in the overall system efficiency's diminution.

Gain:

Effectively measures the overall efficiency of an antenna. [29] If gain equals the value of that of the directivity it's said to be 100% gain and vice-versa. Numerous dynamics are responsible in affecting and trimming down the overall efficacy noteworthy of which are losses (material, random and network losses) and impedance matching. Thus, there are a lot of adversities that antennas in effect need to overcome for acceptable gain. [29] Usually, it can also be represented as the ratio of the antenna's radiated power to that of an isotropic antenna.

Various gains and their respective formulations:

Directive Gain:

$$G_D(\vartheta,\phi)=\frac{4\pi U(\theta,\phi)}{P_r}=\frac{4\pi|\bar{E}(\theta,\phi)|^2}{\int_0^{2\pi}\int_0^{\pi}|\bar{E}(\theta,\phi)|^2\sin\theta\,d\theta\,d\phi}$$

(2.1) [29]

Power Gain:

$$G_P=\frac{4\pi U_{max}}{P_i}$$

[29] where $P_i=P_r+P_l$; P_i being total input power and P_l denoting loss

(2.2)

Radiation Efficiency:

$$\eta_r=\frac{G_p}{D}=\frac{P_r}{P_i}$$

(2.3)[29]

Radiation Pattern:

A functional representation of directional coordinates, it is a means to know exactly how antennas direct the energy they emit. 100% efficiency signifies that the antenna will radiate the same total energy for equal input power irrespective of what shape the pattern takes. Mostly evaluated in the far-field region, it gives valuable information about field strength, Directivity, power flux density, polarisation and other such radiation properties. Relative DB scale is their usual mode of presentation.

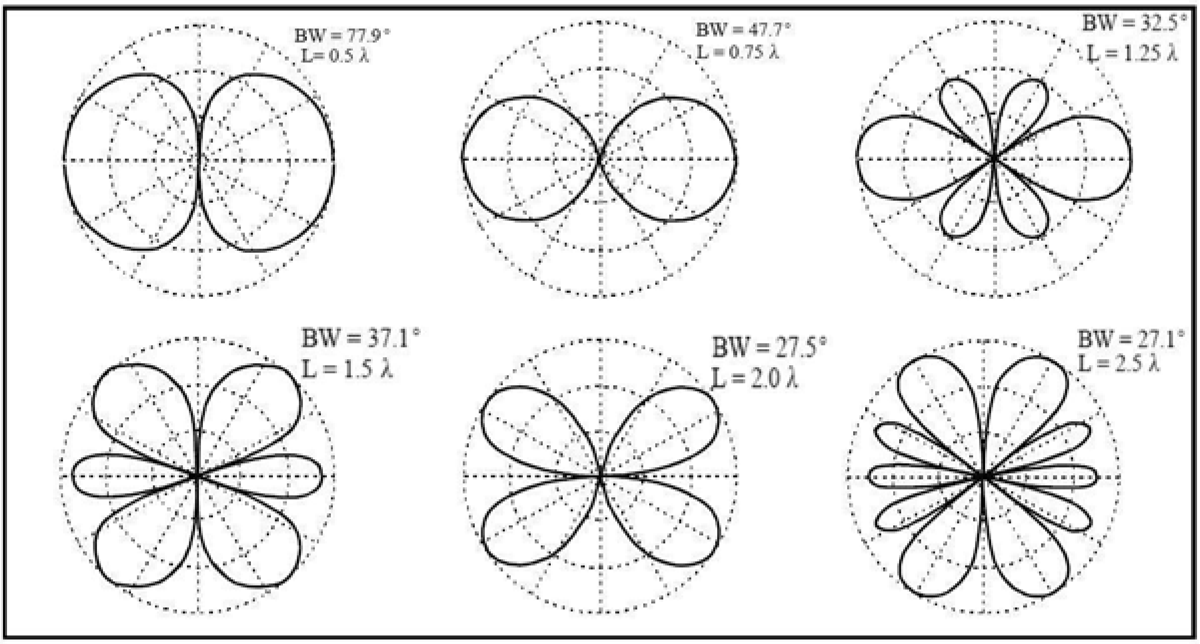


Figure 2.2: Radiation Pattern

HPBW (Half-power BeamWidth): Width of the main beam (angular) between the -3dB points which signify the half-power levels.

Side-Lobe Level: ($|E_{Max}|$ in one of the side lobes)/($|E_{Max}|$ in main beam)

Null Positions: There exist certain directions in the far-field territory which have 0 radiation. These are called the Null Positions.

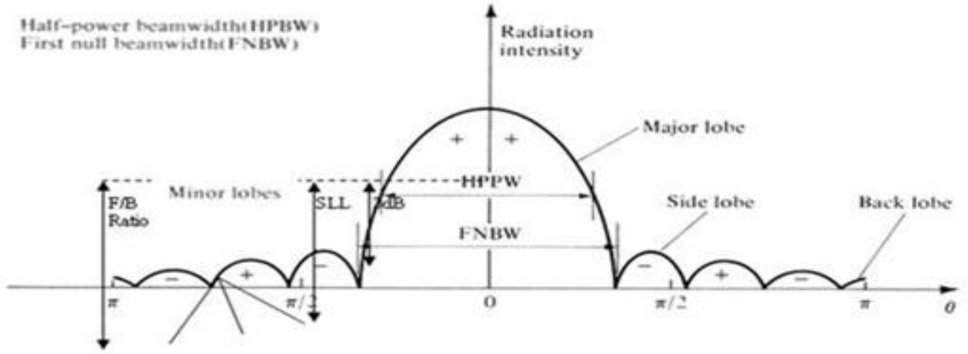


Figure 2.3: Beamwidth and lobes

Directivity (D):

Directivity signifies the gain maxima in any particular orientation or direction. Therefore, it's an important parameter that measures the antenna's capability of focusing radiated energy. Defined as the ratio of maximum radiated power to the average power of a reference isotropic antenna (which, in turn, is an ideal case with omnidirectional uniform radiation and unity directivity)

It's described by the following equation:

$$D = \frac{F_{max}}{F_0}$$

(2.4)

Where F_{max} and F_0 are respectively maximum radiated energy and isotropic antenna's radiated energy.

Directivity:

$$D = \frac{4\pi U_{max}}{P_r} = \frac{4\pi |\bar{E}_{\max}|^2}{\int_0^{2\pi}\int_0^{\pi} |\bar{E}(\theta,\phi)|^2 \sin\theta \, d\theta d\phi}$$

where $$U = R^2 P_{av} \propto \ R^2 |\bar{E}|^2$$

(2.5)

Where

$$P_{rad} = \oint P_{av}\, dS = \oint U d\Omega \propto R^2 \int_0^{2\pi} \int_0^{\pi} |\bar{E}|^2 \sin\theta d\theta d\phi$$

(2.6)

is the radiated power (time-averaged).

Polarization:

Polarisation of any given radiating system is given by that of the wave it radiates. [29] In a sense it gives a crisp description about the sense and orientation of the wave's electric field vector. [30] Three fundamental categories of the same are Linear, Elliptical and Circular. [29] In general, most of the radiated waves are either linearly or circularly polarised, thus making it the usual polarisation of the radiators.

Bandwidth:

Bandwidth alludes to a certain rage of frequencies over which the antenna displays certain required or pre-defined properties. In other words, the range over where certain sets of conditions are satisfied. [30] The trade-offs in various performance parameters is what is the matter of concern while determining a particular bandwidth. Two methods by which bandwidth are calculated are:

Narrowband by %:

$$BW_p = \frac{f_h - f_l}{f_c} * 100\%$$

(2.7)

Broadband by Ratio:

$$BW_b = {}^{f_h}\!/\!_{f_l}$$

(2.8)

Where f_c : Center Frequency

f_h: Higher Cut-off frequency

f_l : Lower Cut-off Frequency

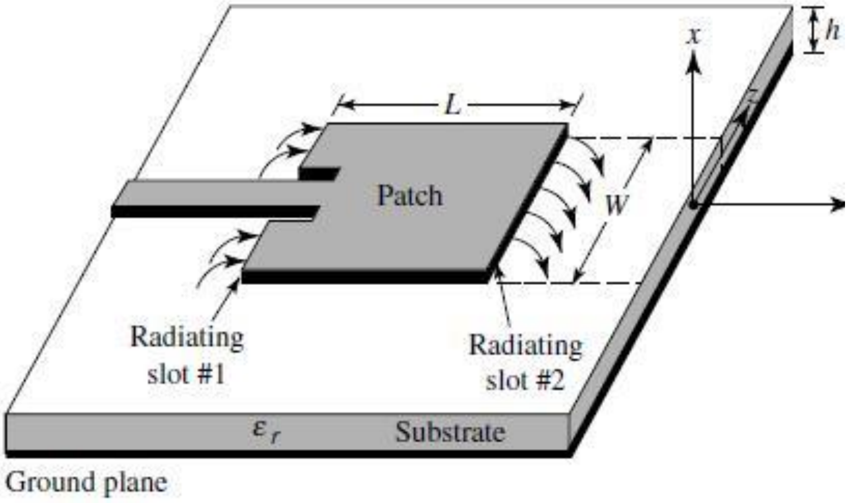
The UWB (Ultra Wide Band) frequency band was named as such by the FCC (Federal Communication Commission) in 2002, when the bandwidth of 3.l-10.6 GHz was allocated for commercial use. The –10dB bandwidth of the UWB emission forms the basis of the frequency band of operation. UWB technology was permitted by existing wireless communications' framework to overlap and superimpose in the 3.1 to 10.6GHz range, with the already on hand services such as the IEEE 802.11 WLANs & Wi-MAX. As per FCC Rule, any signal with fractional bandwidth, greater than 0.25 or occupying at least 500MHz spectrum can be used in UWB systems. UWB is applicable to all the technologies that use 500MHz spectrum as well as comply with all other requirements for UWB, is what it essentially means. [31]

2.2 Microstrip Antennas

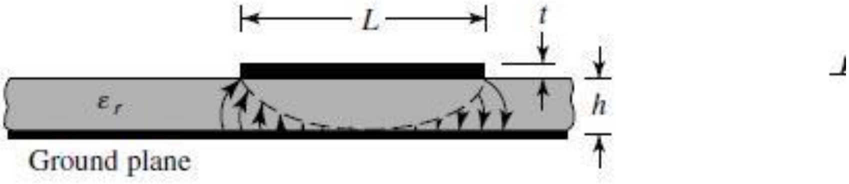
One of the most booming topics in recent years in the field of antenna architecture design and theory is the Microstrip Planar Antenna and is increasingly being a part of numerous modern microwave systems. The very idea of MPAs traces back to 1953 [32] and 1955 dated patent [33]. But it came into focus starting mainly in the 1960s and 70s when microwave devices started to be manufactured; fabricated on low volume semiconductor chips and affixed on aptly planned packages.

As more stress was given on the production of low cost and compact antennas, owing to the ever increasing demands for portable and personal devices for mobile communications, Microstrip or simply, as they are often referred to, 'patch' antennas came into the limelight. In its most basic configuration, a patch antenna is a radiating patch attached with a metallic path, called a 'feed line', printed on the front side of a di-electric substrate, which is grounded on the other side. The aforementioned radiating patch can assume various shapes, ranging from circle to triangular, from rectangular to annular rings as shown in the following page in Fig. 2.4. These feed lines and radiating patches are printed using photolithography or printed circuit technique, on the dielectric substrate. The side and top view of a rectangular patch antenna is also shown in the subsequent Fig. 2.5 [5]

The basic properties of the patch antennas have been evaluated in the referential literature [34, 35].



(a) Microstrip antenna



(b) Side view

Figure 2.4: Rectangular Microstrip Patch Antenna

Essentially, of the two types of radiation, one is the end-fire radiation and broadside radiation being the other. If maximum of the radiation pattern is perpendicular to the axis of the antenna or the patch, then the radiation is referred to as Broad-side radiation. However, for those radiations in which the maximum is in the direction of the antenna axis, the term used is End-fire radiation.

The micro strip patch antennas are devised in such a way that the direction of the pattern maximum is perpendicular to the direction of the antenna axis or patch. In other words, its behaviour is similar to that of a broadside radiator. The realisation of the same is carried out by accurate mode selection; mode being the configuration of the field of the excitation that lays beneath the patch. Proper mode selection can also render the possibility of end-fire radiation. As shown in the Fig 2.4, the patch and the ground plane are separated by the dielectric sheet.

A voltage between ground plane and feed probe drives the antenna, in transmission mode of operation. From there on, current exits on to the ground plane and patch. Electrically speaking the dielectric substance is usually thin. So, the dielectric components which are in parallel to the ground plane are essentially very small through the substrate. If the length of the patch element is half, large current and field amplitudes result at resonance. The magnetic current and surface current density which is induced on the patch results in the radiation.

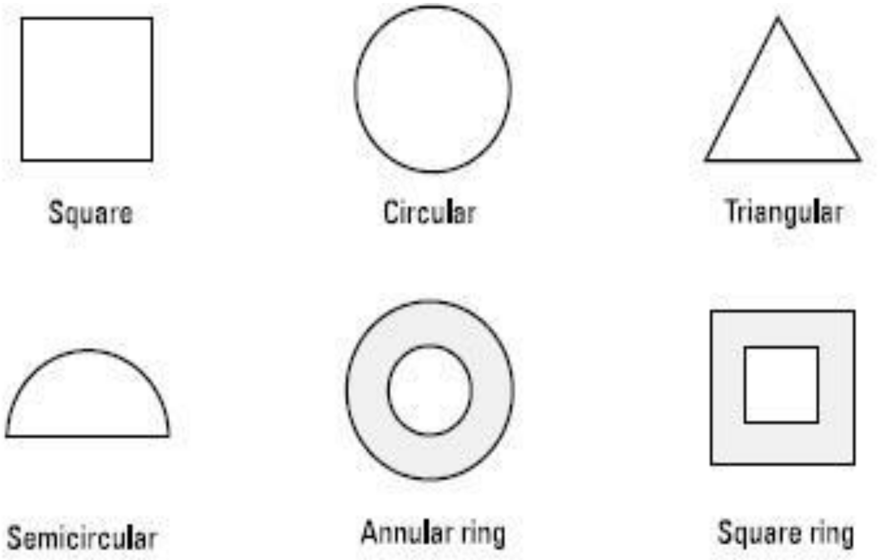


Figure 2.5: Various patch shapes

For the crafting of patch antennas several substrates have been and are used. The range of the dielectric constant is usually $2.2 \leq \epsilon_r \leq 12$. Depending on the functionality, substrates can be chosen. Substrates with low dielectric constant with considerable thickness are chosen for better performance of the antenna in terms of the efficiency which is bettered, better radiation into space as fields become loosely bounded and bandwidth which is enlarged. However, the element size increases as well which is its principal trade-off. Substrates whose dielectric constants are high and have lower thickness essentially come with tightly bound fields. Thus, they find use for microwave circuitry as the aforementioned property renders coupling and minimal undesired radiation. This, in turn, results in smaller sizes of the elements. However, attributable to their greater loss tendency, their bandwidths are relatively smaller and their efficiency is low. [36]

In view of the fact that patch antennas need to be integrated usually with other microwave circuitry, a middle ground is found between circuit design and antenna performance in terms of parameters such as efficiency, bandwidth etc. [29]

2.2.1 Feeding methods

To enable the antenna operate at the transmission’s full power, feed-lines are important. Devising feeding techniques for antennas to operate at high frequencies is a tasking task. The proportionality of feeding's input loss on the frequency is a major concern, albeit and may leave huge repercussions on the overall design of the antenna.

Micro-strip patch antennas are fed by various feeding techniques, popular among whom are as under: [29]

- Microstrip line
- Coaxial Probe
- Proximity Coupling
- Aperture Coupling
- Coplanar Wave Guide (CPW) feeding

Microstrip Feedline:

Also known as the conducting strip, its width is much smaller than that of the patch. Characteristically it's associated with thicker substrate which is proportionate to the surface waves. [30] This feed-line is associated with ease of modelling and fabrication as the feed can simply be etched along with the patch on the substrate in turn resulting in a planar structure. The inset feed position can be manipulated and thus matching is effortless.

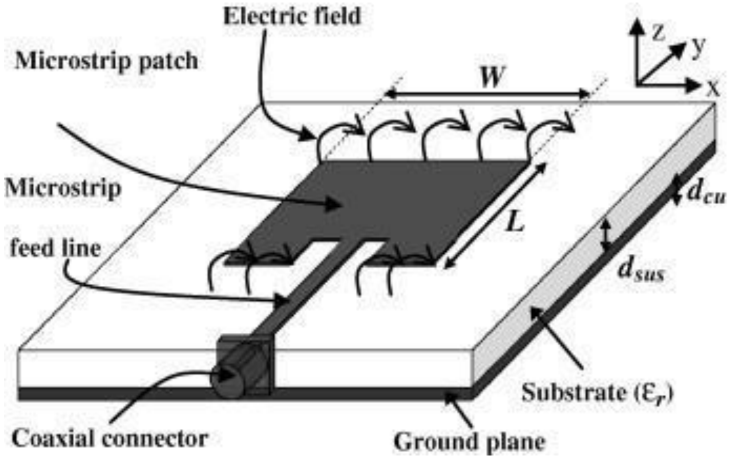


Figure 2.6: Microstrip Line Feeding

However one major con of this method of feeding is that as the surface waves are proportional to surface thickness, an increase in the thickness of the surface results in spurious radiation which in turn results in the bandwidth getting limited; the limit of radiation bandwidth being 2% to 5%.

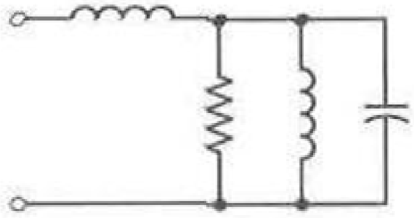


Figure 2.7: Equivalent Circuit of Microstrip Feed Line

Coaxial Probe Feed:

In this technique of feeding, the coaxial's inner conductor is connected to the patch which is responsible for radiation while contact is made with the ground plane via the outer conductor. They are widely used and one of the primary reasons is its inherent advantages like the ease of matching and fabrication. Add to that the fact that, the spurious radiation associated with it is also pretty low.

However, it has its own characteristic shortcomings. It is characterised by narrow bandwidth and is very difficult to model especially for substrates with higher thickness.

