

FACULDADE DE ENGENHARIA DA UNIVERSIDADE DO PORTO



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Fractal Antennas for Wireless Communication Systems

Filipe Monteiro Lopes

Integrated Master in Electrical and Computers Engineering - Telecommunication Major

Supervisor: Prof. Henrique Salgado (Ph.D)

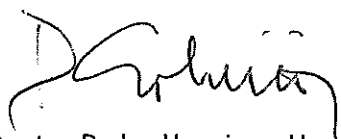
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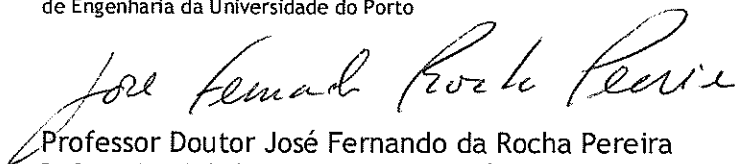
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Presidente Professor Doutor Pedro Henrique Henriques Guedes de Oliveira
Professor Catedrático do Departamento de Engenharia Electrotécnica e de Computadores da Faculdade
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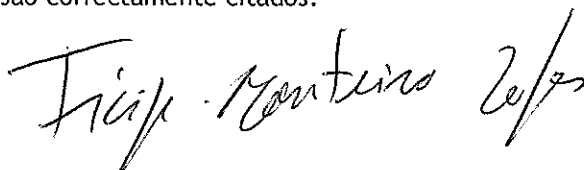


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Professor Associado do Departamento de Engenharia Electrotécnica e de Computadores da Faculdade de
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Autor - FILIPE MONTEIRO LOPES

Faculdade de Engenharia da Universidade do Porto

Abstract

Nowadays wireless communications systems (GSM/UMTS/WIFI) require compact antennas which are capable of operating at different bands. Fractal geometry antennas are being studied in order to answer those requirements.

Recent studies on fractal antennas show that these structures have their own specific characteristics that improve certain properties when talking about low profile antennas.

The Cohen-Minkowski structure will be studied, analysed, designed and described in order to obtain the desired performance properties. Due to the fractal complexity of these structures a Matlab script was accomplished in order to easily achieve the number of iterations pretended. The antennas properties, input impedance, VSWR, coefficient reflection and radiation patterns will be studied to achieve the best performance. Simulation using HFSS and implementation were done and results are presented.

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Firstly I want to thank my parents, Jose and Celeste for giving me the opportunity to take a Integrated Master degree. They have been great support throughout these five years.

My sincere thank you to my girlfriend and best friend Ana Graciela, without whose love, encouragement and editing assistance, I would not have finished this thesis.

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My especial gratitude goes to my man Qi Luo from whom I learnt a lot.

Filipe Monteiro Lopes

“Technology is dominated by those who manage what they do not understand.”

Murphy’s Law

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Abbreviations and Symbols

GSM	Global System for Mobile Communication
UMTS	Universal Mobile Telecommunication System
SWR	Standing Wave Ratio
HPBW	Half Power Beamwidth
BW	Bandwidth
PCB	Printed Circuit Board
IFS	Iterated Function Systems
LPDA	Log Periodic Dipole Array
UHF	Ultra High Frequency
dB	Decibel
ADS	Advance Design System
PC	Perimeter Compression

Chapter 1

Introduction

1.1 Brief Technical Overview

Nowadays, in order to face the technological development, humankind needs to keep up with the evolution. This evolution lead to the development of cellular devices. This brought up many new areas of investigation, the one with main interest for this project is the research of antennas with fractal geometries.

The main problem of common antennas is that they only operate at one or two frequencies, restricting the number of bands that an equipment is capable of supporting. Another issue is the size of a common antenna. Due to the very strict space that a handset has, setting up more than one antenna is very difficult. To help these problems, the use of fractal shaped antennas is being studied.

In this project a Cohen-Minkowski monopole was developed for wireless USB applications. The USB applications require very low profile antennas capable to operate at different frequencies (see section [1.3](#)).

1.2 Motivation

As previously mentioned, fractal antennas are being studied to integrate systems that require operation in different bands. These technologies need small size and high performance antennas. Example of such communication systems are mobile phones, wireless network cards, military communications.

In our modern society people need to be in touch with the world, for that technology is being developed in such way that anyone can communicate or be informed about everything just by using a small handset cellular device. This equipment needs to operate in a wide range of frequencies, allowing people to connect to the WEB (standards 802.11a, 802.11b or 802.11g), make phone calls (GSM), video conferences (UMTS) and other utilities. All these technologies operate in different

frequencies demanding a high efficient multi-band antenna with a very compact size. This work will show that fractal geometry antennas may help answer these requirements.

1.3 Objectives

The goal of this assignment is to study, analyse, design and describe fractal antennas capable of facing modern wireless communication transceivers. Various structures of fractals are going to be tested in order to achieve a comparison between them. Return loss, radiation patterns, SWR curves, input impedance are used to compare the antennas.

Main objective is to make an antenna capable to operate according to the IEEE 802.11 standard, which means that the operating frequencies are:

- 802.11a -> 5,235 - 5,875 GHz and 5,725 - 5,875 GHz
- 802.11b -> 2,412 - 2,472 GHz
- 802.11g -> 2,412 - 2,472 GHz

1.4 Methodology

The methodology is as follow:

- Study the characteristics of an antenna (fractal) for instance, the return loss, VSWR, input impedance and radiation pattern
- Prove that fractal shaped antennas have multi-band behaviour
- Design a Cohen-Minkowski monopole with ANSOFT HFSS (see chapter 4) and ADS (see chapter 5)
- Antenna implementation
- Comparison between simulation and developed antennas

1.5 Report Organization

This thesis is organized in 6 chapters.

Following this chapter, a review on antenna theory is presented. Microstrip, patch and monopole antennas are also referred in chapter 2.

In chapter 3 fractal antennas are introduced and its geometries are described. The generation of the Cohen-Minkowski structure is also presented in this chapter.

Chapter 4 presents the simulation of the Cohen-Minkowski monopoles. In this chapter we describe the simulation of two monopoles multiband antennas for wireless USB applications. Antenna A was first designed and simulated. An optimization of the first antenna led to antenna B with improved performance.