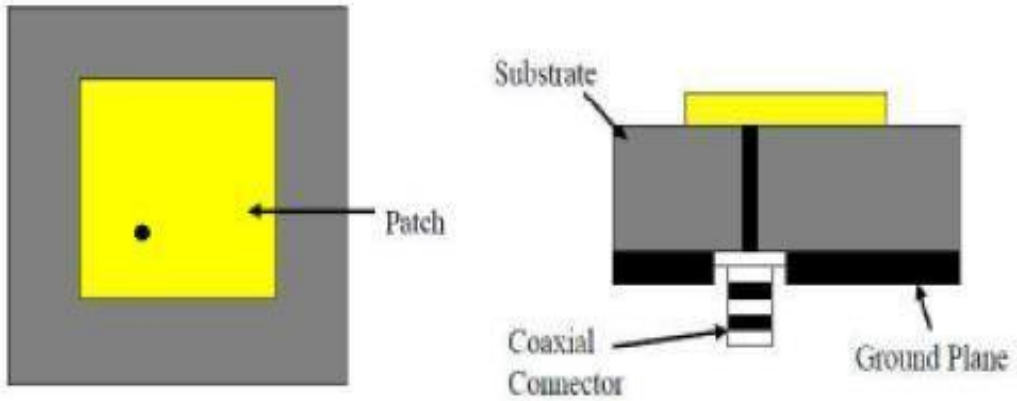


Figure 2.8: Coaxial Feeding

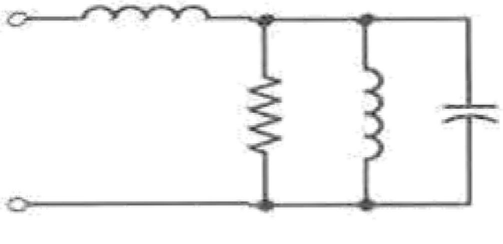


Figure 2.9: Equivalent circuit of Coaxial Probe Feed

Both the coaxial probe and the microstrip line feed generate higher order modes because of their associated asymmetries. This in turn leads to cross-polarisd radiation. To overcome this, introduction of non-contacting aperture coupling has been done.

Aperture Coupling:

In this technique, a ground plane separates two substrates. There’s a microstrip feed line underneath the lower substrate. Its energy, via a slot in the ground plane betwixt the two substrates is coupled to the radiating patch. The radiating element and the feed mechanism are thus independently optimised through this procedure. The dielectric permittivity of the lower substrate is typically high while for the substrate above the ground, low dielectricity with good thickness is preferable. Also polarisation purity is achieved as the separation of the two substrates by the ground plane isolates the radiating element and the feed, thereby minimising spurious radiation’s interferences for formation of patterns. [5]

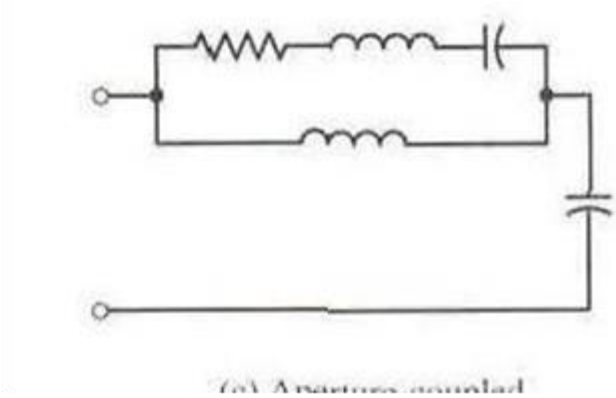


Figure 2.10: Equivalent circuit of Aperture Coupled Feed

The design can be optimised by using the width of the feedline, size and position of the slot and other electrical parameters of the substrate. By controlling the slot’s length and the feed’s width, matching can be achieved.

Magnetic coupling will dominate if the slot’s position is right below the patch at the centre, where ideally for the dominant mode, H-field is max and E-field is null.

Small bandwidth happens to be the worst possible demerit of micro strip antennas which essentially necessitates the increase its bandwidth. Proximity coupling is one such method.

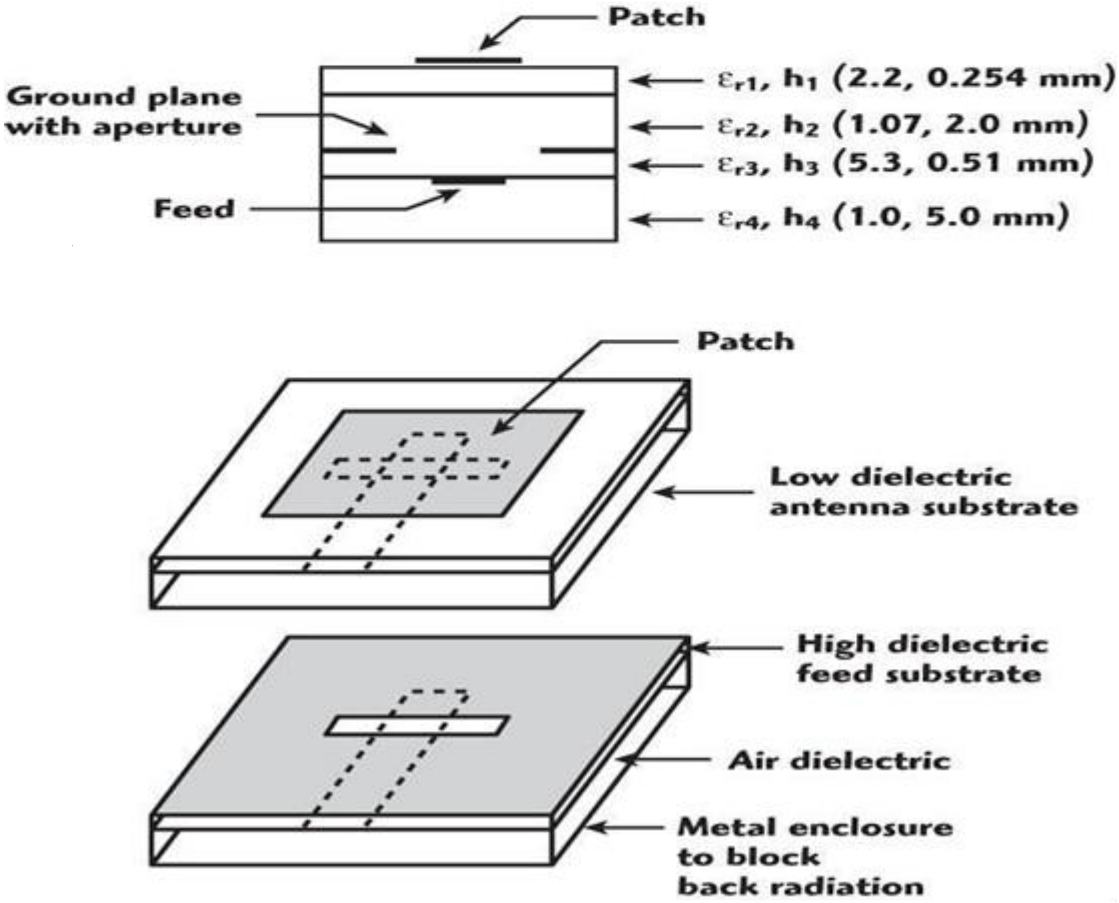


Figure 2.11: Aperture Coupled Feed

Proximity Coupling:

In this technique there is a ground plane which lies beneath with two substrates above. Between the two substrates, at the boundary, using a proximity-coupled micro strip feed line to a patch antenna, bandwidth is enhanced. The aforesaid patch antenna is printed just above the feed-line on a substrate.

The two types of bandwidth namely, *Impedance bandwidth* (the range of frequencies over which antenna and the feed-line remain matched up to some predefined level) and the *pattern bandwidth* (the range of frequencies over where the pattern maintains its fidelity) are satisfied by the ideal broadband radiating element. Thus, it characteristically possesses large bandwidth, in fact, the largest of all the feeding schemes. It’s also associated with low spurious radiation. Albeit it’s easier to model, there is essentially a lot of difficulty associated with the fabrication.

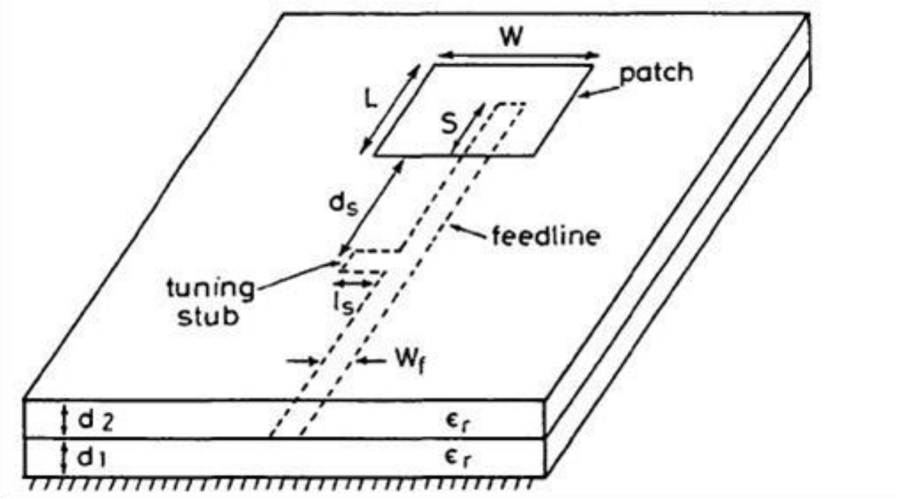


Figure 2.12: Proximity Coupled Feeding

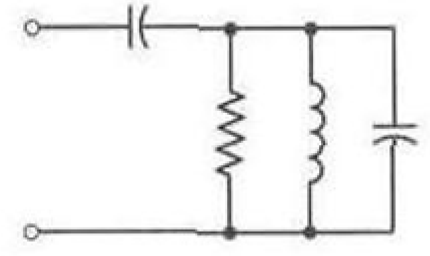


Figure 2.13: Equivalent circuit diagram

Co-Planar Waveguide (CPW):

In this technique, a separate ground plane ceases to exist. Rather it's above the substrate on both sides of the feed line as shown in the figure that follows. Wideband techniques such as proximity coupled and aperture coupled feeding experience alignment problem between the feed line and the slot. But having etched both of them on the same side of the substrate, the CPW technique suffers from no such disadvantage.

It has a simple configuration having absolutely no need for coupling via holes and can match impedance better given that it's on a single metallic layer. Easily integrated with circuits, this method among other advantages has less dispersion and low radiation loss. The associated bandwidth is fairly large as well.

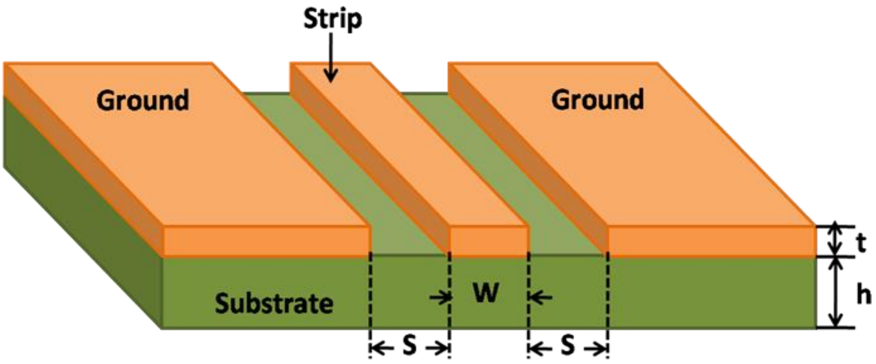


Figure 2.14: Co-planar Waveguide feeding

2.2.2 Structural Analysis of MPA

There are several popular models for the analysis of MPAs major of which are namely, Transmission Line model, Full wave model and Cavity model. While cavity model is associated with more accuracy but therein lays the inherent rise in complexity and difficulty to model coupling. Full wave model is the most advanced of the lot capable of treating single elements as well as stacked ones, infinite arrays and coupling with versatility and accuracy.

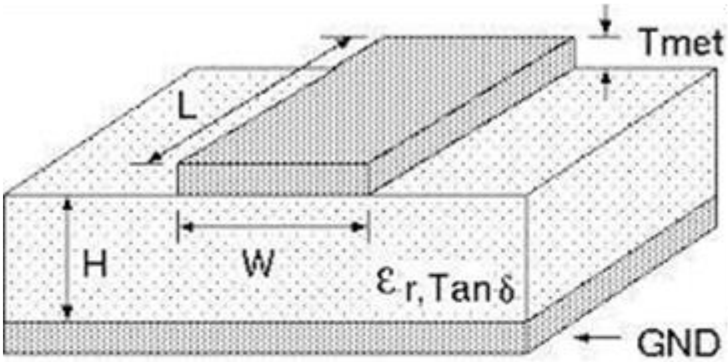


Figure 2.15: Microstrip Line

Although Transmission line model is neither accurate nor versatile, it's the simplest of all. It represents the micro strip antenna just by a low-impedance transmission line of length L, width W and height H separating two slots as shown in the previous page.

2.2.2.1 Fringing Fields

The patch's dimensions can only be finite whether it's along the width or the length. Therein lays the root source of the fringing fields which undergo fringing at the patch's edges. Illustrated below is the fringing of fields for a micro-strip antenna with two radiating slots.

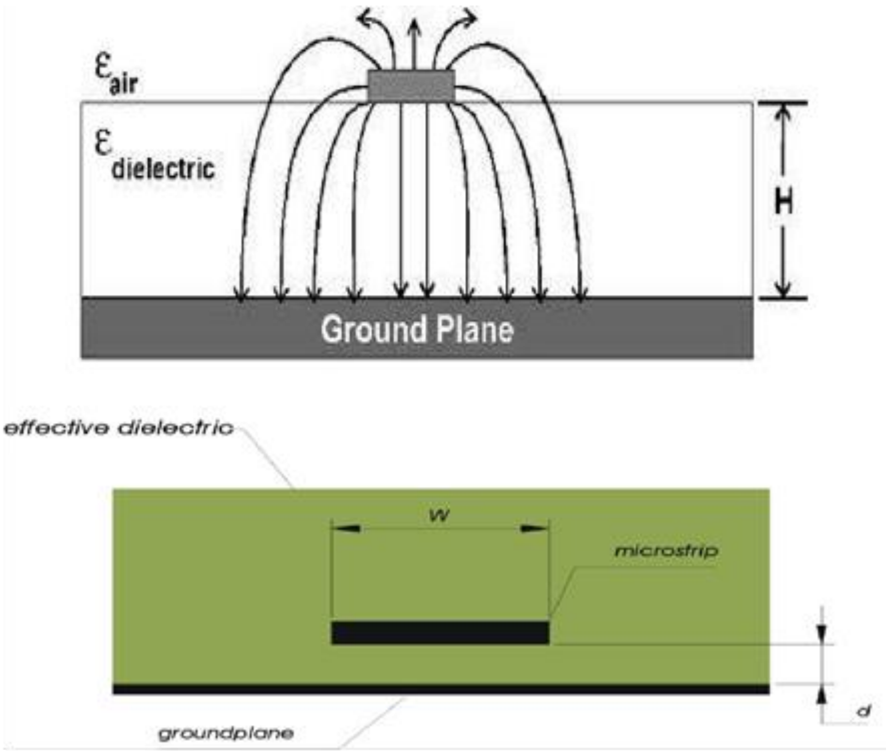


Figure 2.16: Effective Dielectric Constant and E-field Lines

The height of the substrate and the patch dimensions are the major deciding parameters of the amount of fringing. Typical E- field lines of a micro-strip antenna are as shown above. As W/H >>1 and $\epsilon_r \gg 1$ and as illustrated in the figure most of the aforementioned lines lie in the substrate itself. There exists only a part of it in the adjoining air medium. Thus making it the two dielectrics', namely substrate and air, line a non- homogenous one. The electrical dimensions of the microstrip look wider than they are physically due to fringing. While some waves travel through the substrate, some do so through air. So to take into consideration both the aforesaid type of wave propagation and the fringing there is the introduction of an *effective dielectric constant (EDC),* ϵ_{reff} denoted by [29]

$$\epsilon_{reff} = \frac{\epsilon_r + 1}{2} + \frac{\epsilon_r - 1}{2}\left(\frac{1}{\sqrt[2]{\frac{12H}{W} + 1}}\right) \tag{2.9}$$

Valid for W/H > 1 for low frequency of operation where H is the substrate's height and W is the width of the feed line. ϵ_r is the substrate's dielectric constant.

Thus, it can be concluded with conviction that for if ϵ_r of the substrate is much greater than unity the value of EDC would be much closer to the substrate's dielectric constant in actuality. $1 < \epsilon_{reff} < \epsilon_r$, if air is the medium above the substrate. Frequency of operation, however, also affects the EDC. With an increase in frequency, there is an associated increase in the E-field lines concentration in the substrate. [29] EDC remains constant for low frequency of operation. $\epsilon_{reff} \rightarrow \epsilon_r$ at intermediate frequencies.

The height of the substrate H and the W, the feedline's width also affect the characteristic impedance Z_0.

$$Z_o = \frac{60}{\epsilon_{reff}} \ln\left(\frac{8H}{W} + \frac{W}{4H}\right); \ \frac{W}{H} \leq 1 \qquad (2.10)$$

$$= \frac{120\pi}{\epsilon_{reff}} \ln\left(\frac{8H}{W} + \frac{W}{4H}\right); \ \frac{W}{H} > 1 \qquad (2.11)$$

H and W are decided by parameters A and B, which in turn depend upon dielectric constant of the substrate and the characteristic impedance given by the following two equations.

$$\frac{W}{H} = \frac{8e^A}{e^{2A} - 2}; \ \frac{W}{H} < 2$$

$$\frac{W}{H} = \frac{2}{\pi}\left[B - 1 - \ln(2B - 1) + \frac{\epsilon_r - 1}{2\epsilon_r}\left\{\ln(B - 1) + 0.39 - \frac{0.61}{\epsilon_r}\right\}\right]; \ \frac{W}{H} > 2$$

(2.12)

The values of A and B are respectively given by the following equations:

$$A = \frac{Z_0}{60}\sqrt{\frac{\epsilon_r + 1}{2}} + \frac{\epsilon_r - 1}{\epsilon_r + 1}\left(.23 + \frac{.11}{\epsilon_r}\right)$$

$$B = \frac{377\pi}{2Z_0\sqrt{\epsilon_r}}$$

Now since fringing has an effect on the antenna’s resonant frequency it should be looked into and reduced.