Measurements and characterization of both antennas simulated in chapter 4, as well as the fabrication process in microstrip technology is described in chapter 5.

Chapter 6 gives the final conclusion of this project.

Chapter 2

Theory of Antennas

2.1 Introduction

An antenna is a metallic structure that sends or receives electromagnetic waves, such as radio waves. In other words, antennas convert radio frequency fields into electrical currents.

This chapter presents a review of the theory of antennas. Antenna parameters (VSWR, input impedance, gain, radiation pattern, Half-power beam width (HPBW), directivity, polarization and bandwidth) are described with an overview on scattering parameters. Microstrip antennas technology is then presented together with its advantages and disadvantages. Microstrip patch and monopole antennas are briefly presented. Matching techniques are also described in this chapter.

2.2 Antennas Background

There is a wide variety of antenna structures allowing operation on just one band, narrow-band antennas, or several bands, known as multi-band or broadband antennas.

Narrow band antennas include not only single dipoles or verticals but also directive arrays. Such arrays have high gain and directivity to make the antennas more efficient to a certain direction. With these antennas signals coming from the back will be rejected due to its Front to Back ratio, this is the ratio of the maximum directivity of an antenna to its directivity in the opposite direction. Yagi-Uda antenna, developed by Dr. Hidetsu Yagi and Dr. Shintaro Uda, is the commonest directive antenna in the world.

The directivity of this antenna depends on the number of parasitic elements, usually known as directors that are placed in front of the driven element. See figure [2.1](#)

The most interesting multi-band antenna is the log-periodic, also known as log-periodic dipole array (LPDA). These antennas are broadband, multi-element, unidirectional with an impedance and radiation characteristics that are continually repeated as a logarithmic function of the excitation frequency, see figure [2.2](#).

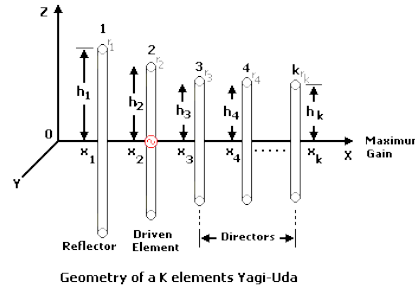


Figure 2.1: Yagi antenna

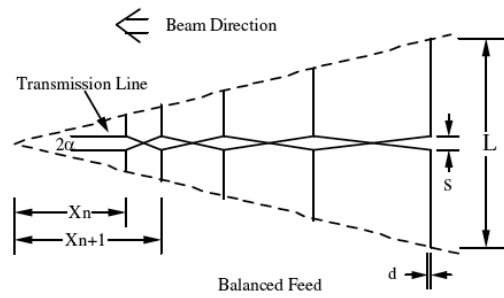
(adapted from http://yagi-uda.com/images/yagi-uda_geometry.png)

Figure 2.2: Log Periodic antenna

(adapted from http://upload.wikimedia.org/wikibooks/en/4/4d/Log_periodic_antenna.gif)

These antennas are calculated to be self-similar therefore; they could be considered as fractal antennas. LDPA was originally designed at the University of Illinois in the USA.

2.3 Antenna Parameters

- **VSWR: Voltage Standing Wave Ratio** is the ratio of maximum radio-frequency voltage to minimum radio-frequency voltage on a transmission line. It is given by:

$$VSWR = \frac{V_{max}}{V_{min}} \quad (2.1)$$

The VSWR can also be calculated from the return loss (S_{11}) (see section 2.4) which means that it is also an indicator of an antennas efficiency. With the return loss we can determine the mismatch between the characteristic impedance of the transmission line and the antennas terminal input impedance.

If the the magnitude of the reflection coefficient is known the VSWR can be determined by:

$$VSWR = \frac{1 + |S_{11}|}{1 - |S_{11}|} \quad (2.2)$$

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

- **Input Impedance:** Generally, an antenna is seen as a load to a transmission line with a certain impedance. This impedance is known as the input impedance of an antenna and it can be determined by the following expressions:

$$Z_{in} = R_l + R_r + jX_a \quad (2.3)$$

where Z_{in} represents the input impedance, R_l is the loss resistance, R_r is the radiation resistance and X_a represents the reactance.

If the reflection coefficient is known:

$$Z_{in} = Z_0 \left(\frac{1 + S_{11}}{1 - S_{11}} \right) \quad (2.4)$$

where Z_{in} represents the input impedance, Z_0 is the characteristic impedance of the transmission line and S_{11} is a S-parameter also known as reflection coefficient, a parameter which is explained in section 2.4.

The input impedance can be used to determine the maximum power transfer between the transmission line and the antenna, this will only occur when both impedances are equal. If there is a mismatch between both impedances, power will be reflected back to the transmitter and this might cause damage to the device.

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

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

$$G(\theta, \phi) = \frac{U(\theta, \phi)}{U_0} \quad (2.5)$$

$$U_0 \text{ is given by : } U_0 = \frac{P_{in}}{4\pi} \quad (2.6)$$

where $G(\theta, \phi)$ is the gain of the antenna in a certain direction, $U(\theta, \phi)$ is the radiation intensity in a certain direction and U_0 is the radiation intensity of an isotropic antenna. P_{in} is the input power.

The Absolute Gain is expressed in *dBi* as its reference is an isotropic antenna.

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

The Relative Gain is expressed according to reference antenna.

- **Directivity:** This is an important parameter that allows us to measure the concentration of radiated power in a certain direction. It is given by:

$$D(\theta, \phi) = \frac{U(\theta, \phi)}{U_0} \quad (2.7)$$

where $D(\theta, \phi)$ is the directivity of the antenna in a certain direction, $U(\theta, \phi)$ is the radiation intensity in a certain direction and U_0 is the radiation intensity of an isotropic antenna and as given by 2.6.

Another way of measuring the directivity of an antenna is to calculate the *HPBW*.

- **Efficiency:** An antennas efficiency is defined as the ratio of the total radiated power to the input power and it is given by:

$$e_{cd} = \frac{P_{rad}}{P_{in}} \quad (2.8)$$

Using the equations 2.5, 2.6 and 2.8 we can achieve a relation between an antennas gain and its directivity:

$$G(\theta, \phi) = \frac{4\pi U(\theta, \phi)}{P_{in}} = e_{cd} \frac{4\pi U(\theta, \phi)}{P_{rad}} = e_{cd} D(\theta, \phi) \quad (2.9)$$

- **Radiation Pattern:** The radiation pattern is a graphical representation of the characteristics of an antenna radiation in a certain direction as shown in 2.3 . These characteristics include, radiation intensity, field intensity and polarization.