Typically, 50Ω is taken as the feed line’s characteristic impedance for the following reasons:

- 50Ω is the internal impedance all available source ports. *Maximum Power Theorem* dictates that for transferring maximum power 50Ω needs to be selected as the patch antenna’s feed line’s characteristic impedance.[5]
- Theoretically, for minimum attenuation 76Ω is required in the line and for maximum power transfer 37Ω is the calculated ideal impedance. Compromising, the average of the two values is selected. [5]

2.2.3 Advantages and Disadvantages

Modern communication systems widely use the MPAs. Ranging from satellite communications to usage in missile systems for military purposes to GPS, patch antennas have numerous utilities. Owing to their characteristic features, discussion about their numerous advantages is done below:

Advantages:

- Lightweight and Small Volume.
- Low Profile Planar configuration
- Conform to any surface
- Using PCB technology, can be produced en masse leading to lower cost or less expensive means of fabrication
- Given the same substrate it’s considerably easier for integrating with other MICs
- Both circular as well as linear polarisation is allowed for.
- Low volume renders them compact; can be used for personal mobile comms
- Are operable at multiple frequencies
- Cavity backing is avoidable
- Scattering cross section is low
- Ease of attaching to missiles and other such space critical devices

Disadvantages:

- Gain is pretty low
- Bandwidth is narrow and is associated with tolerance issues
- Associated with large losses or high Q factor
- Difficulty in achieving purity in terms of polarisation
- Power handling capacity is not very great
- Extraneous radiation reduces efficiency
- High performance arrays require complex feed structures
- Surface waves are easily excited
- At high frequencies, unacceptable levels of mutual coupling and cross-polarisation

Some methods to minimise limitations:

- Limitations associated with excitation of surface waves like radiation pattern degradation, increased mutual coupling, lesser gain and lesser efficiency can be dealt with using photonic band-gap structures [29]

- Low power handling and lower gain can be overcome using an array configuration

With an increase in the substrate height H, there is an associated increase in bandwith and therefore efficiency. The trade-off associated with this is the generation of surface waves which result in losses.

2.3 Fractal Antenna

Antenna theory has become one of the latest fields where fractal geometry's use has made a significant impact. As a matter of fact, some of the antennas commercially used in the telecom sector have already been replaced by that using fractal geometry. Several improvements have already been observed in the case of antennas that make use of the aforementioned geometry. What's in fact missing is a direct connection between the usage of the properties of the underlying fractal geometry and the antenna features. [30]

Some of the significant improvements attributed to fractals are size reduction of antennas and introduction of multi-band nature. They continue to remain the prime motivation, albeit more utilities have come into the scene. Using fractal gaskets (Sierpinski), for instance, reports of many dipole and monopole antennas have been made. Given that these qualitative links are not always fool-proof, design optimisation necessitates the existence of a quantitative connection. It’s an area of continuous research to link to do the same, i.e. to establish a mathematical relation betwixt the fractal dimensions and antenna behaviour.

2.3.1 Fractal theory

Self- similar geometrical shapes which repeat themselves are called fractals. This repetition is over different scales. The fact that length of the antenna increases without altering area is a major plus which makes the geometry an important fact of consideration. A mathematical process is used to arrive at the fractal’s shape. This is called the IFS (Iterative Function Scheme). Analysis of all different types of fractals reveal the impossibility of knowing the level one is examining while doing so with fractals. This is so because at finer scales the same pattern tends to re-appear.

There are two stages of fractal generation: Initiator and Generator.

1) 0th stage (Initiator): It’s the basis of the next step of design and any shape can be it ranging from rectangle to any other polygon.

2) Generator: This is the shape which scaling results. Subsequent stages of scaling of the initiator are required to be done to get the final design. Initiators generate generators.

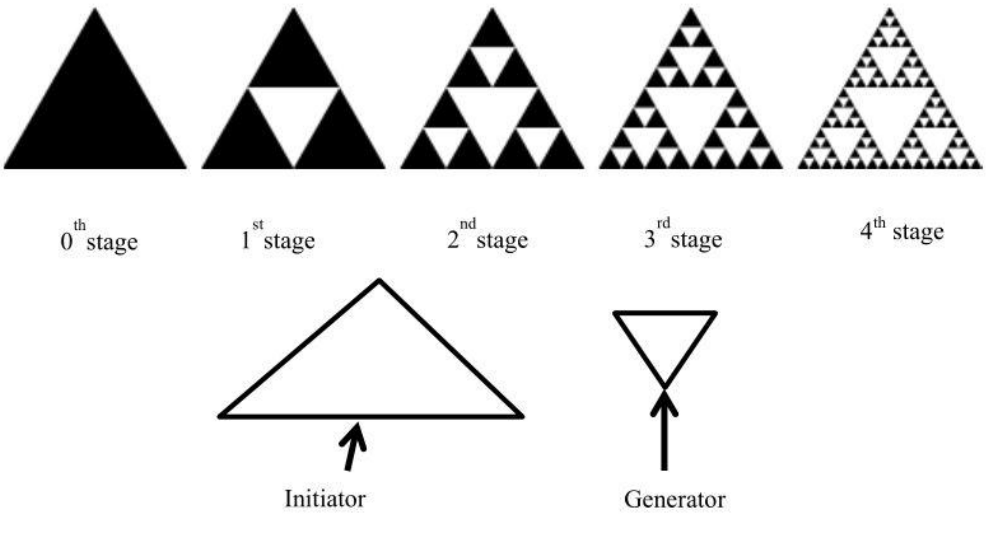


Figure 2.17: Initiator and Generator Stages of Sierpinski Gasket

Owing to their features, fractals have numerous utilities.

Table 2.1: Property Vs Utility

Property	Utility
Self- Similarity	Multi-band Antenna
Small Dimension	Small antennas (electrically)
Space Filling property	Fitting the same electrical length into a compact volume results in antenna miniaturisation
Ease of further iterations	Resonant Frequency decreases with each iteration; length increases electrically
Sharp discontinuities (edges, corners)	Efficient antenna radiation
Absence of Characteristic Sizes	Frequency independence & multi- wavelength operation

[5]

There are some essential features that make Fractals very different from Patch antennas:

- NO characteristic shape, shapes are very irregular
- Presence of infinite scaling results in repetition of the same shape at smaller scales with equal proportionality.
- High Convolution

Associated with infinite complexity, fractals can be used for antennas with operational capabilities at multiple capabilities as the structure just keeps on repeating every time one zooms in. With respect to Euclidean geometry, its efficiency in filling the space available is much better. For a given volume this leads to more energy coupling. Virtually endless length is rendered owing to the presence of irregularities in enormous amounts and these are naturally broadband at higher frequencies.

Table 2.2: Comparison of Fractal and Euclidean Geometries

Euclidean Geometry	Fractal Geometry
Defined by formula	Defined by iterative rule
Applicable for artificial objects	Applicable for natural objects
Scaling changes Shapes	Self-similar, Invariant under scaling
Analytical equations define objects	Recursive algorithms define object
Differentiable Locally smooth,	Not differentiable Locally rough,
Elements: vertices, surfaces, edges	Elements: functions’ iteration

[4]

2.3.2 Classes of Fractals

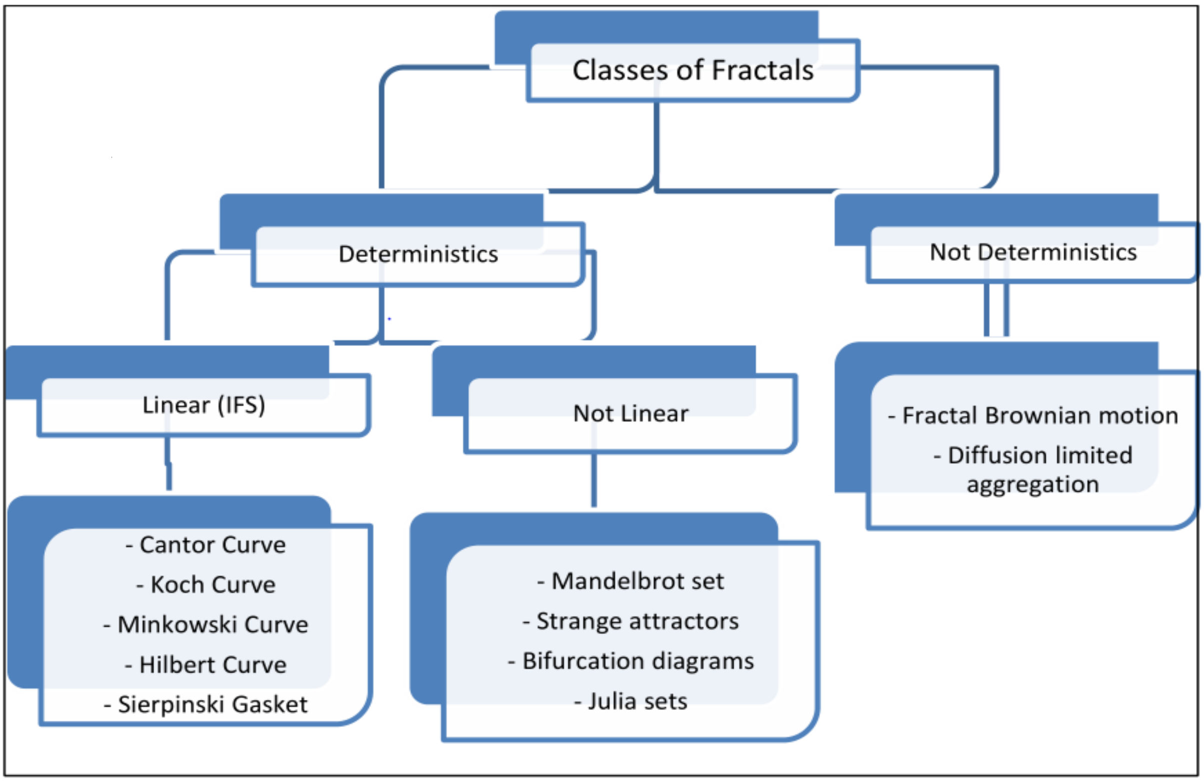


Figure 2.18: Classes of fractals

Description about various fractal classes is given in the flowchart that shown. Basically, two types of Fractals are there, Deterministic and Non Deterministic. Deterministic Fractals are further classified as Linear and Non Linear. *Iterative Function System* is used to derive the linear geometry.

Koch curve, Sierpinski gasket ,Cantor curve, Minkowski curve, etc are examples of linear fractals.

Koch curve: Of the several miniaturized wideband/multiband antennas, this space filling self-similar fractal is one. [37] Several limitations of using antennas which are small in shape are overcome by the features associated with this fractal. [38] Reduction of total height at resonance of the antenna is one major motivation of using this as a dipole antenna. Being non-differentiable at all points, the piecewise- continuous derivative is non-existent. It’s characterised by highly uneven and rough shape.

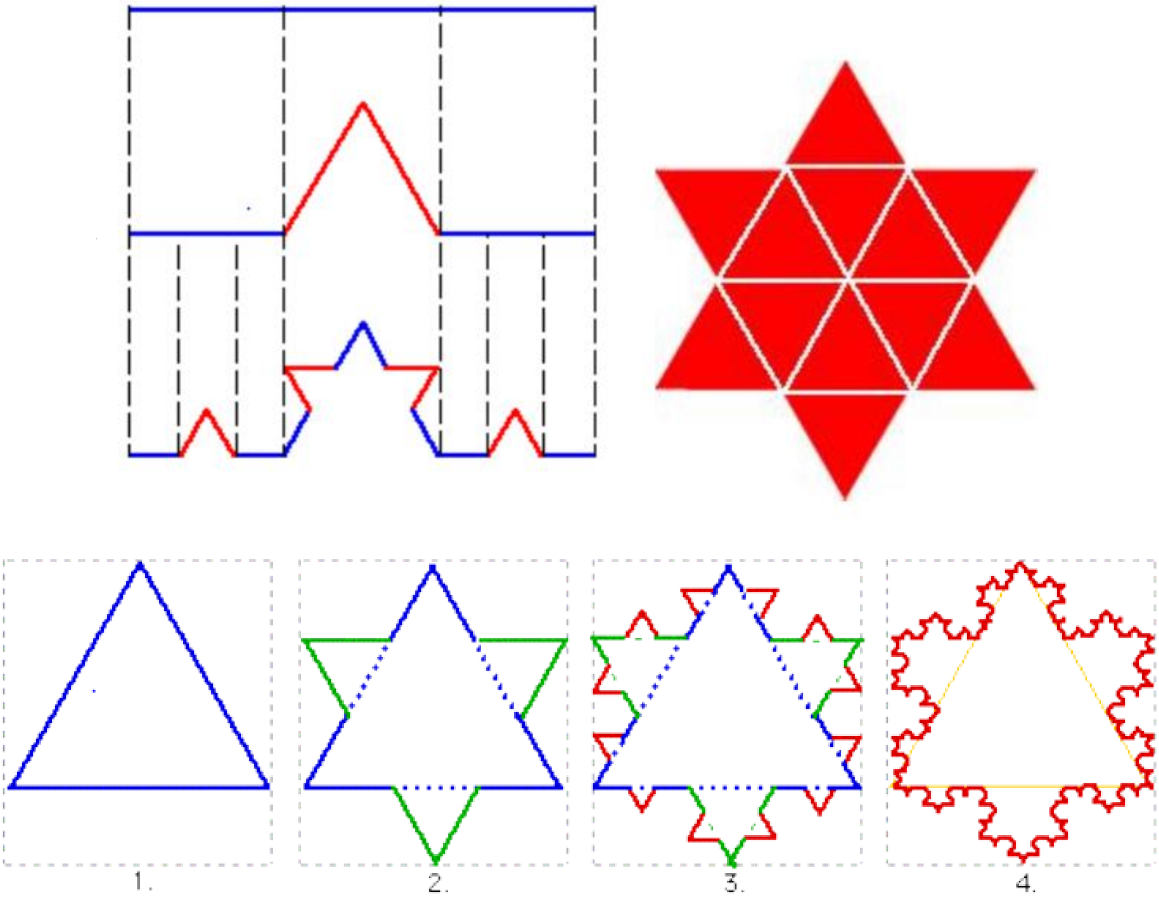


Figure 2.19: Koch Curve and Steps in the Construction of Koch Curve

Minkowski loop: Increment in the efficiency of space-filling with electrical length results in an antenna of reduced size. One wavelength is the perimeter. Beside the expected broadband effect, due to the wire-coupling multiband effect is also displayed by the Minkowski fractal. The complications associated with the coupling, increases with each iteration, thereby resulting in resonance at different frequencies. Miniaturisation in antennas is achievable via this method without altering the square loop antenna's EM performance

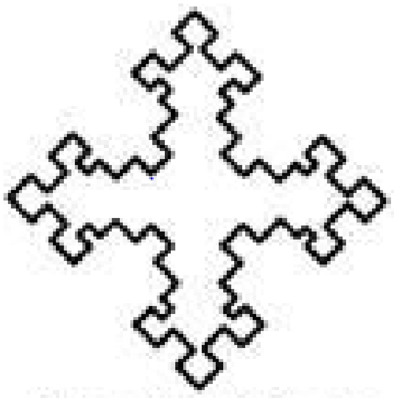


Figure 2.20: Minkowski Loop

Sierpinski gasket: Discovered Waclaw Sierpinski, a Polish mathematician, these fractals owing to their self-similarity, possess multiband behaviour. For purposes of antenna design this is one of the most popular and studied fractal. Initially, a triangle is taken as the initiator. Scaling the size to ½, another triangle is removed from the initiator such that its vertices are the midpoints of the triangle mentioned earlier and the process is looped. Sierpinski triangle's area is 0. Remnant area after each iteration, is three-fourth of the area of the previous figure.

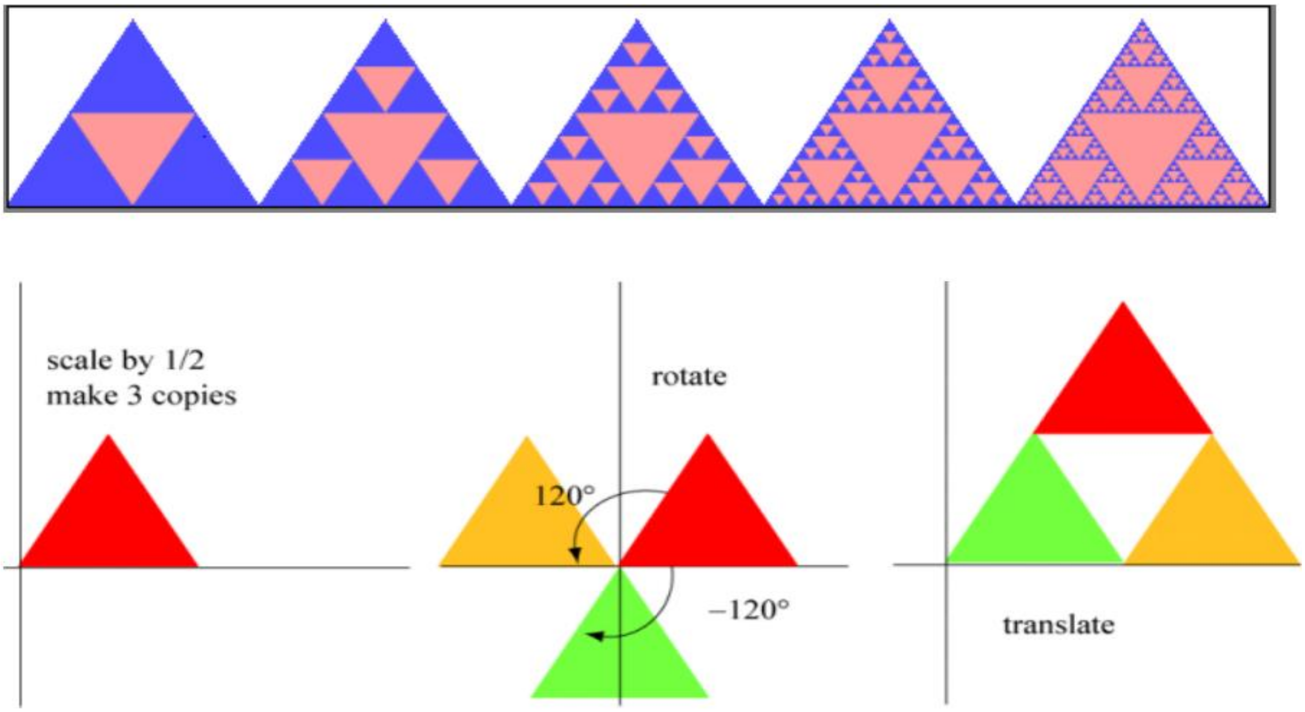


Figure 2.21: Sierpinski Gasket and steps involved in its construction

Cantor Set: Discovered by H J S Smith, it was introduced by George Cantor in 1883. On a line segment, the cantor set would be a point's set having numerous observable properties. It's formed by a third part of a line segment of unit length on each occasion for iteration.

Sierpinski Carpet: Similar to the gasket, it's different in the fact that it uses squares in place of triangles. In its simplest configuration, a square (initiator) is congruently divided into nine squares. The central piece is then removed. The same procedure is repeated with the next eight squares.