It is normally represented with rectangular or polar plots and it is expressed in *dB*. The radiation pattern is a plane cut and represents one frequency and one polarization.

- **HPBW:** The *HPBW Half Power Beamwidth* is a way of measuring the antenna directivity. This means that if the main lobe of an antenna is too narrow, the directivity is higher. It can be determined by taking out *3dB* (half power) with respect to the main lobe power level. The *HPBW* can be determined in the polar plot of an antenna radiation pattern, see figure 2.3.
- **Polarization:** Represents the sense and orientation of the electromagnetic waves far from the source. There are three main types of polarization:

- Elliptical: Elliptical left hand, Elliptical right hand
- Circular: Circular left hand, Circular right hand
- Linear: Vertical, Horizontal

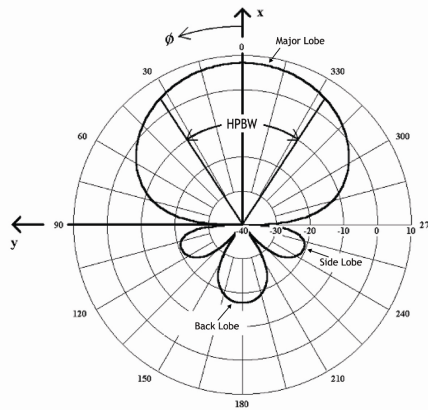


Figure 2.3: Example of radiation pattern

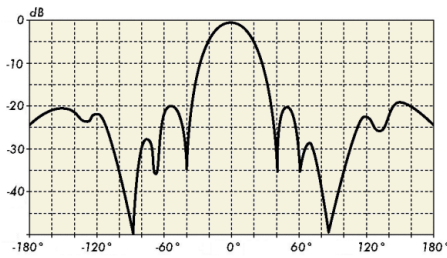


Figure 2.4: Example of radiation pattern, rectangular plot

(adapted from http://www.vias.org/wirelessnetw/wndw_06_05_05.html)

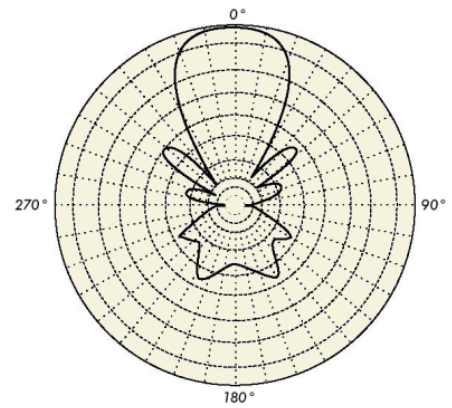


Figure 2.5: Example of radiation pattern, polar plot

(adapted from http://www.vias.org/wirelessnetw/wndw_06_05_05.html)

- **Bandwidth:** The Bandwidth BW is a measure of how much frequency variation is available while still obtaining a coefficient reflection (see section 2.4) or a VSWR within a specified interval.

$$BW = \left(\frac{F_h - F_l}{F_c} \right) \times 100 \quad (2.10)$$

$$F_c = \frac{F_h + F_l}{2} \quad (2.11)$$

where, F_h represents the highest frequency which the VSWR (2:1 or less) or the coefficient reflection (see section 2.4) ($-10dB$ or less) is still acceptable; F_l represents the lowest frequency which the VSWR (2:1 or less) or the coefficient reflection 2.4 ($-10dB$ or less) is still acceptable; F_c represents the central frequency.

2.4 Brief Overview on Scattering Parameters

Scattering Parameters also known as S-Parameters, are the reflection and transmission descriptors between the incident and reflection waves, which for a two port system is given by:

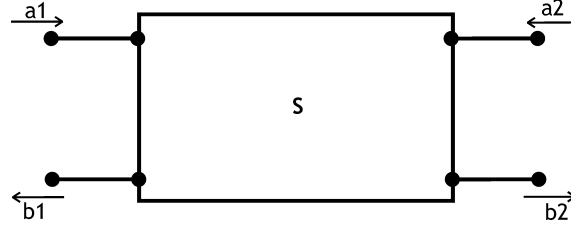


Figure 2.6: Generalized two port network, [S] represents the scattering matrix

$$\begin{bmatrix} b_1 \\ b_2 \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \end{bmatrix}$$

S_{11} : reflection coefficient on the input with 50Ω terminated output. a_1 and b_1 represents electric fields. The ratio between these two electric fields results in a reflection coefficient.

$$S_{11} = \frac{b_1}{a_1}, a_2 = 0 \quad (2.12)$$

S_{21} : forward transmission coefficient of 50Ω terminated output.

$$S_{21} = \frac{b_2}{a_1}, a_2 = 0 \quad (2.13)$$

S_{12} : reverse transmission coefficient of 50Ω terminated input.

$$S_{12} = \frac{b_1}{a_2}, a_1 = 0 \quad (2.14)$$

S_{22} : reflection coefficient on the output with 50Ω terminated input.

$$S_{22} = \frac{b_2}{a_2}, a_1 = 0 \quad (2.15)$$

To measure S_{11} we inject a signal at port 1 with port two terminated with an impedance matched to the characteristic impedance of the transmission line ($a_2=0$), and measure its reflected signal. No signal was injected into port 2 so we consider $a_2 = 0$.

To measure S_{21} we inject a signal at port 1, terminate port 2 and measure the resulting signal exiting on port 2.

To measure S_{12} we inject a signal at port 2, terminate port 1 and measure the resulting signal on port 1.

To measure S_{22} we inject a signal at port 2, terminate port 1 and measure its reflected signal.

All the S-Parameter measurements are made with only one signal injected in one port at a time, the other port being terminated with a matched impedance.

2.5 Microstrip Antennas

Microstrip antennas also known as printed antennas, as shown in figures 2.7 and 2.8, consist of a radiating patch on one side and on the other side of the substrate a ground plane. The size of a microstrip antenna is inversely desired to the pretended resonant frequency. Microstrip antennas only make sense when talking about UHF and above due to the fact that antennas for these frequencies are centimeter antennas.