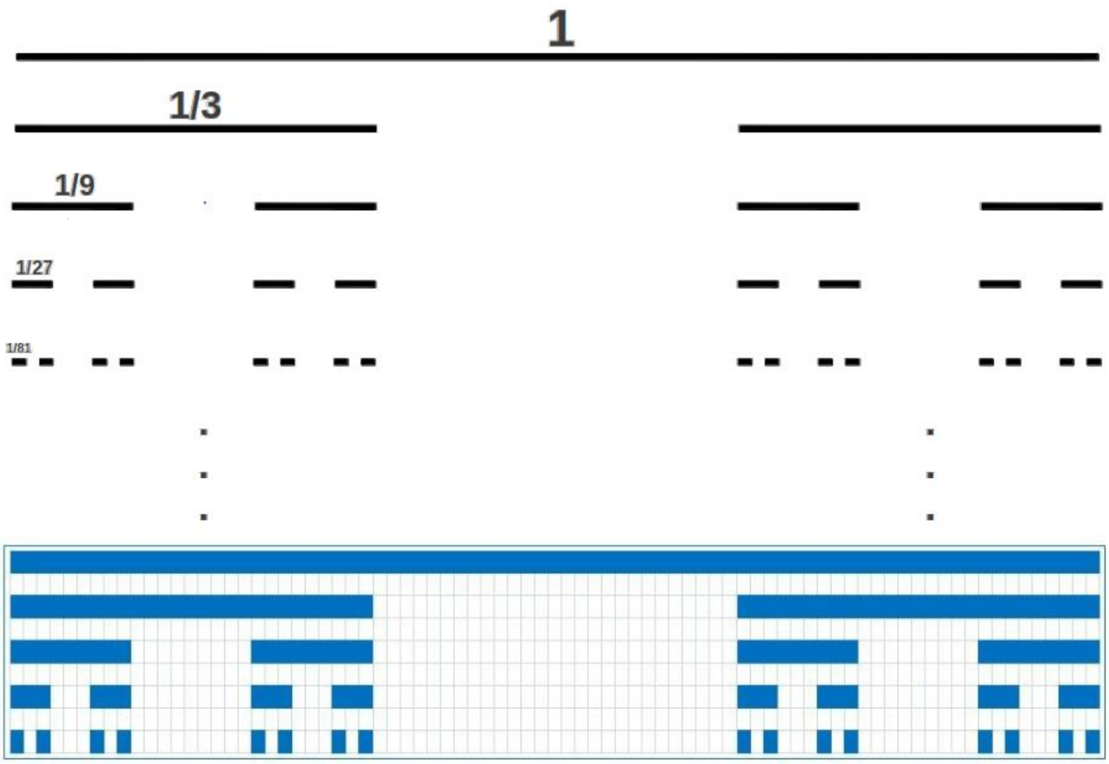


Figure 2.22: Cantor Set

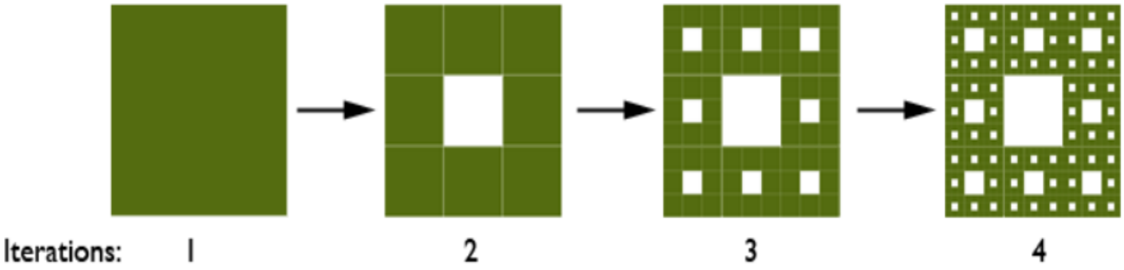


Figure: 2.23: Sierpinski Carpet

2.3.3 Fractal Dimensions

In the general sense we are acquainted with integral dimensions, 0-D, 1-D lines, 2-D planes, 3-D solids. However, Fractals pertain to non-integral dimensions like 1.5-D, 3.87-D etc., also called fractal dimensions. Some of them are Similarity Dimension, Box-Counting Dimension, the Hausdorff Dimension, etc. These are important parameters as dimensions characterize fractals.

Similarity Dimension is one of such key structural parameters. Its definition is made by partitioning the volume containing the fractal to sides of δ. There is close association between scaling and that of the dimension concept. [5]

Considering a line N (length) divided into equal portions of side δ, then the scaling ratio is δ.

For Unit Line $L= N \delta=1$

For Unit Area $A= N \delta^2=1$

For Unit Volume $V=N \delta^3=1$

Thus setting the exponent as a parameter measuring the object's dimension,

$$N \delta^{DS}=1$$

Therefore $DS= \log (N)/ \log (1/ \delta)$

where DS denotes the similarity dimension.

For Cantor set, two identical copies are contained within the set.

So $N=2$, $\delta = 1/3$.

Hence, $DS= \log (N)/ \log (1/ \delta) = 0.6309$

Thus, for Cantor's Set the fractal dimension turns out to be fractional, as predicted. [5]

2.3.4 Advantages and Disadvantages

Illustrations of the advantages of combining antenna theory and fractal geometry are given here.

- Without altering performance size can be shrunk
- At non-harmonic frequencies exhibition of multiband operations is done.
- Improvement in reliability
- Naturally broadband, at higher frequencies; non requirement of any matching components whatsoever.[5]
- Reduced costs of installations
- Can be operational at multiple wavelengths or frequency independent.
- Better radiation efficiency
- Mechanical Simplicity and Robustness
- Compact Size

Disadvantages:

- Low Gain
- Too complex geometry

- Numerical Limitations
- Guest of a few iterations; benefits start to diminish soon after.

2.4 Summary

A discussion about various terms and lexicons associated with antennas was done in this chapter. Also a brief treatise was given about the basics of MPAs. Various feeding mechanisms with respect to compact and low volume antennas, for wireless applications were discussed as well. The reason behind using the 50Ω transmission line was briefly thrown light upon. Besides deduction of the patch antenna theory, the pros and cons and the methods useful to reduce such limitations were also briefly dealt with. Discussions on Fractal geometry were also done. Combining attributes of antenna theory & fractal geometry Fractal antenna engineering is the hub of research. Fractals' use for space-filling enables effectively fitting long lengths and miniaturising antennas. Besides comparing the traditional Euclidean with the Fractal geometry, the latter's pros and cons were also discussed.

Chapter 3

Narrow Band Fractal Antenna

3.1 Introduction

This chapter presents the design and analysis of a Fractal hybrid showcasing narrowband behaviour. The design consists of a Giuseppe Peanu fractal that constitutes the base on which another fractal geometry, Sierpinski geometry is implemented. The patch as a whole is on top of the FR4 substrate of dielectric constant 4.4. The choice of FR4 is based primarily on its ease of availability and lower cost associated. Beneath the substrate lies a ground which itself is a combination of rectangular patch and a circular segment. The antenna exhibits narrowband characteristic. For an antenna to be designated as a narrow-band one, the impedance bandwidth must be less than 50%, i.e.

$$BW_p = \frac{f_h - f_l}{f_c} * 100\% < 50\% \tag{3.1}$$

where

f_h is the higher cut off frequency

f_l is the lower cut off frequency

f_c is the central resonance frequency.

As will be shown in the subsequent section the Bandwidth Percentage of this antenna turns out to be 40.421% which in turns qualifies it to be a narrowband antenna. But before proceeding into the design details, simulation results and the conclusion drawn thereof, a brief discussion about pros and cons of narrow-band is presented.

The principal demerit associated with narrowband is that because of lower bandwidth, for high speed communication of data, it becomes a very uphill task. Also, the installation cost and size of narrowband modules is higher than that of wideband ones. However, it’s more than compensated in its merits. It’s very helpful in realising stability of long range communications. The associated transmission spectrum’s carrier purity is also quite high. It therefore helps in efficiently managing a lot of radio devices operational at the same time within the same frequency range, i.e. high efficiency in usage of radio waves is achieved within the same range of frequency. Thus, for sites with multiple devices which are radio-controlled, it becomes ideal especially in industrial plants and construction sites.

3.2 Antenna Design

In this section, the details regarding the antenna's design are provided followed by the results of the simulations that were carried out

Design Parameters:

The proposed design is composed of a rectangular patch element, subjected to Giuseppe Peanu fractal slots which in turn form the basis for a Sierpinski Circular slot arrangement, on a dielectric layer beneath which lies the ground plane which again is a combination of a rectangular patch and a circular segment whose diameter is same as the substrate width, i.e. 12.5 mm. The substrate is low cost fiberglass 1.6 mm thick with $\varepsilon_r = 4.3$. The Ground consists of a rectangular patch 3mm X 25mm.

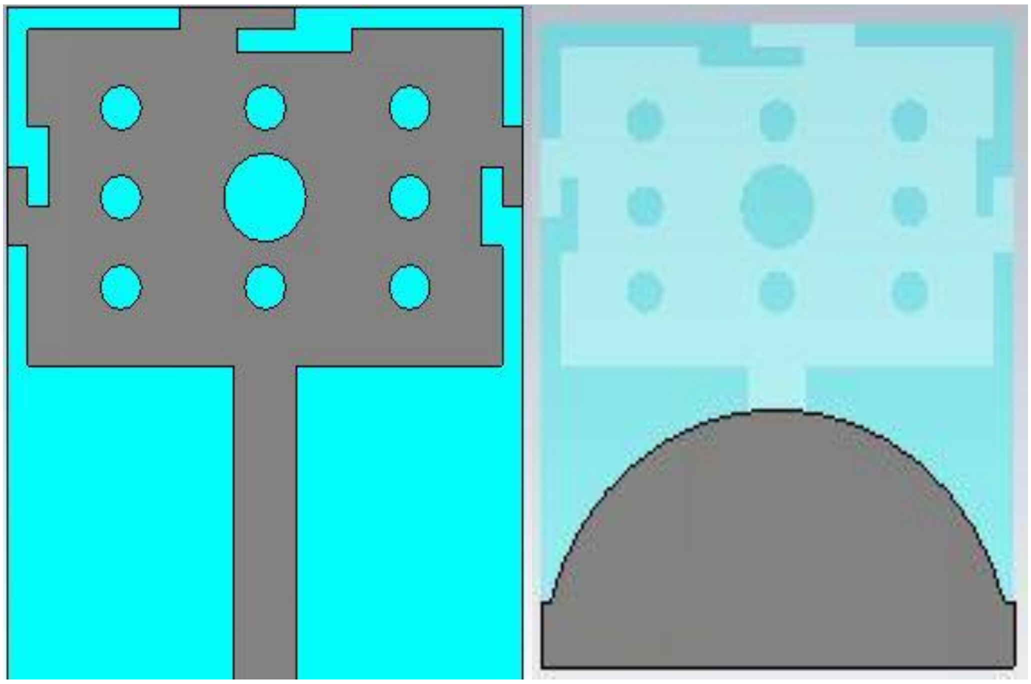


Figure 3.1 (a) Front View

(b) Back View

Table 3.1: Dimensions of the design

Length of the substrate	30 mm	Width of the substrate	25 mm
Length of the patch (Front)	16 mm	Length of the notch on patch	W/3 or L/3
Length of the patch (back)	3 mm	Width of the notch	1 mm
Center of the Circle (back)	(0, -16)	Center of the first circle (Front)	(0, 6.5)
R1(radius of BIGGER circle)	2 mm	R2(radius of SMALLER circles)	1 mm

N.B: Taking the centre of the substrate as the origin, rest of the coordinates are determined. The entire patch is fed with a 50-ohm micro strip feed line with dimensions 9mm X 3mm. The first fractal is devised using the Giuseppe Peanu design whose steps of generation in case of single line, are as under.

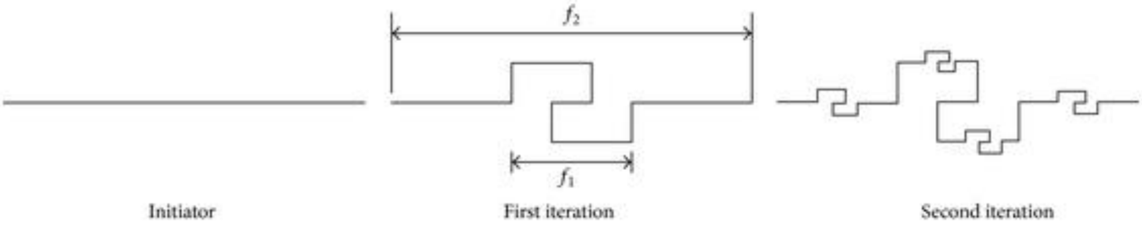


Figure 3.2: Steps involved in the generation of Giuseppe Peanu Fractal

In case of the proposed design, a rectangular patch of dimensions 25mm X 16mm is subjected to the Giuseppe Peanu iteration over the length and the breadth taking the notch length to be one third of the total length of the side and width to be 1 mm.

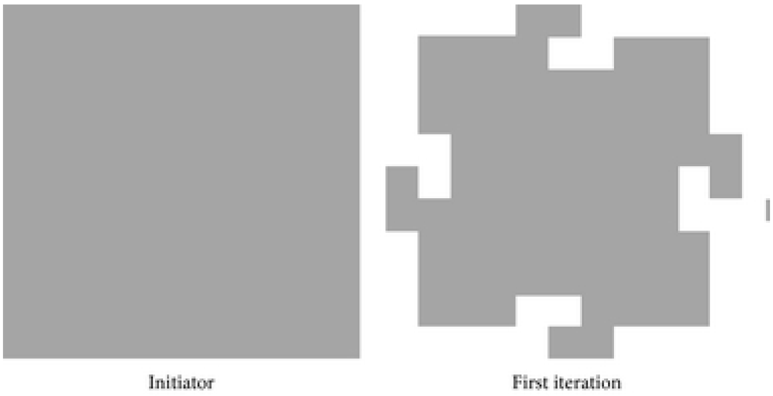


Figure 3.3: Generation of Giuseppe Peanu fractal over rectangular patch

The patch that remains is again subjected to Sierpinski carpet through etching out of 9 circles of which the central one is of radius 2 mm and the rest 8 are in form of a rectangle’s edges and are of radius 1mm each. The design is then simulated through the CST microwave studio over a frequency range of 2 GHz to 14 GHz. The return loss plot, S_{11} parameter graph is shown as under.

Simulation Results:

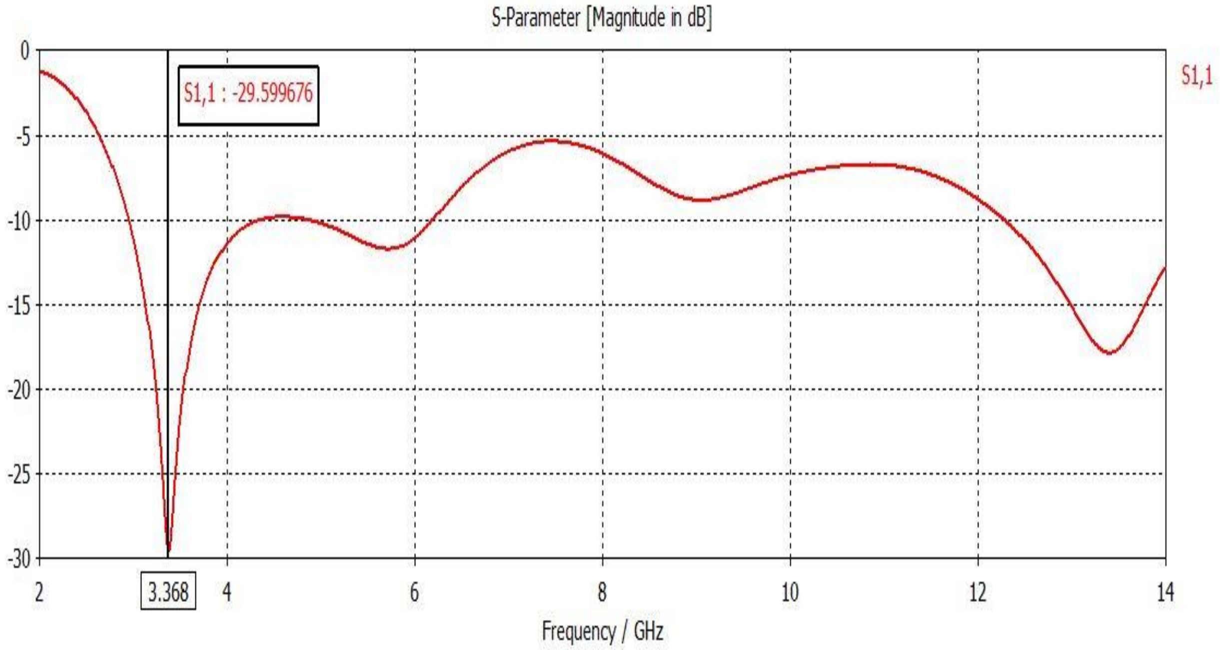


Figure 3.4: S_{11} plot

As is visible from the graph and calculated thereafter the difference between the high cut off frequency and the low cut off frequency turns out to be 1.3614 GHz which when divided by 3.368 GHz gives the impedance bandwidth percentage.

$$(1.3614/3.368)*100\% = 40.421\% < 50\%$$

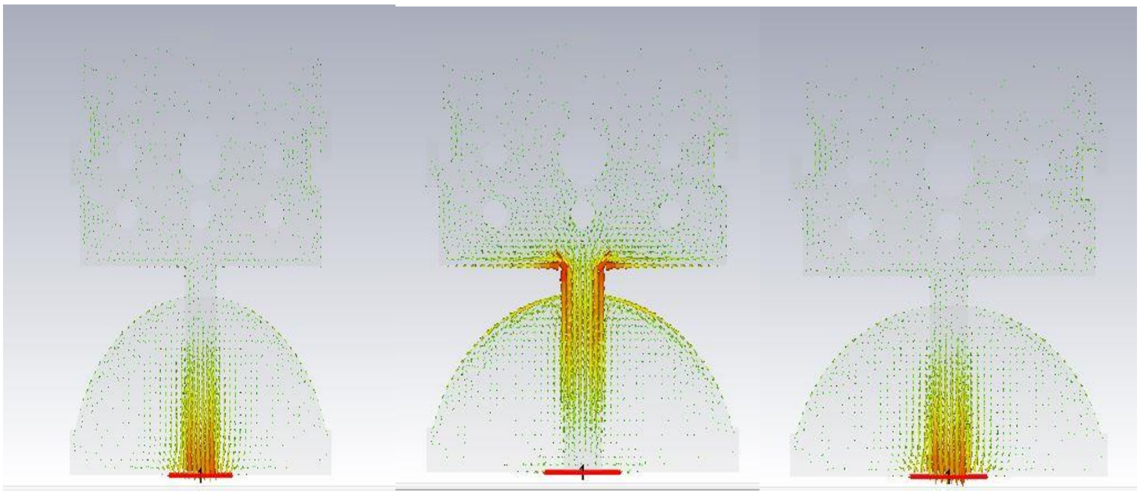
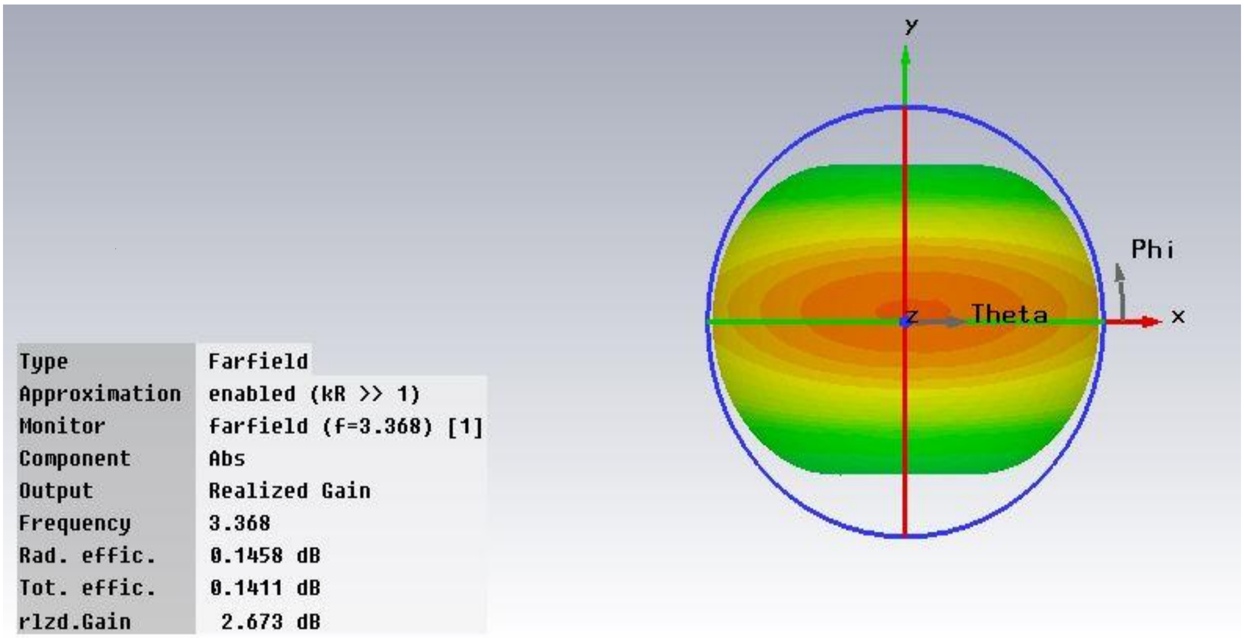
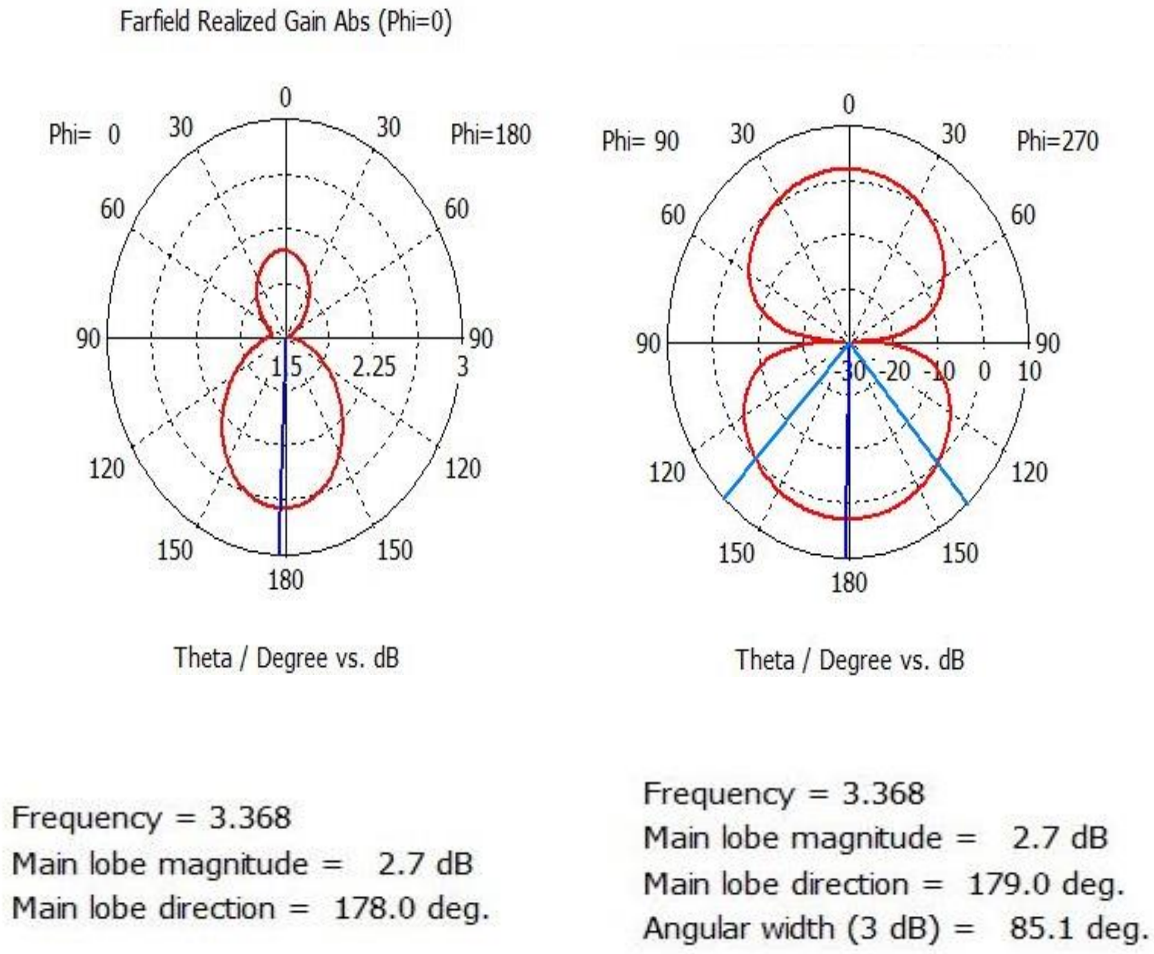


Figure 3.5: The Surface Current plot at different Instances



Type	Farfield
Approximation	enabled (kR >> 1)
Monitor	farfield (f=3.368) [1]
Component	Abs
Output	Realized Gain
Frequency	3.368
Rad. effic.	0.1458 dB
Tot. effic.	0.1411 dB
rlzd.Gain	2.673 dB

Figure 3.6: Realized Gain



Frequency = 3.368
Main lobe magnitude = 2.7 dB
Main lobe direction = 178.0 deg.

Frequency = 3.368
Main lobe magnitude = 2.7 dB
Main lobe direction = 179.0 deg.
Angular width (3 dB) = 85.1 deg.

Figure 3.7: Radiation Patterns

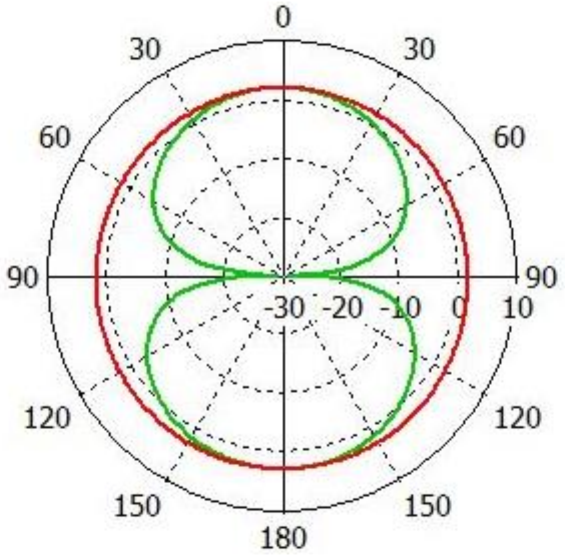


Figure 3.8: E and H plane graphs

3.3 Summary

Thus, the antenna is therefore proved to be narrow-band operational. The Narrow- Band Antenna operating at the f_c = 3.386 GHz, which falls in the S-band of SHF, can be used for wireless communications esp. WiMAX. This is also a usable frequency for amateur radio and satellite operators. This band can also find use in radars, for weather detection, Surface ship and for space communication as this is used by NASA for communication with ISS and shuttles. [wiki]

CHAPTER 4

Multi Band Fractal Antenna

4.1 Introduction

The range of frequencies between 3 GHz and 30 GHz is designated as SHF (Super High Frequency). ‘Microwave’ is also another name for the waves carrying such frequencies. Line of sight communications is what they are mostly used for. Cell phones, WLANs, Radars mostly use frequencies in this range. A third of its spectrum is anticipated to be used by Wireless USB, a futuristic proposal. S, C, X, Ku, K, Ka are the various IEEE designations allotted to frequencies in this band.

SHF is one of its kind frequency ranges, a sweet-spot vying for exploitation. Directing them in narrow beams even with not very huge antennas is possible such that no interference occurs with nearby radiators, lowest band of frequency where that’s possible. Also, they don’t get absorbed by the atmosphere thereby becoming the highest band useful for terrestrial communication over long distances.

The next design proposed herein, is a fractal antenna with the scope for utilisation of the aforementioned properties. With resonant frequencies occurring at multiple positions over the SHF, it can be fabricated to utilise the properties of the respective bands.

It’s a CPW fed fractal that’s generated by iteratively carving out circles within squares such that electrical connectivity always remains, over a dielectric substrate FR4 of dielectric constant of 4.4 without any ground plane. The resultant antenna radiates at multiple frequencies over the SHF range thereby rendering it multi-band functionality.

Organisation of this chapter is as the previous one. 4.2 deals with the details of the design and the dimensions are provided in the subsequent chapter. Also attached are the radiation pattern and gain details at each of the resonant frequencies of the antenna.

4.2 Antenna Design

Design Parameters:

The antenna is designed by continuously and iteratively carving out circles out of squares whose dimensions are provided in the table that follows. The patch is fed by Co Planar Waveguide feeding technique whose details are also provided in the aforementioned table.

But before that the design of the antenna follows:

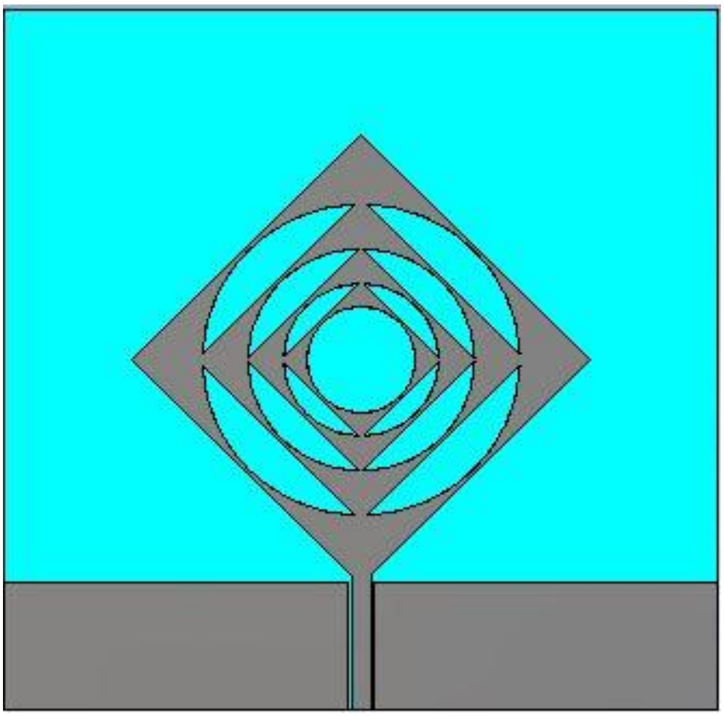


Figure 4.1: CPW Fed Fractal

Table 4.1: Dimensions of the squares and the circle

Iteration No.	Length of Edge of the square	Internal Radius
1	50 mm	24.5 mm
2	36 mm	17.5 mm
3	25 mm	12 mm
4	17.6 mm	8.4 mm

Table 4.2: Dimension details of the design

Width = Length of the substrate	110 mm
Thickness of the Substrate	1.53 mm
Spacing between FEED and Adjacent Ground	0.5 mm
Length of the feed	24.5 mm
Width of the Feed	3 mm
Length of the CPW ground	24.5 mm

Simulation Results:

The S_{11} parameter plot (Return Loss) of the design as follows:

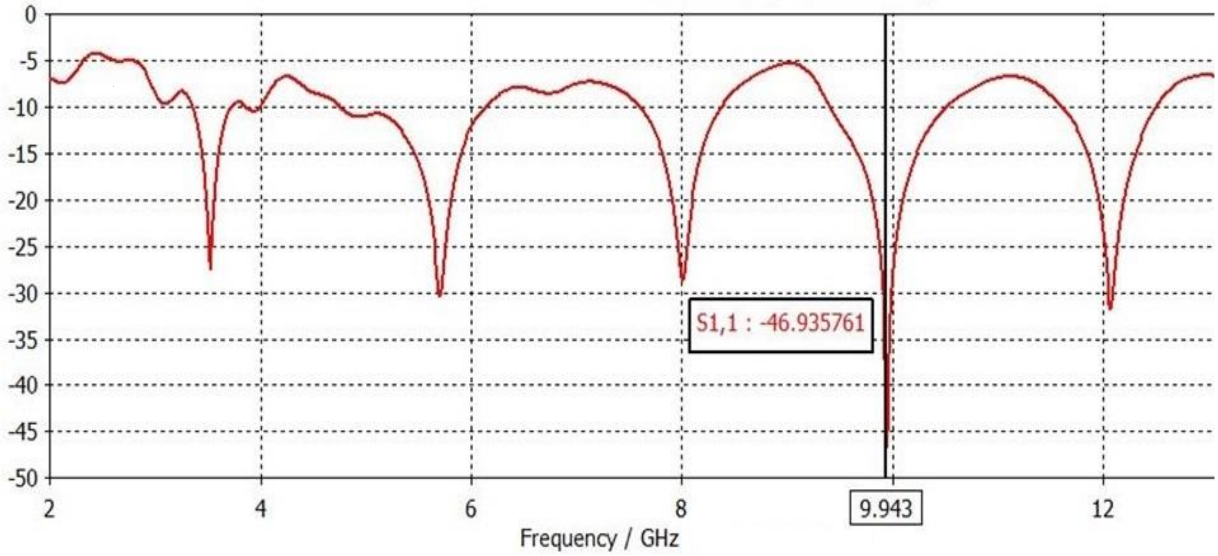


Figure 4.2: Return Loss Graph

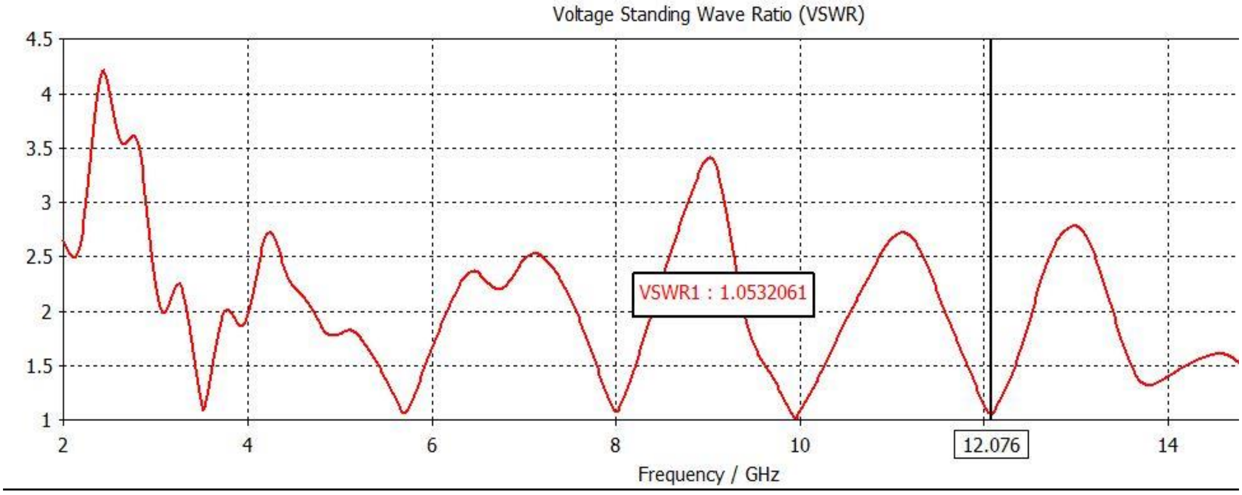


Figure 4.3: VSWR plot

As can be seen from both the above figures, 4.2 and 4.3, the resonant frequencies or in other words the frequencies of the multi-band antenna are 3.5209 GHz, 5.70 GHz, 8.04 GHz, 9.94 Ghz and 12.07 Ghz. It’s worthy to note that at the aforesaid frequencies the VSWR plot goes below 2 which essentially mean the S_{11} plot goes beyond -10 dB levels at those points.