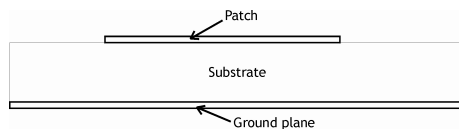


Figure 2.7: Side view of microstrip patch

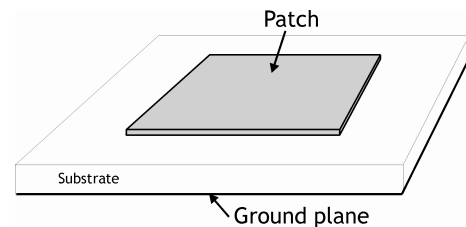


Figure 2.8: Top view of microstrip patch

Advantages in using microstrip antennas:

1. Easily built with PCB technology
2. Light weight and small size
3. Low profile structure allowing it to be mounted in thin devices
4. Supports both linear and circular polarizations
5. Capable of multi-band operation (use of fractals)
6. Resonant type antennas due to efficient radiation (around 95% efficiency)
7. Low cost to fabricate

Disadvantages in using microstrip antennas:

1. Narrow bandwidth
2. Not capable of handling high powers
3. Surface wave excitation
4. Low gain

The low profile of these antennas allows them to be mounted on mobile radio communication devices, such as GSM Phones. Most fractal antennas use this type of implementation due to its complex geometries, therefore the fractal geometries are printed on the dielectric substrate.

2.6 Microstrip Patch Antennas

Microstrip Patch is an antenna type which is printed on a substrate and has a feed line (transmission line) and a patch on one side and ground plane on the other side of the substrate as shown in figure 2.9.

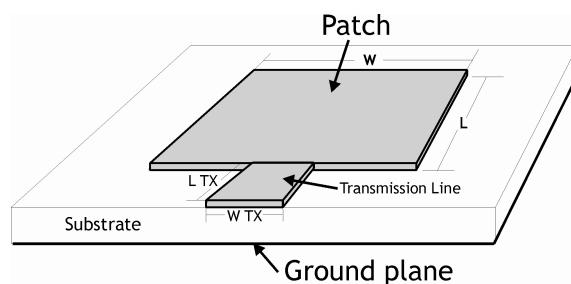


Figure 2.9: Microstrip Patch Antenna

The patch and ground plane are usually made of copper and can take any shape. This helps to face the high complex geometry fractal antennas use.

Microstrip patch antennas are good radiators due to the fact that they have a fringing field between the patch edge and the ground plane. The best performance of an antenna is achieved with a thick dielectric substrate with a low dielectric constant. This kind of substrate will provide better efficiency, larger bandwidth and better radiation. Unfortunately this leads to a larger antenna, therefore, a substrate with higher dielectric constant must be used.

The feeding system shown in figure 2.9 is known as microstrip transmission line, a strip line is connected directly to the microstrip patch. The length L_{TX} and width W_{TX} are calculated so that at the end of the strip line the impedance matches the patch impedance.

2.7 Monopole Antennas

A monopole antenna is a kind of vertical dipole antenna in which half of it is replaced with a ground plane at right angles to the remaining half. The antenna will perform as dipole as if its reflection in the ground plane formed the missing half of the dipole.

This is the kind of antenna used in our project, since we use a ground plane at right angles to the antenna. This will make the antenna radiate like a monopole and not as a patch antenna. The ground plane also provides a define impedance for the feed line, which can be controlled by changing the width of the microstrip line.

2.8 Matching Techniques

Most transmitters have an output impedance of 50Ω or 75Ω unfortunately an antennas input impedance is not always close to these values consequently, a matching technique needs to be applied. When an antenna is not properly matched, if the reflected power is high it can damage the device connected to it, thus to avoid excessive heating on the equipment matching techniques are used to reduce the VSWR. For example, a $1/2$ wave dipole has a midpoint impedance of 73Ω , so coaxial cable transmission line which has a characteristic impedance of 75Ω is used to feed the antenna. The theory of matching techniques is described in [1].

There are numerous matching techniques:

- **Delta match:** This type of matching is used with an unsplitted $\lambda/2$ dipole antenna. Considering the dipole resonance, its capacitive reactance (X_c) and inductive reactance (X_L) cancel each other making the input impedance only resistive. Consequently the antenna impedance is the resistance between any two middle points from the centre and thus transmission lines having characteristic impedances of 300Ω to 600Ω may be used by using two points of the antenna to feed the signal to the antenna in a position where it offers a feed point impedance equal to transmission line impedance.
- **T match:** In this type of impedance performance, two coaxial cables are held side by side and both their outer covering are connected to the midpoint of the non divided dipole, while two points are chosen on the dipole where inner parts going parallel to each other are connected.
- **LC network match:** The LC network match consists of a network of capacitors and inductors that are used to transform the antenna impedance into the feed line impedance. There are three types of LC matching networks:
 - L-network
 - T-network
 - π -network

The advantage of this type of matching is that any two values of impedance may be matched and there are formulas available that permit computation of all component values necessary to achieve a match. The only disadvantage, and for some applications it is a very important issue, is that the network will only match the impedances over a relatively narrow bandwidth.

- **Stub match:** An open stub of $\lambda/4$ can be connected to the dipole. Here the low midpoint impedance of 73Ω of the dipole is repeated at the close end of the stub. However there are certain points on the stub which would offer as high as 600Ω impedance while matching with 73Ω transmission line.

- $\lambda/4$ **transformer match:** The most used technique is the quarter-wave transformer. One of the advantages of using this type of technique is that it can easily be built and it is applied to a wide range of frequencies. A disadvantage is that it is only useful in narrow bandwidth. Considering that the antenna's impedance is real, the transformer is attached directly to the load. If the impedance is complex, the transformer is placed at a distance d away from the load. This distance is used to guarantee the input impedance toward the load is real. To match the antenna's impedance the characteristic of the transformer's impedance should be:

$$Z_0 = \sqrt{Z_L Z_{in}}$$

2.9 Summary

In this chapter the theory of antennas was presented. The parameters that define an antenna and its efficiency were detailed namely, VSWR, input impedance, gain, radiation pattern, HPBW, directivity, polarization and bandwidth. A brief overview on scattering parameters was accomplished to a better understanding of the coefficient reflection. Advantages and disadvantages of using microstrip antennas are listed as well as reference to microstrip patch antennas. Monopole antennas are also briefly mentioned. Although they were not used, matching techniques are also described.

In the next chapter a study about fractal antennas is made with an overview on fractal geometries.

Chapter 3

Fractal Antennas

3.1 Introduction

In this chapter the approach to fractal antennas is described by steps, firstly a description of natural fractal geometries can be found followed by a brief overview on fractal antennas. The generation process, using IFS iterations, of fractal antennas is discussed in this chapter for a better understanding of the complexity of generating fractal structures. Some fractal geometries are described, mainly the Koch Curve, the Sierpinski Gasket, the Minkowski Curve and the Cohen-Minkowski Curve.

3.2 Fractals

Although fractal geometries have been known for almost a century, the study of fractal antennas is a relatively new area. The fractal term was coined in 1975 by the French mathematician, Benoît B. Mandelbrot. Since Mandelbrot work a wide variety of application areas for fractals have been found and studied, an area in particular is fractal electrodynamics [2]. This area combines electromagnetic theory with fractal geometry, this combination results in new radiation patterns, propagation and scattering problems, as described in [2, 3]. Studies in this area show that fractals have good electromagnetic radiation patterns and advantages over traditional antennas. Such advantages face modern wireless communication problems. For instance, they can be used as compact multi-band antennas.

A fractal can be described as a rough or fragmented geometric shape that can be separated into parts which are an approximation to the whole geometry but in a reduced size. Fractals are known as infinitely complex because of its similarity at all levels of magnification. There are only two types of fractals, natural and mathematical.

Fractal geometries, to a certain level, can be found all around us, even though we are not aware of

that, these are the natural fractals. Examples of natural fractals are: coastlines 3.1, lightning 3.2, earthquakes, plants, vegetables 3.3, rivers, galaxies, clouds, all these examples have fractal geometry.



Figure 3.1: Coastline
(adapted from [4])



Figure 3.2: Lightning
(adapted from [4])



Figure 3.3: Brocoli
(adapted from [4])



Figure 3.4: Snowflake
(adapted from [4])

The mathematical fractal geometry has been known for a century and these are based in equations that undergo iteration, a form of feedback based on recursion. Examples of these mathematical structures are: von Koch snowflake 3.8, Sierpinski carpet 3.5, the Mandelbrot set 3.7, the Lorenz attractor 3.6, and the Minkowski curve.

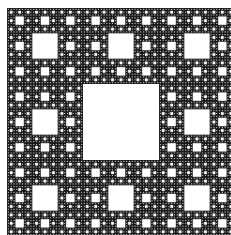


Figure 3.5: Sierpinski Carpet

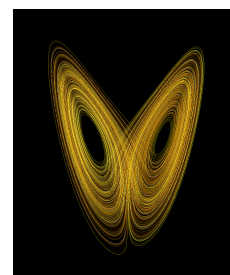


Figure 3.6: Lorenz attractor

3.3 Fractal Antennas

Nathan Cohen built the first known fractal antenna in 1988, then a professor at Boston University [5]. Cohen's efforts were first published in 1995, the first scientific publication about fractal antennas, since then a number of patents have been issued.

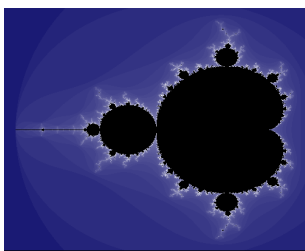


Figure 3.7: Mandelbrot set

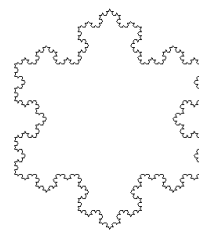


Figure 3.8: Koch Snowflake

In a series of articles Cohen introduced the concept of fractalizing the geometry of a dipole or loop antenna. This concept consists in bending the wire in such fractal way that the overall length of the antenna remains the same but the size is respectively reduced with the addition of consecutive iterations. If this concept is properly implemented an efficient miniaturized antenna design can be achieved.

In [6] Cohen compares the perimeter of an Euclidean antenna with a fractal antenna and he states that the fractal antenna has a perimeter that is not directly proportional to area. He concludes that the in a multi-iteration fractal the area will be as small or smaller than an Euclidean antenna.

Cohen also defines a parameter named Perimeter Compression (PC) and it is given by:

$$PC = \frac{\text{full-size antenna element length}}{\text{fractal-reduced antenna element length}} \quad (3.1)$$

He states that the radiation resistance of a fractal antenna decreases as a small power of the PC and a fractal loop or island presents a higher radiation resistance compared to the Euclidean loop antenna of equal size. Despite the fractal antenna being smaller than the Euclidean it exhibits the same or higher gain, frequencies of resonance and a 50Ω termination impedance.

Fractal antennas use a fractal, self-similar design to maximize the length and with this technique we can achieve multiple frequencies since different parts of the antenna are self-similar at different scale. Compared to a conventional antenna, fractals have greater bandwidth and they are very compact in size. With fractal antennas we can achieve resonant frequencies that are multi-band and these frequencies are not harmonics, also stated by Cohen in [6].

Fractal antennas can have different geometries, the most interesting ones are: the Koch curve, the Sierpinski gasket and the Minkowski curve.

The fractal dimension D of a curve can be given by the Hausdorff-Besicovitch equation:

$$D = \frac{\log(N)}{\log(r)} \quad (3.2)$$

The total length l of a curve is given by:

$$l = h \left(\frac{N}{r} \right)^n \quad (3.3)$$

where N represents the number of segments the geometry has, r the number that each segment is divided on each iteration and h the height of the curve. n is the number of iterations.