The Gain Vs Frequency plot of the proposed antenna is shown below:

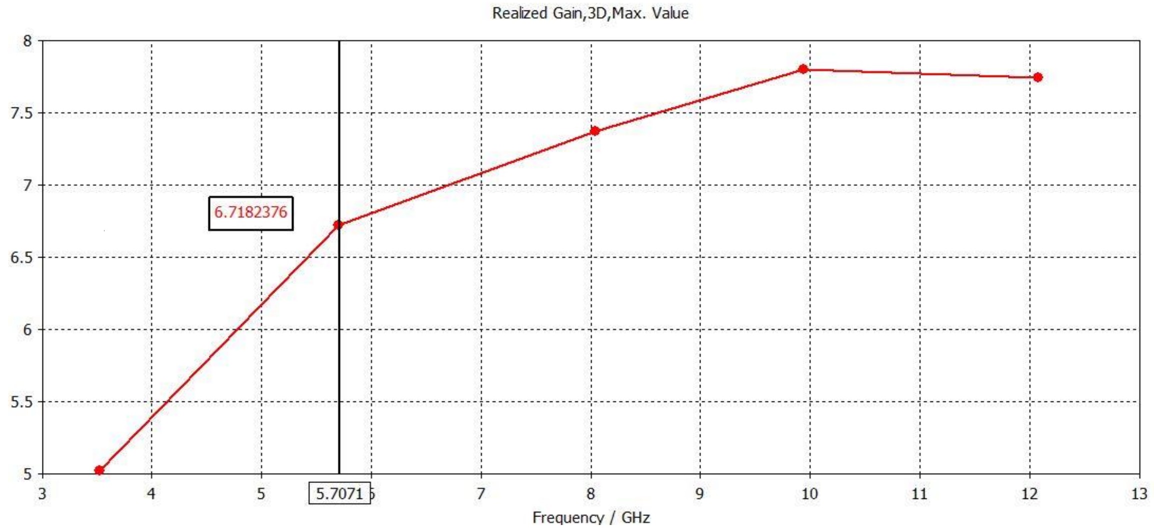
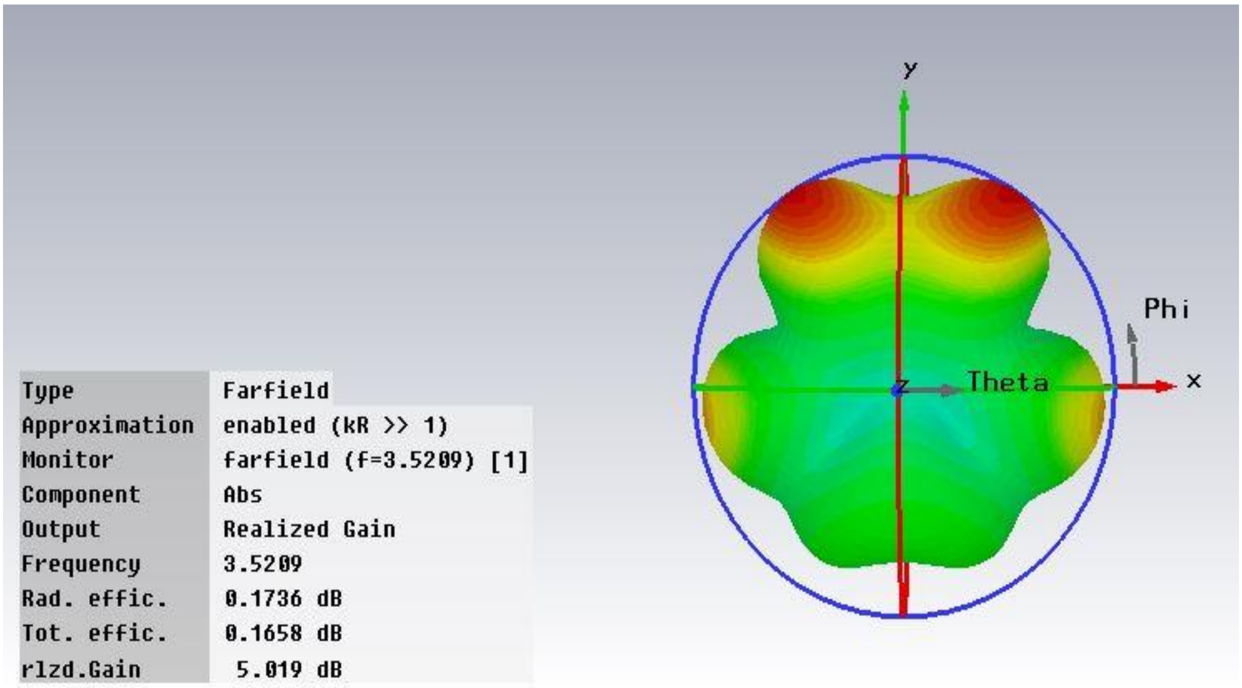


Figure 4.4: Realised gain Vs Frequency Plot

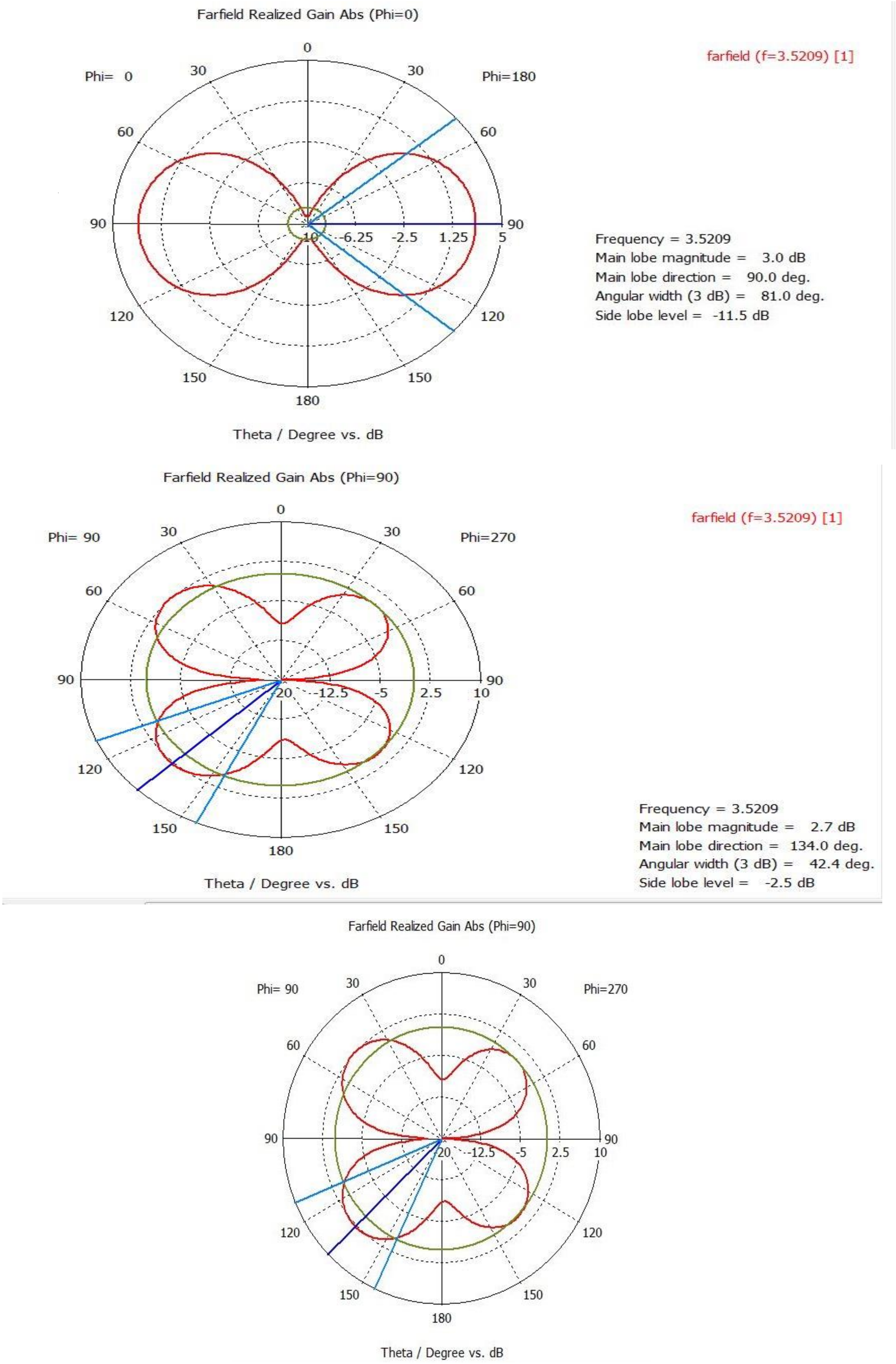
The results of individual simulations at the various resonant frequencies are attached hereby and as follows:

For $f_c = 3.52$ GHz:



Type	Farfield
Approximation	enabled (kR >> 1)
Monitor	farfield (f=3.5209) [1]
Component	Abs
Output	Realized Gain
Frequency	3.5209
Rad. effic.	0.1736 dB
Tot. effic.	0.1658 dB
rlzd.Gain	5.019 dB

Figure 4.5: Realised Gain (3D)



```
Frequency = 3.5209
Main lobe magnitude =   3.0 dB
Main lobe direction =   90.0 deg.
Angular width (3 dB) =   81.0 deg.
Side lobe level =  -11.5 dB
```

```
Frequency = 3.5209
Main lobe magnitude =   2.7 dB
Main lobe direction =  134.0 deg.
Angular width (3 dB) =   42.4 deg.
Side lobe level =   -2.5 dB
```

Figure 4.6: Radiation Patterns

For $\mathbf{f_c = 5.7}$ GHz:

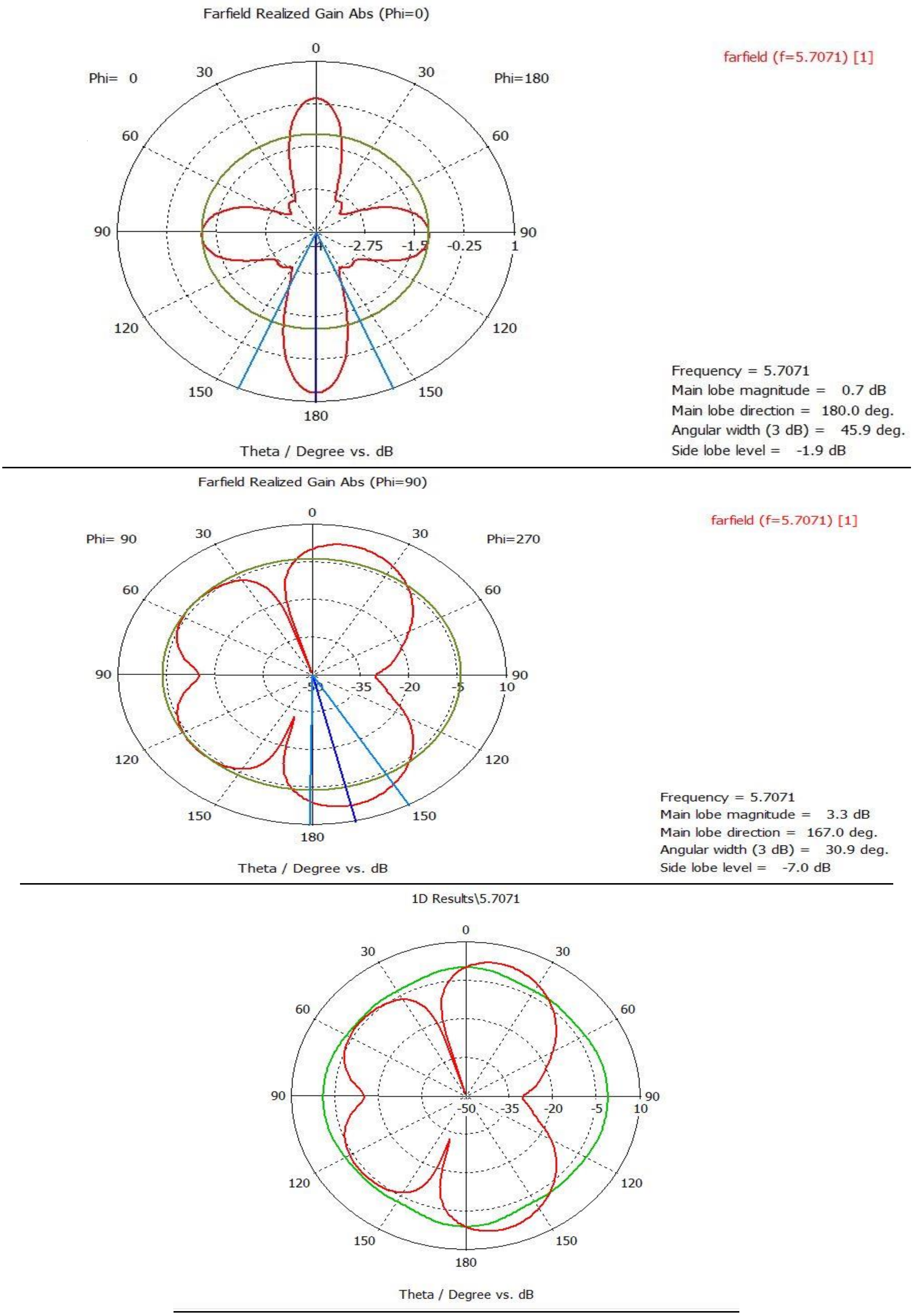
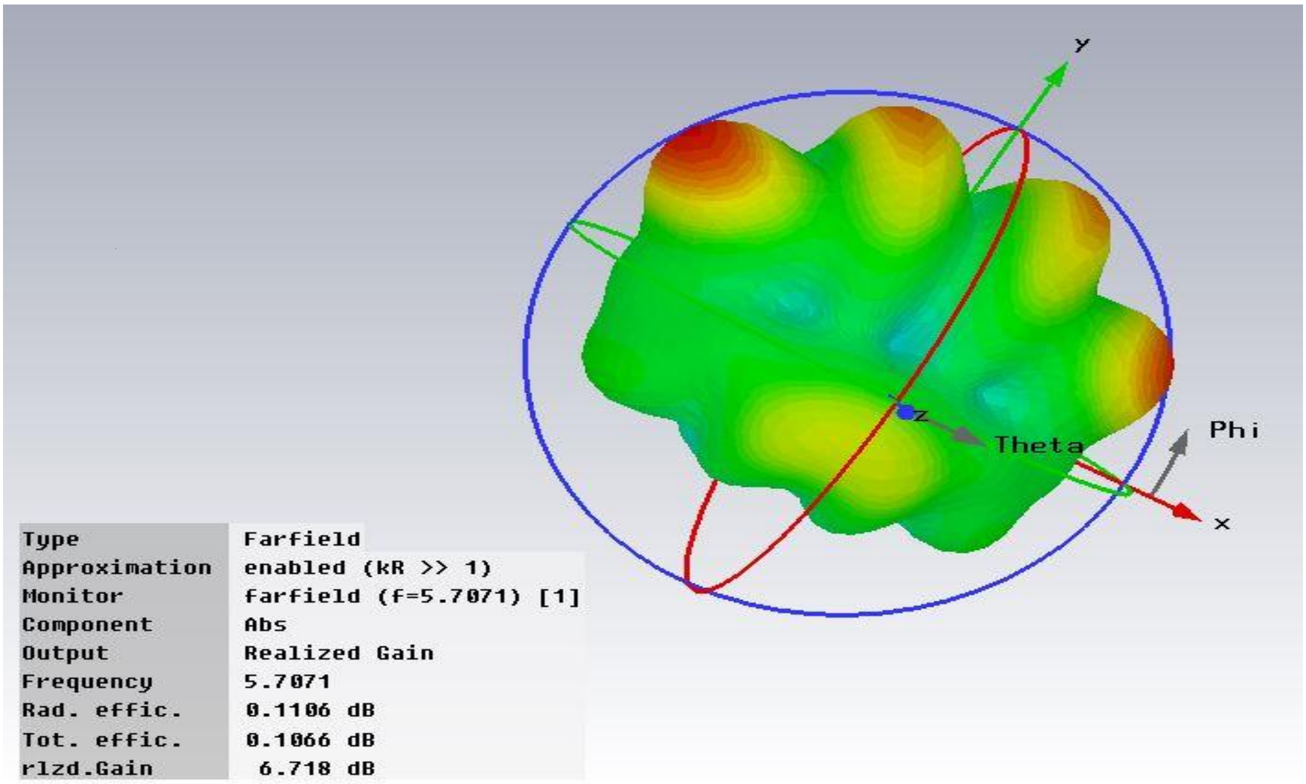


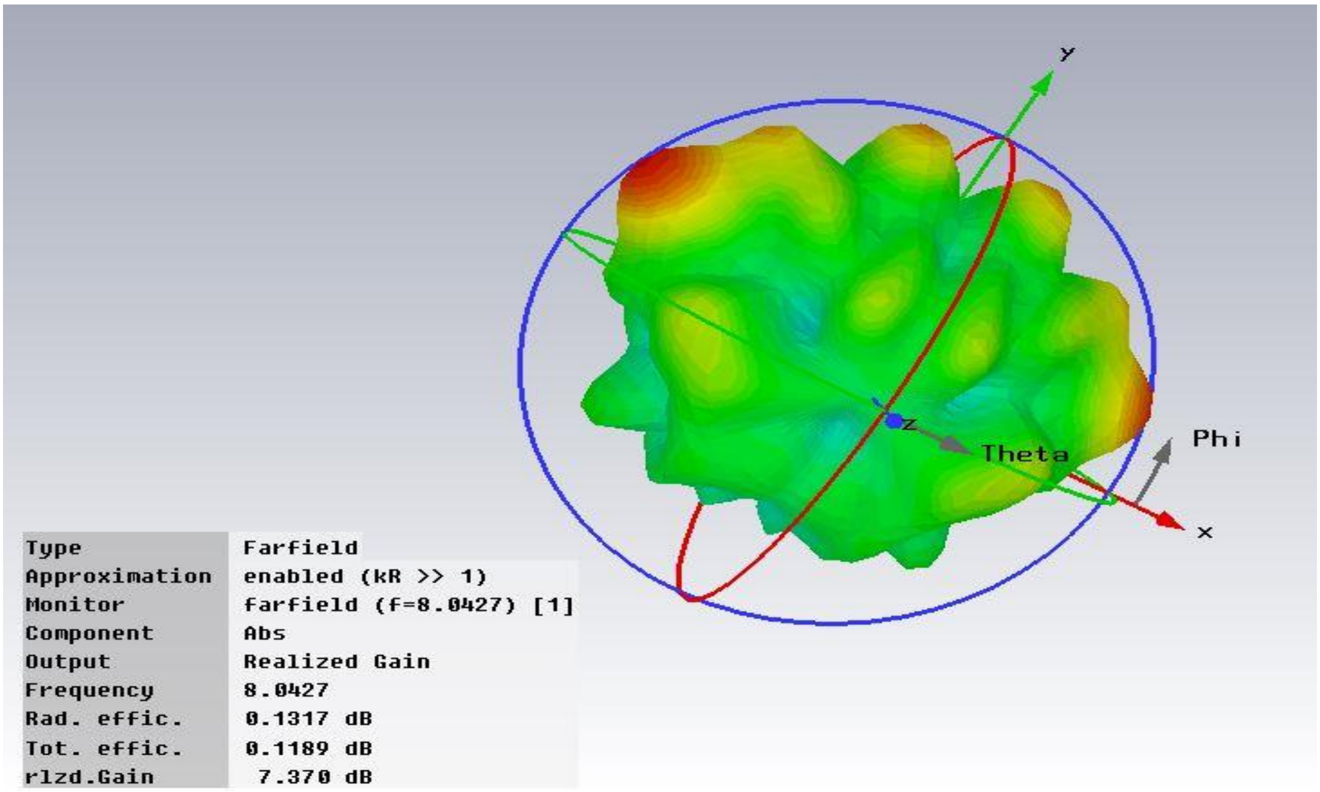
Figure 4.7: Radiation pattern



Type	Farfield
Approximation	enabled (kR >> 1)
Monitor	farfield (f=5.7071) [1]
Component	Abs
Output	Realized Gain
Frequency	5.7071
Rad. effic.	0.1106 dB
Tot. effic.	0.1066 dB
rlzd.Gain	6.718 dB

Figure 4.8 Realised Gain (3-D)

For $\mathrm{f_c} = 8.04$ GHz:



Type	Farfield
Approximation	enabled (kR >> 1)
Monitor	farfield (f=8.0427) [1]
Component	Abs
Output	Realized Gain
Frequency	8.0427
Rad. effic.	0.1317 dB
Tot. effic.	0.1189 dB
rlzd.Gain	7.370 dB

Figure 4.9: Realised Gain (3-D)