3.4 Iterated Function Systems (IFS)

Certain fractals can be constructed using iterations, this procedure is normally called Iterated Function Systems (IFS). Fractals are made up from the sum up of copies from itself, each copy smaller than the previous iteration. IFS works by applying a series of affine transformations w to an elementary shape A through many iterations. The affine transformation w , comprising rotation, scaling and translation, is given by [7]:

$$W(x) = Ax + t = \begin{bmatrix} a & b \\ c & d \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} e \\ f \end{bmatrix} \quad (3.4)$$

The matrix A is given by:

$$A = \begin{bmatrix} (1/s) \cos(\theta) & -(1/s) \sin(\theta) \\ (1/s) \sin(\theta) & (1/s) \cos(\theta) \end{bmatrix} \quad (3.5)$$

Where:

x_1, x_2 are coordinates of a point x

r is the scale factor

θ is the rotation angle

t is the translation factor

s is the scaling factor

3.5 Fractal Geometries

3.5.1 Koch Curve

The von Koch curve was firstly introduced by the Swedish mathematician Helge von Koch. The Koch curve was created to show how to construct a continuous curve that did not have any tangent line.

The von Koch antenna was first studied to reduce the size of quarter-wave monopoles for low frequency applications. It is known that the Koch geometry is very complex, so it is most reliably

implemented using printed antenna techniques (microstrip patches), as mentioned in section 2.5. The antenna is printed on a PCB using a dielectric substrate instead of the common wire, allowing precision on making the antenna work on specific bands.

Studies made by C. Puente et al. in [8] show that the input resistance increases with the increase length of the antenna and the reactance is reduced. Furthermore, the resonant frequency is shifted to lower frequencies making it resonant in the small antenna region, such behaviour can be physically explained by the increasing number of sharp corners and bends of the antenna improving its radiation. IFS algorithm can also be applied effectively to the von Koch curve to generate its basis.

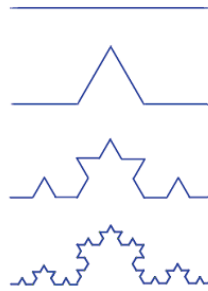


Figure 3.9: Three iterations of the Koch fractal
(adapted from [9])

It is constructed by starting with a straight line. Divide the line in three parts. Replace the center part by an equilateral triangle with the base removed. This procedure is repeated on every straight line continuing in an infinite process resulting in a curve with no smooth sections. Figure 3.9 illustrates three iterations of this process.

The whole length of the element, as described in [8, 10], is giving by: $l = h \left(\frac{4}{3} \right)^n$, where n is the number of iterations and h is the high of the monopole.

The self-similarity dimension is given by: $D = \frac{\log(4)}{\log(3)} = 1.26$

3.5.2 Sierpinski Gasket

The Sierpinski gasket, also known as Sierpinski triangle was named after the Polish mathematician Sierpinski who described its main properties in 1916 as referred in [11].

This monopole is well know due to its resemblance to the triangular monopole antenna.

Just like the von Koch fractal it is most reliable to implement this structure using printed antenna techniques, as referred in section 2.5.

It is generated according to the IFS method as mentioned in [3, 10]. A triangular elementary shape is iteratively shaped, rotated and translated, then removed from the original shape in order to generate a fractal as we see in figure 3.10.

Figures 3.10 and 3.11 show four-scaled versions of the Sierpinski gasket. The scale factor among the four iterations is $\delta = 2$ so we should also have resonance at frequencies spaced by a factor of 2, as mentioned in [11].



Figure 3.10: Four iterations of the Sierpinski fractal
(adapted from [11])

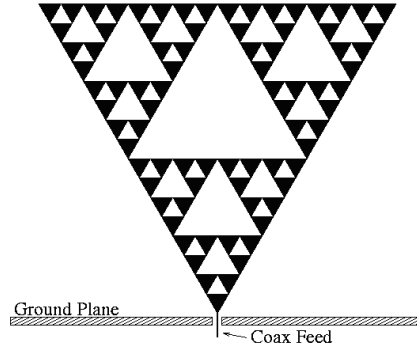


Figure 3.11: Sierpinski Gasket monopole
(adapted from [11])

C. Puente et al. described in [11] the relation between frequency resonance and physical dimensions of fractal antennas. These dimensions, namely the total high, flare angle and the scale factor are the basic parameters that characterise the geometrical self-similarity properties of fractals.

The formula below expresses the resonant frequencies of the antenna:

$$f_n = k \frac{c}{h} \cos(\alpha - 2) \delta^n \quad (3.6)$$

where c is the speed of light, n is a natural number that refers to the operating band, h is the high of the largest gasket and δ is the scale factor and α is the flare angle.

The self-similarity dimension of the Sierpinski gasket is given by: $D = \frac{\log(3)}{\log(2)} = 1.585$

As we can observe in figure 3.12 the way of feeding this antenna is quite simple owing to the triangular structure. The feeding system is referred in 2.6.

The monopole is fed with current through a connector at the bottom, this current will be inducted in a certain region of the antenna allowing it to radiate on different frequencies, figure 3.13.

3.5.3 Minkowski Curve

The Minkowski curve is also known as Minkowski Sausage and was dated back to 1907 where Hermann Minkowski, a German mathematician investigated quadratic forms and continued fractions. The construction of the Minkowski curve is based on a recursive procedure, at each recursion an eight side generator is applied to each segment of the curve as we see in figure 3.14.

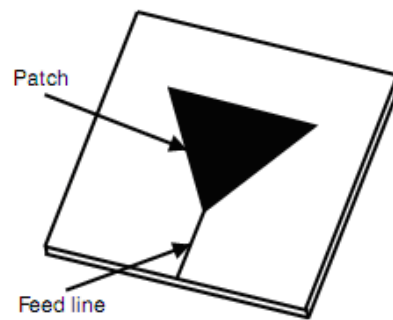


Figure 3.12: Feed line system
(adapted from [3])

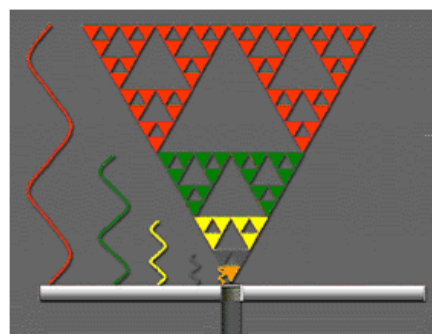


Figure 3.13: Frequency radiation (one antenna 4 bands)
(adapted from [9])

It always starts with a straight line. M. Ahmed et al. demonstrate in [7] that Minkowski curve

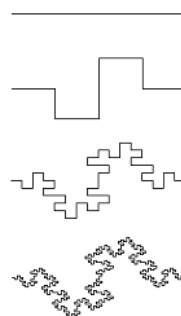


Figure 3.14: Three iterations of the Minkowski curve

fractal antenna reveals to have excellent performance at the resonant frequencies and has radiation patterns very similar to the straight wire dipole at the same frequencies. It is also demonstrated in [7] that Minkowski geometry helps reducing the size of an antenna by 24% in its first iteration and 44% on the second and that the self similarity of the fractal shape shows multiband behaviour. This was also concluded by Paulo H. da F. Silva in [12] who analyzed the frequencies from 2.620

– 2.650 GHz and 5.725 – 5.875 GHz and results were very promising. A third iteration of the Minkowski curve was used in [12] and a reduction of 45,6% was achieved.

The length of Minkowski curve increases at each iteration and is given by: $l = h \left(\frac{8}{4} \right)^n$, where n is the number of steps of generation and h is the high of the monopole.

The self-similarity dimension is given by: $D = \frac{\log(8)}{\log(4)} = 1.5$

3.5.4 Cohen-Minkowski Geometry

As referred in section 3.3, Nathan Cohen was the first one to build a fractal antenna. He introduced the concept of fractalizing the geometry of a loop or dipole antenna.

In patent [6] Cohen refers various kinds of geometries and the most interesting one for this project is the one he names Rectangular-Shaped Minkowski Fractal.

The generation of this structure is detailed in section 4.2.

The length of the Cohen-Minkowski geometry increases at each iteration and is given by: $l = h \left(\frac{5}{3} \right)^n$, where n is the number of steps of generation and h is the high of the monopole.

The self-similarity dimension is given by: $D = \frac{\log(5)}{\log(3)} = 1.46$

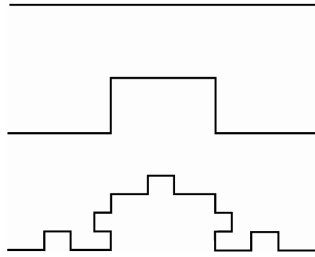


Figure 3.15: Two iterations of the Cohen-Minkowski geometry

3.6 Summary

This chapter presented fractal antennas its geometries. Natural and mathematical fractals were presented as well as the most common geometries used in antennas namely, the Koch curve, the Sierpinski gasket, the Minkowski curve and the Cohen-Minkowski geometry. The reasons for using fractal antennas are described and also calculations of a fractal dimension and the length of a curve are presented. The IFS procedure for designing fractal geometries is also described in this chapter.

The design of the Cohen-Minkowski fractal monopole is presented in next chapter as well as simulation results.

Chapter 4

Design of the Cohen-Minkowski Monopole

4.1 Introduction

In this chapter a presentation of the Cohen-Minkowski geometry is made. The affine transformations used to realize the IFS algorithm are presented as well as its description. Then an overview of the software used for simulation is presented. A comparison between the common FR4 and the substrate used is detailed. The simulation results of two antennas are presented and discussed.

The purpose of building this antenna is to implement a multi-band antenna for USB applications. In USB applications space is a limitation making the use of fractal geometries an interesting case of study case. The operating frequencies chosen for the design of the Cohen-Minkowski monopole were discussed in [1.3](#).

4.2 Cohen-Minkowski Geometry

The reasons for choosing the Cohen-Minkowski geometry and not any other structure are listed bellow:

- Suitable for USB applications due to its fractal size.
- The fractal dimension D is 1.46 while the Koch is 1.26. The Minkowski is 1.5 but the complexity of this structure is higher.
- Two iterations of this structure can reduce the total size of an antenna almost by three times.
- With two optimized parts of this structure we can get the three desired resonant frequencies.

The Cohen-Minkowski geometry is based on a recursive procedure and due to its complexity it needs to be automatically generated. Therefore a *MATLAB* script was created. This code is listed in the appendix A.

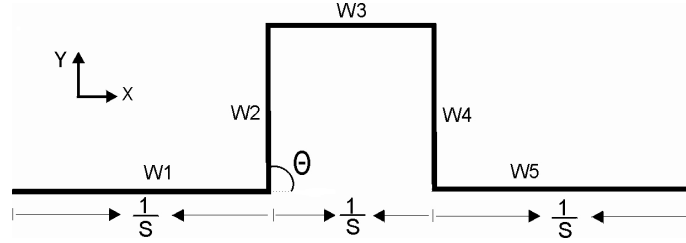


Figure 4.1: First iteration of the Cohen-Minkowski structure

The IFS algorithm 3.4 was realized using the affine transformations presented in 4.1. This geometry consists of repetitive procedure of the application of IFS transformations as mentioned above. The first iteration of the Cohen-Minkowski geometry is presented in figure 4.1. The parameter h defines the height of the third section of the structure. In this iteration, the affine transform W_1 scales a line to $1/3$ of its original length. The transform W_2 scales a line to $1/h$, rotates it to 90° and moves it to $1/3$ in x . The transform W_3 is another scaling to $1/3$ and a translation of $1/3$ in x and y . The transform W_4 scales a line to $1/h$, rotates it to -90° and moves it to $2/3$ in x and $1/3$ in y . The transform W_5 scales a line to $1/3$ of its original length and translates it to $2/3$ in x .

$$\begin{aligned}
 W_1(x) &= \begin{bmatrix} \frac{1}{3} & 0 \\ 0 & \frac{1}{h} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \end{bmatrix} \\
 W_2(x) &= \begin{bmatrix} 0 & -\frac{1}{h} \\ \frac{1}{3} & 0 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} \frac{1}{3} \\ 0 \end{bmatrix} \\
 W_3(x) &= \begin{bmatrix} \frac{1}{3} & 0 \\ 0 & \frac{1}{h} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} \frac{1}{3} \\ \frac{1}{3} \end{bmatrix} \\
 W_4(x) &= \begin{bmatrix} 0 & \frac{1}{h} \\ -\frac{1}{3} & 0 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} \frac{2}{3} \\ \frac{1}{3} \end{bmatrix} \\
 W_5(x) &= \begin{bmatrix} \frac{1}{3} & 0 \\ 0 & \frac{1}{h} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} \frac{2}{3} \\ 0 \end{bmatrix}
 \end{aligned} \tag{4.1}$$

$$W(A) = W_1(A) \cup W_2(A) \cup W_3(A) \cup W_4(A) \cup W_5(A) \tag{4.2}$$

Only two iterations, as shown in figure 4.1, of the Cohen-Minkowski geometry were used due to the fact that higher iteration would cause printing issues and also some coupling between the elements of the geometry could cause problems.