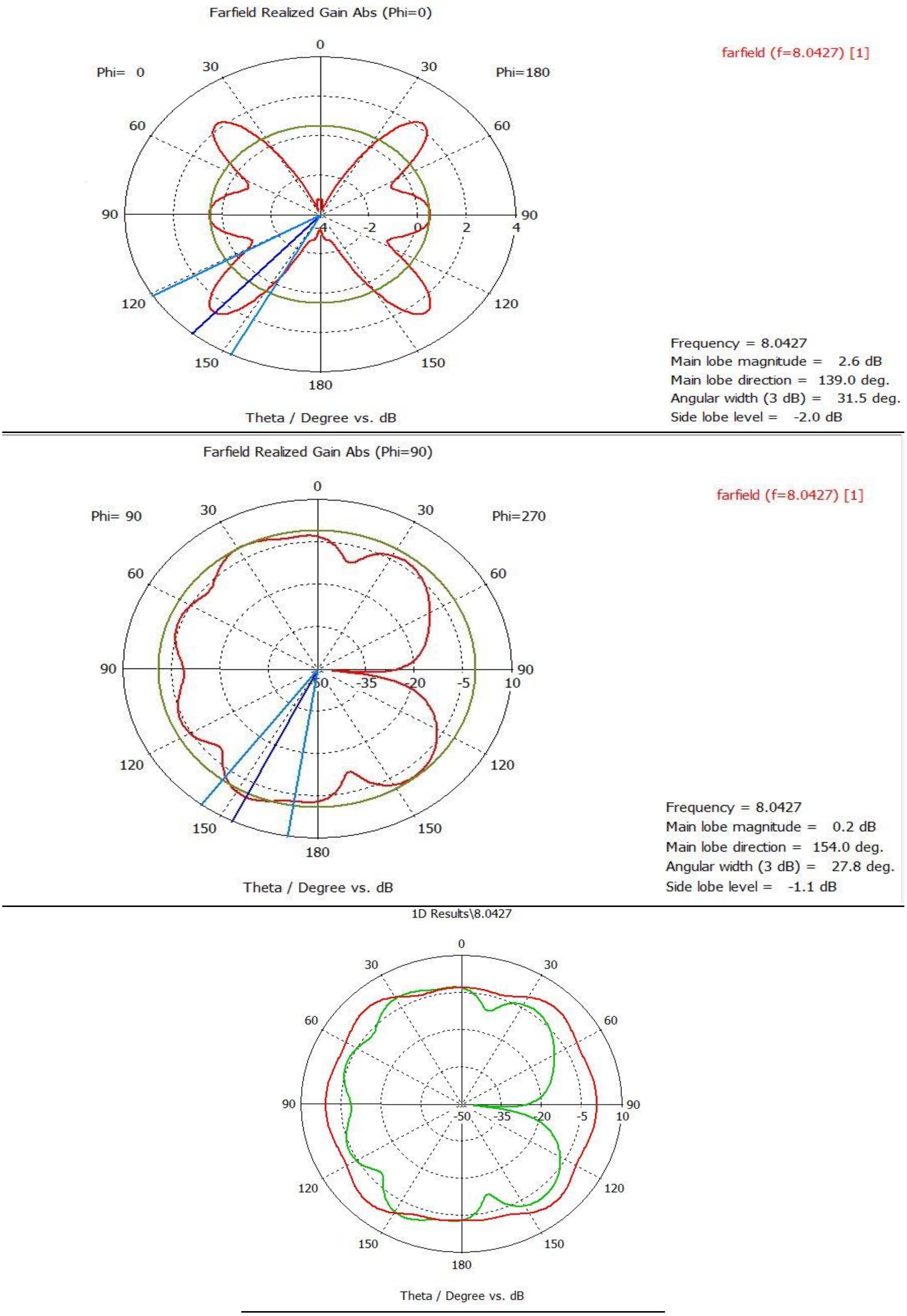
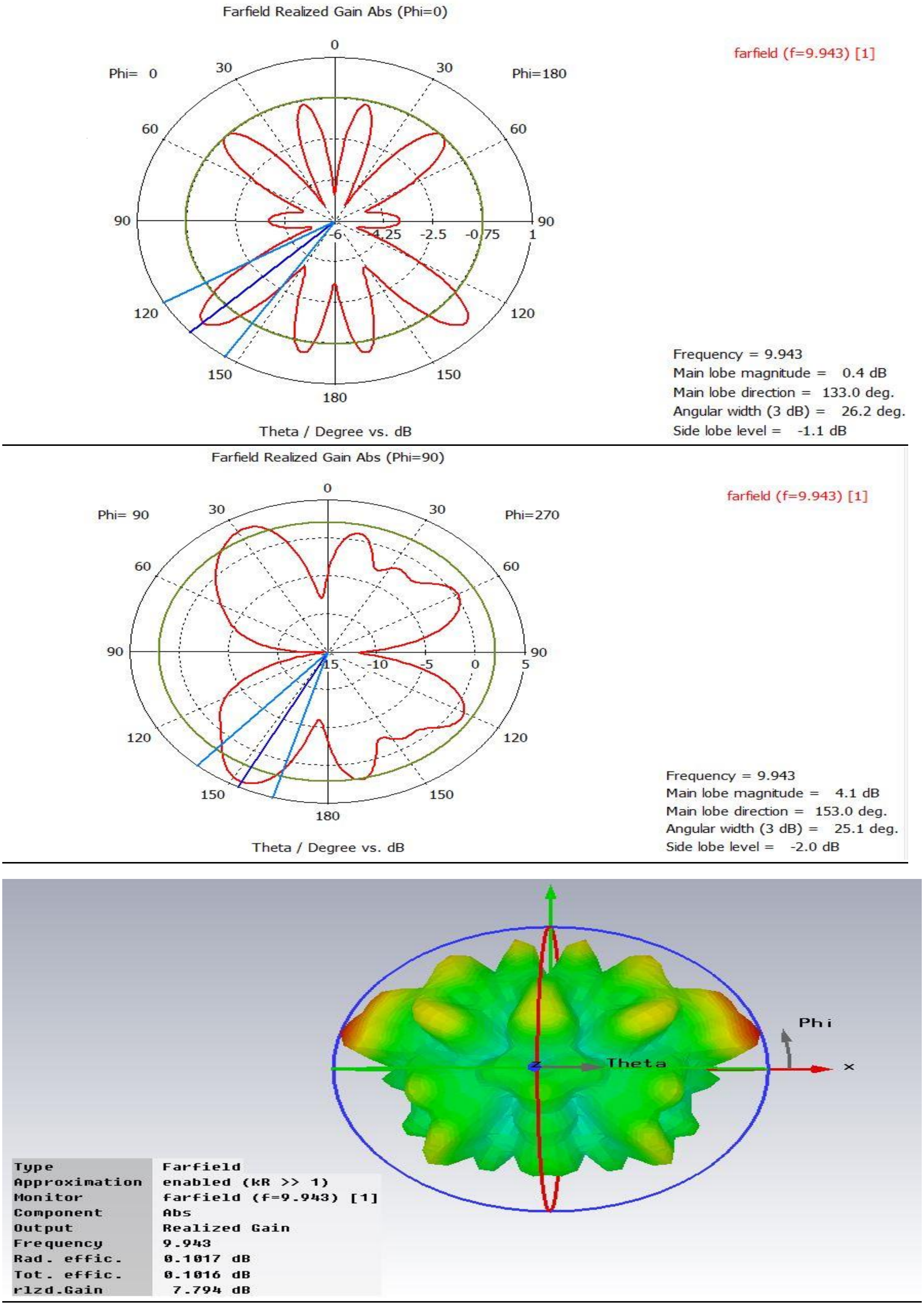


Figure 4.10: Radiation Patterns

For $f_c = 9.943$ GHz:



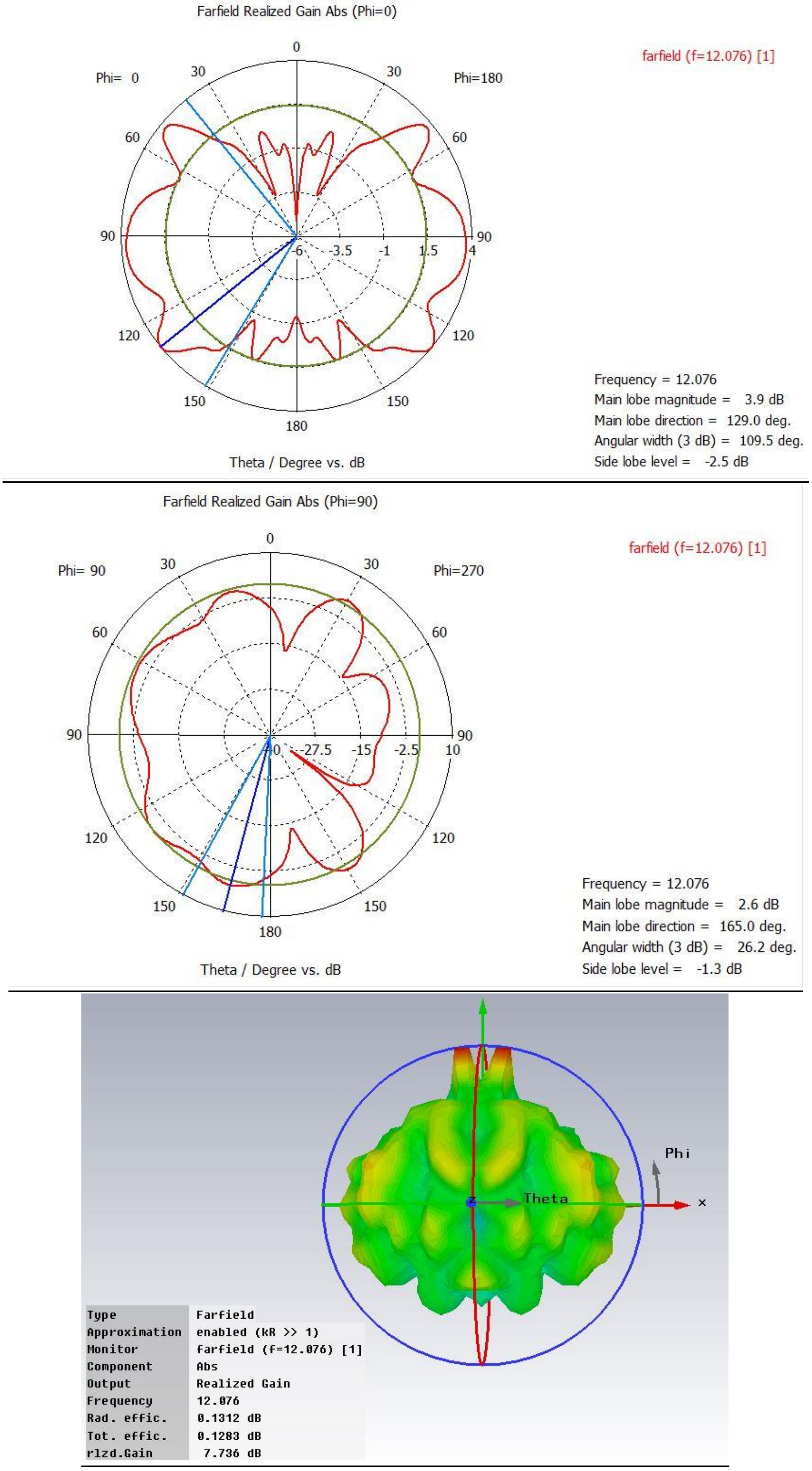
Frequency = 9.943
Main lobe magnitude = 0.4 dB
Main lobe direction = 133.0 deg.
Angular width (3 dB) = 26.2 deg.
Side lobe level = -1.1 dB

Frequency = 9.943
Main lobe magnitude = 4.1 dB
Main lobe direction = 153.0 deg.
Angular width (3 dB) = 25.1 deg.
Side lobe level = -2.0 dB

Type	Farfield
Approximation	enabled (kR >> 1)
Monitor	farfield (f=9.943) [1]
Component	Abs
Output	Realized Gain
Frequency	9.943
Rad. effic.	0.1017 dB
Tot. effic.	0.1016 dB
rlzd.Gain	7.794 dB

Figure 4.11: Radiation Pattern & Realised Gain

For $\mathbf{f_c = 12.07}$ GHz:



Frequency = 12.076
Main lobe magnitude = 3.9 dB
Main lobe direction = 129.0 deg.
Angular width (3 dB) = 109.5 deg.
Side lobe level = -2.5 dB

Frequency = 12.076
Main lobe magnitude = 2.6 dB
Main lobe direction = 165.0 deg.
Angular width (3 dB) = 26.2 deg.
Side lobe level = -1.3 dB

```
Type            Farfield
Approximation   enabled (kR >> 1)
Monitor         farfield (f=12.076) [1]
Component       Abs
Output          Realized Gain
Frequency       12.076
Rad. effic.     0.1312 dB
Tot. effic.     0.1283 dB
rlzd.Gain        7.736 dB
```

Figure 4.12: Radiation Pattern & Realised gain (3-D)

4.3 Summary

Multi Band Antenna which resonates at 3.5 GHz, 5.7 GHz, 8 GHz, 9.95GHz and 12 GHz can have several applications. 3.5 GHz is, as mentioned earlier, used for WiMAX and in wireless communication systems. The next two frequencies fall under C band and can be used for satellite communications (TV reception) and Wi-Fi devices and also in some weather radar systems. The last frequency, finds use in FSS (Fixed Satellite Service) and DBS (Direct Broadcast Service). Besides, at 12 GHz satellite communications can be made highly focused with smaller dish beam-width. The 9.95 GHz frequency falls in the X Band which is extensively for deep space communication. It‘s also used for terrestrial networking and communications in some countries.

Thus, the proposed antenna can serve numerous purposes.

Chapter 5

Ultra Wide Band Fractal Antenna

CHAPTER 5.1

UWB broadly alludes to technology of radio communications where the range of frequencies is either within 20% (arithmetically) of the center frequency or within 500 MHz whichever is less.[45] Although a hot research topic for many years, due to un-licensing of 3.1GHz to 10.6GHz band this has gained limelight. In communications with high speed requirements or need for high data rates or for short range wireless indoor communications, (Wireless PAN, etc) this is highly promising. Besides, utilizing low power, there results no significant alteration in the noise floor and therein lies the advantage that there would be no interference with narrow-band antennas. [45][4]

Aim of the proposed design is to produce an antenna with UWB functionality. The antenna is a hexagonal fractal with hexagonal slots within circles and CPW feed. This chapter describes in details the parameters of design and results of simulation. At the end, it concludes with utilities for which the proposed design can be used.

5.2 Antenna Design

The antenna is a patch on which a hybrid fractal structure is implemented. The patch is a circular one of radius 10mm. A hexagonal slot is carved out of it of radius 9.95 mm. The difference of the two radii is calculated and evaluated using parametric analysis and found out to be 0.05 mm. This process continues iteratively for five times such that the electrical connectivity never ceases to exist. A CPW feed is attached whose dimensions are given in table 5.2. The substrate is the standard FR4 with dielectric constant 4.4. It’s dimensions are also provided in the aforementioned table

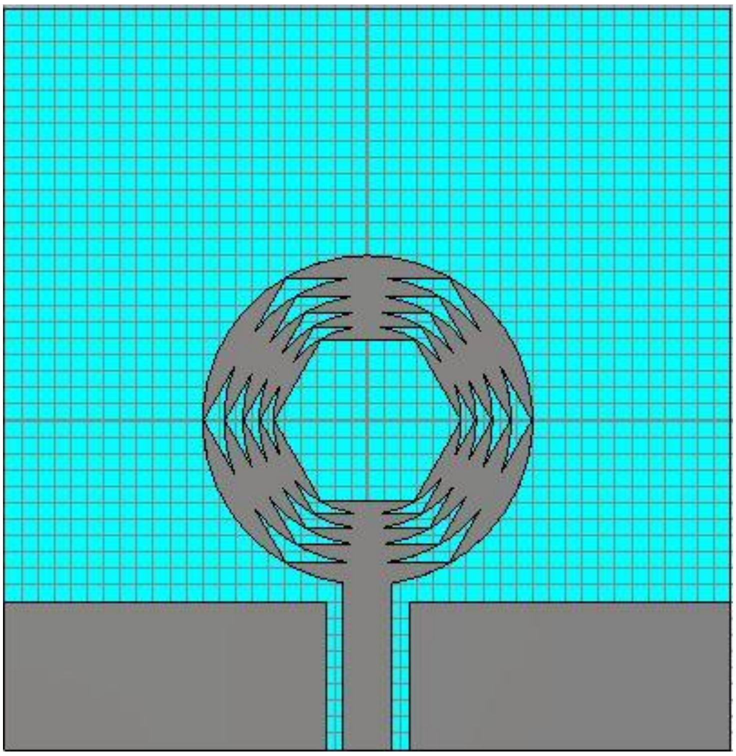


Figure 5.1: Proposed Antenna Design

Design Parameters:

The following table gives the dimensions of the antenna's patch and the slots that are carved out.

Table 5.1

No. of iterations	Radius of Outer Circle (in mm)	Length of sides of the regular hexagon (in mm)
1	10 mm	9.95 mm
2	8.706 mm	8.656 mm
3	7.574 mm	7.524 mm
4	6.583 mm	6.533 mm
5	5.717 mm	5.667 mm

Table 5.2

	Length	Width
Feed-line	11.5 mm	3 mm
Substrate	45 mm	44 mm
Ground Patch	9 mm	19.5 mm

Simulation Results:

The return loss curve which is the first indicator of whether an antenna is UWB or not is plotted as under:

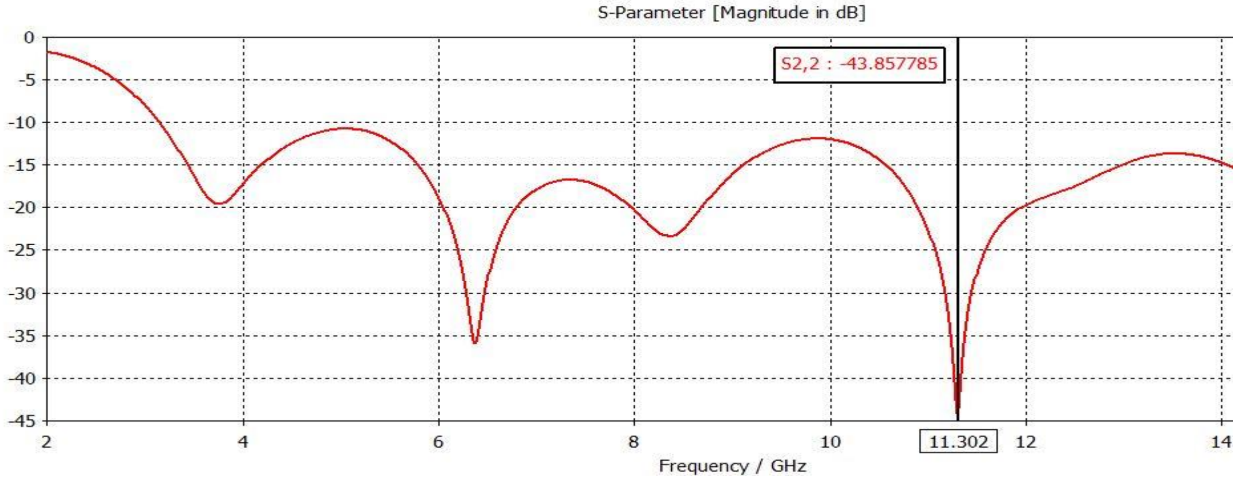


Figure 5.2: S_{11} Plot

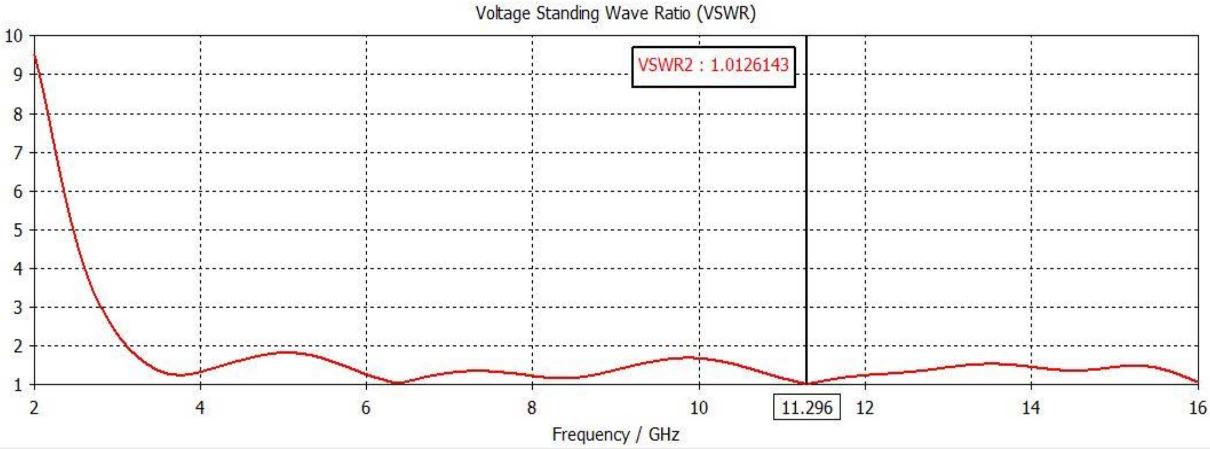


Figure 5.3: VSWR Plot

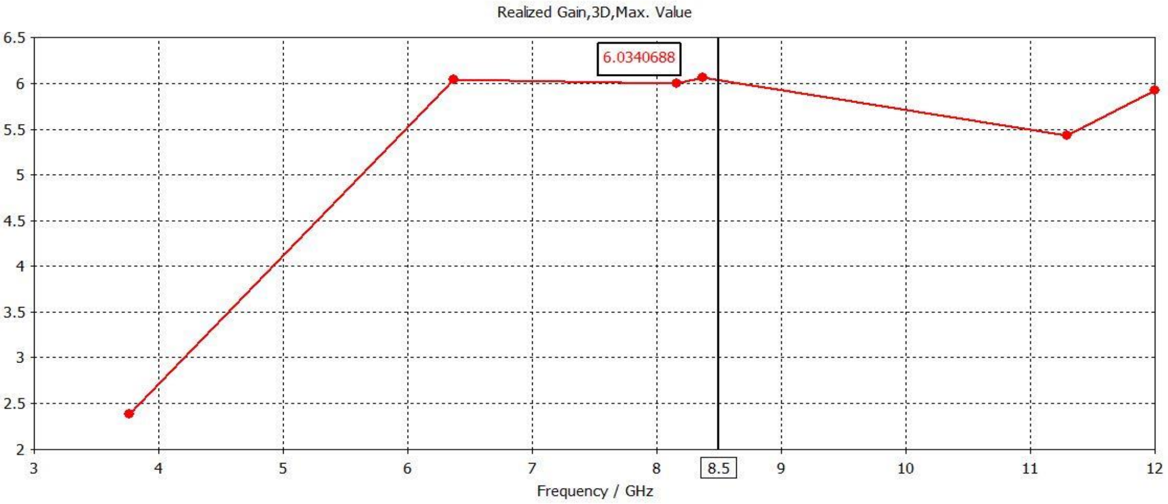


Figure 5.4: Gain Vs Frequency Plot

As expected the VSWR lies completely below 2 once the S_{11} plot crosses the -10dB barrier. The Gain Vs Frequency plots only those points where the resonant frequencies are encountered.

As mentioned earlier, a parametric analysis was done to evaluate and thereby optimise the gap between the circular patch and the hexagonal slot. The results of the same follows:

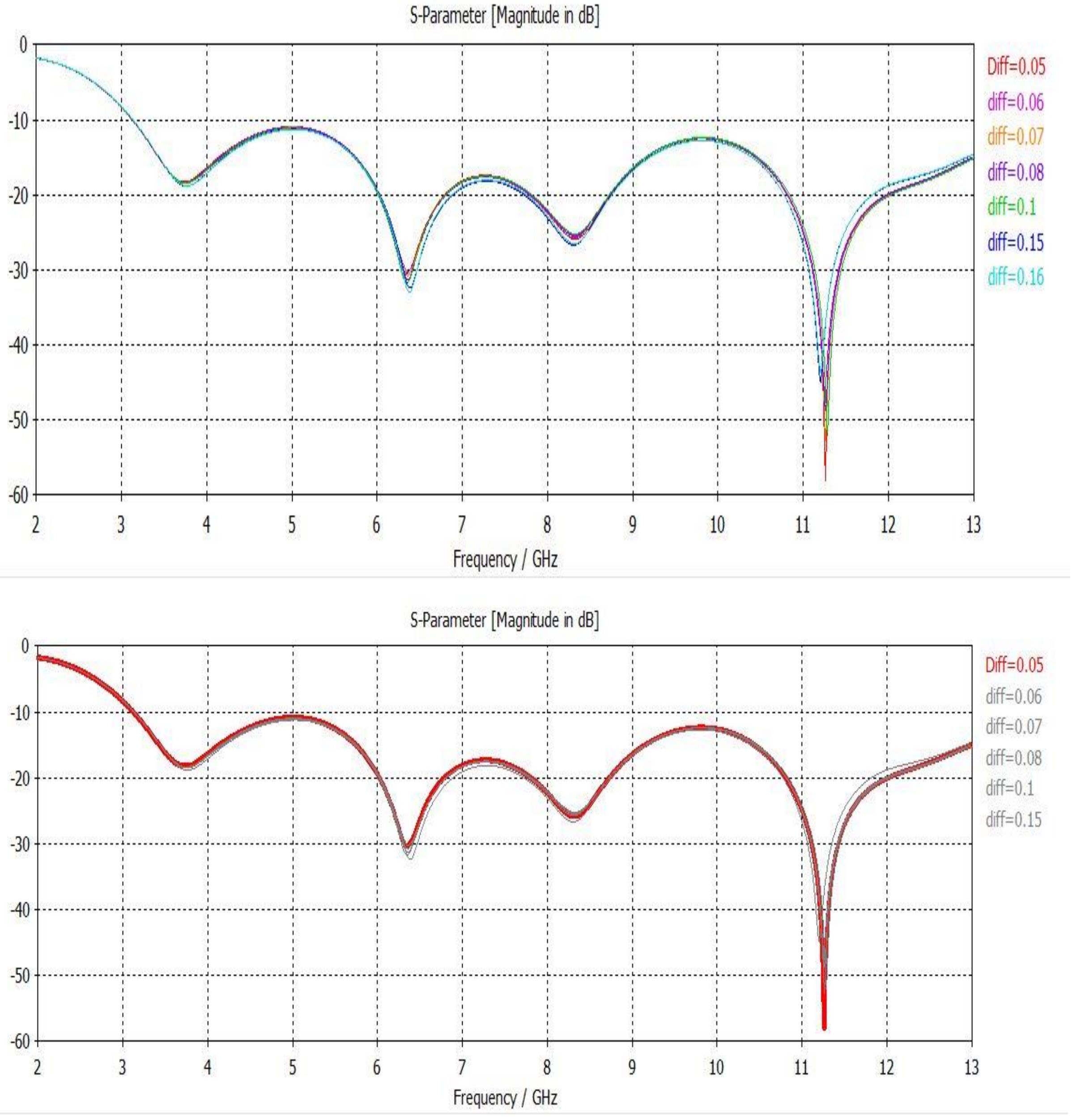


Figure 5.5: Parametric analysis showing the optimised value

The radiation pattern of one of the resonant frequencies is shown hereby:

At f_c= 3.7653 GHz

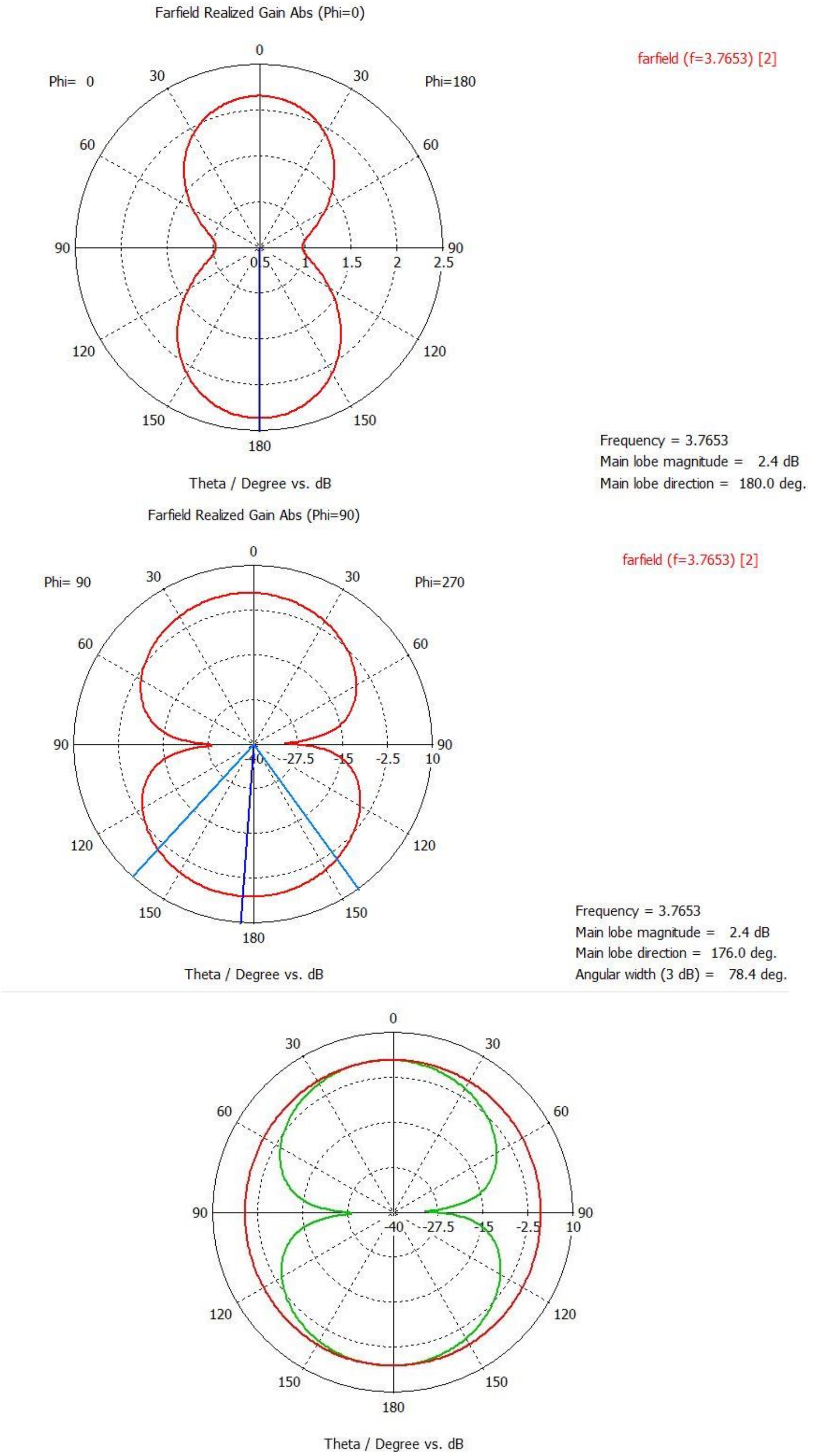
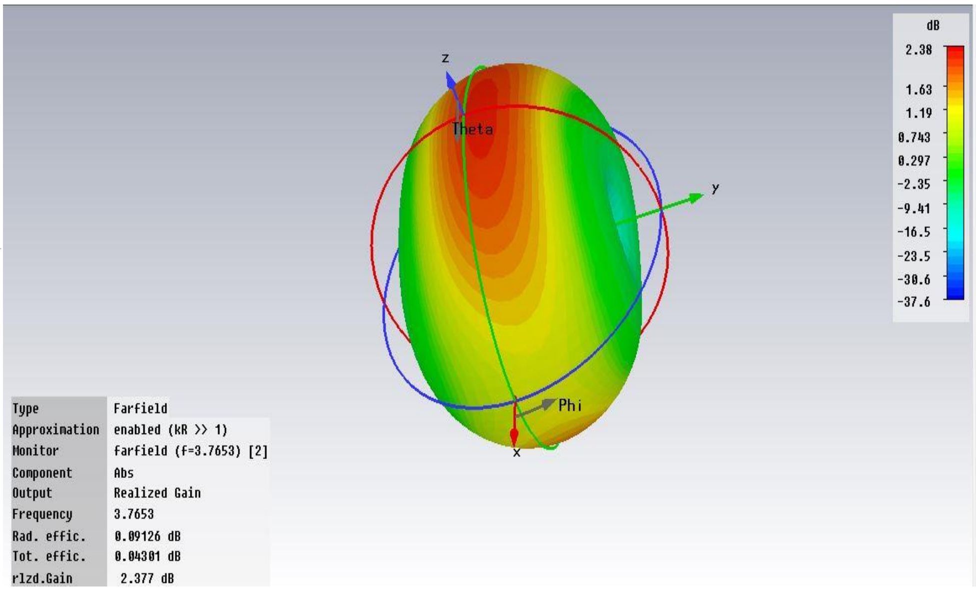


Figure 5.6 Radiation Patterns



```
Type           Farfield
Approximation  enabled (kR >> 1)
Monitor        farfield (f=3.7653) [2]
Component      Abs
Output         Realized Gain
Frequency      3.7653
Rad. effic.    0.09126 dB
Tot. effic.    0.04301 dB
rlzd.Gain       2.377 dB
```

Figure 5.7: Realised Gain (3-D)

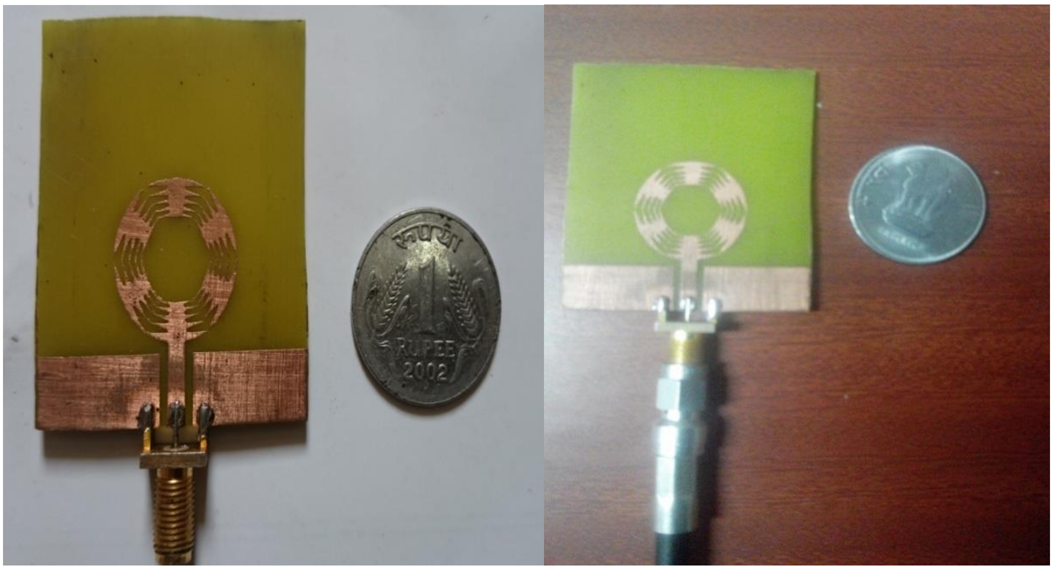


Figure 5.8: Fabricated Antenna

5.3 Summary

The UWB antenna has been fabricated in-house. UWB antennas enable high data rates and use very low power. Plus, they can be used for precision Radar technology and precision locating and tracking (GPR) and in WPAN systems. Also find use in RF sensitive environments like hospitals.

Thus the proposed design has several utilities.

Chapter 6

Conclusion and Future Work

6.1 Conclusion

This thesis has been an effort in the part of the author to understand and contribute in the process towards the antenna theory’s combination with fractal geometry. It contains SIX chapters including this, the last one.

It presents the design methodology and theory of Microstrip and Fractal antennas. Three designs have been proposed, one Narrow-band, one multi-band and one ultra wide band of which the last one has been fabricated. The radiation patterns and gain patterns of each has been analysed thoroughly. The efficacy of incorporating fractal into antenna theory has been presented, in addition.

The THIRD Chapter presented the design and analysis of a Fractal hybrid showcasing narrowband behaviour. The design consisted of a Giuseppe Peanu fractal that constituted the base on which another fractal geometry, Sierpinski geometry was implemented. The Bandwidth Percentage of this antenna turned out to be 40.421% which in turn qualified it to be a narrowband antenna operating at a resonant frequency of 3.386 GHz.

The FOURTH Chapter showed a fractal antenna with the scope for utilisation of the aforementioned properties. With resonant frequencies occurring at multiple positions over the SHF, it can be fabricated to utilise the properties of the respective bands. It was CPW fed fractal that was generated by iteratively carving out circles within squares such that electrical connectivity always remains, over a dielectric substrate FR4 of dielectric constant of 4.4 without any ground plane. The resultant antenna radiated at multiple frequencies (3.52 Ghz, 5.7 GHz, 8 GHz, 9.95GHz and 12 GHz) over the SHF range thereby rendering it multi-band functionality.

The FIFTH chapter presented a novel design for Ultra Wide-Band Applications using hexagonal slots carved within a circular patch iteratively over a FR4 substrate. It was CPW fed and parametric analysis was done to optimise the slot gap. The antenna was fabricated as well. However, measurements could not be carried out owing to lack of sophisticated equipment.

6.2 Future Work

- Fabrication of the aforementioned proposed antennas and comparison of the results thus obtained and the simulated results can be put to publication.
- Study of the effect on Fractal antenna performance of material properties, can be done The last design has been done on lossy substrate. LTCC (low temperature co-fired ceramic) substrates can be used instead. Direct integration with MICs can be thereby done.

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