4.3 Simulation of Cohen-Minkowski Monopole

4.3.1 Software simulation

To simulate this kind of structures the software HFSS v10.0 from ANSOFT [13] was used. HFSS is able to model the radiation of 2D and 3D structures printed in substrates. It is also possible to set finite conductivity on the printed elements so simulations are a better approximation to the reality. See figure 4.2.

With HFSS we can measure the reflection coefficient (S_{11}), VSWR, input impedance (real and imaginary parts), radiation patterns and 3D plots of the radiation patterns.

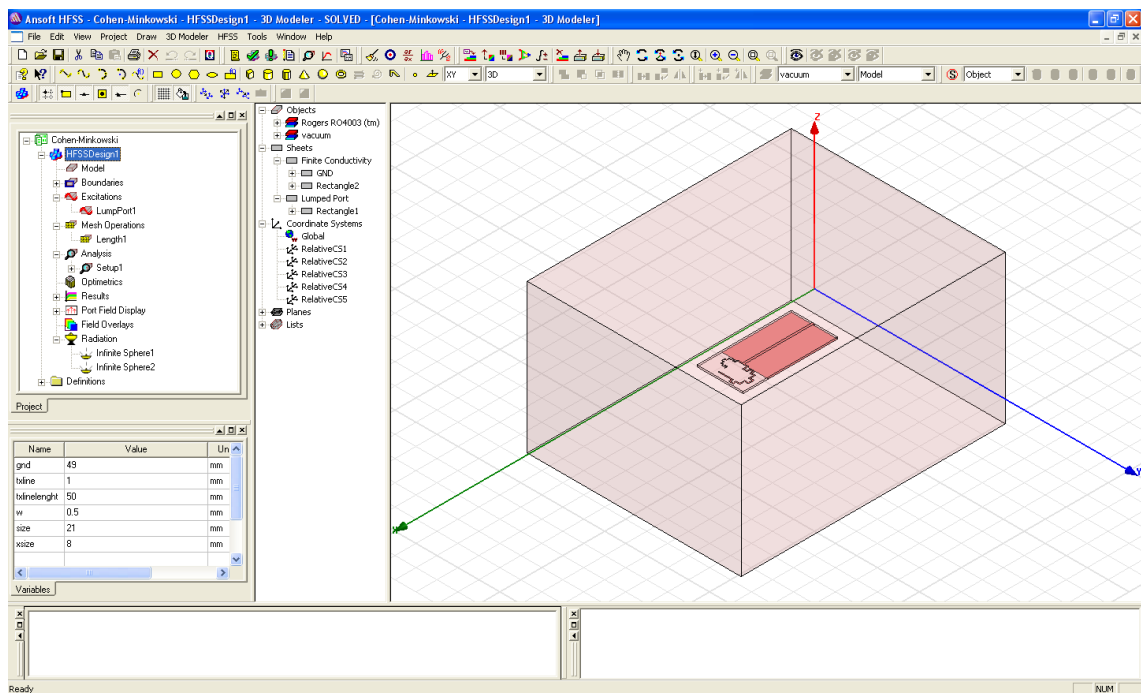


Figure 4.2: Screen shot of HFSS 3D modeler

HFSS has another property very useful for the fractal structures which is the RUN SCRIPT. As fractal structures are quite complex there is a need for these structures to be generated automatically. *MATLAB* is a very useful software in which we can create a script for a certain geometry and then run it in HFSS. HFSS runs .vbs files. An example of a *MATLAB* code can be found in appendix.

4.3.2 Dielectric Substrate

The substrate chosen for this project was the Rogers RO4003. The reasons for choosing RO4003 and not the common FR4 are described below:

- **Dielectric constant ϵ_r :** FR4 is not suitable for RF circuits above 2 GHz although is not very expensive compared to others. Due to the fact that we are going to work with microstrip lines, being able to define impedance accurately is very important, hence ϵ_r is very critical. The ϵ_r for FR4 is rather high, around 4.7 and not very stable, its value is different from different manufactures. The ϵ_r could go as low as 3.8 for the FR4 but only for some companies. Calculating the mean value we would come across with $\epsilon_r = 4.3$ which means that we will never get an optimal performance. The RO4003 has an ϵ_r of 3.38, which is quite good for microstrip lines.
- **Temperature Stability:** Another negative point about the FR4 is the fact it has low stability at high temperatures. The T_g for the FR4 is 125 Celcius. This means that when soldering one must be very careful with the used temperature. RO4003 has a T_g higher than 280 Celcius.
- **Dielectric Loss:** FR4 is ten times more lossy than RO4003, $FR4 = 0.02$ and $RO4003 = 0.0027$.
- **Copper Peel:** One of the only two advantages FR4 has over RO4003 is the copper peel strength. FR4 is 10 while RO4003 is 6.
- **Price:** The other advantage is that the FR4 costs four times less than the RO4003.

4.3.3 Initial Simulation

Antennas for USB applications need to be very small and so the area of antenna is very limited. Initially a single arm of the antenna was simulated and it showed good results around 2.4 GHz and 6 GHz. Firstly the antenna was tuned at 2.4 GHz and as we can see on the simulated antenna the arm for 2.4 GHz is longer. After tuning the antenna for 2.4 GHz a second arm was tuned to work around the 6 GHz band. Joining both arms on the antenna showed good results at the three bands. In addition a minor tuning was carried out to achieve the best performance in terms of operation band (S11).

4.3.4 Simulation of antenna A

Trace line thickness for M1 is 0.5mm and M2 is 0.225mm.

The span used for the simulation was from 1 to 7 GHz for a closer view on resonating frequencies. As we can observe in figure 4.4 and analyzing its results presented in table 4.2 the simulation presents a promising S_{11} (Return loss or reflection coefficient) at 5.8 GHz and 2.4 GHz while at 5.2 GHz it is only $-10.56dB$. Optimization was carried out but without any success due to the complexity of the structures, still this antenna would perform nicely on the 2.4 and 5.8 GHz.

A bandwidth of 14.93% and 23.86% was calculated at 2.41 GHz and 5.8 GHz, respectively.

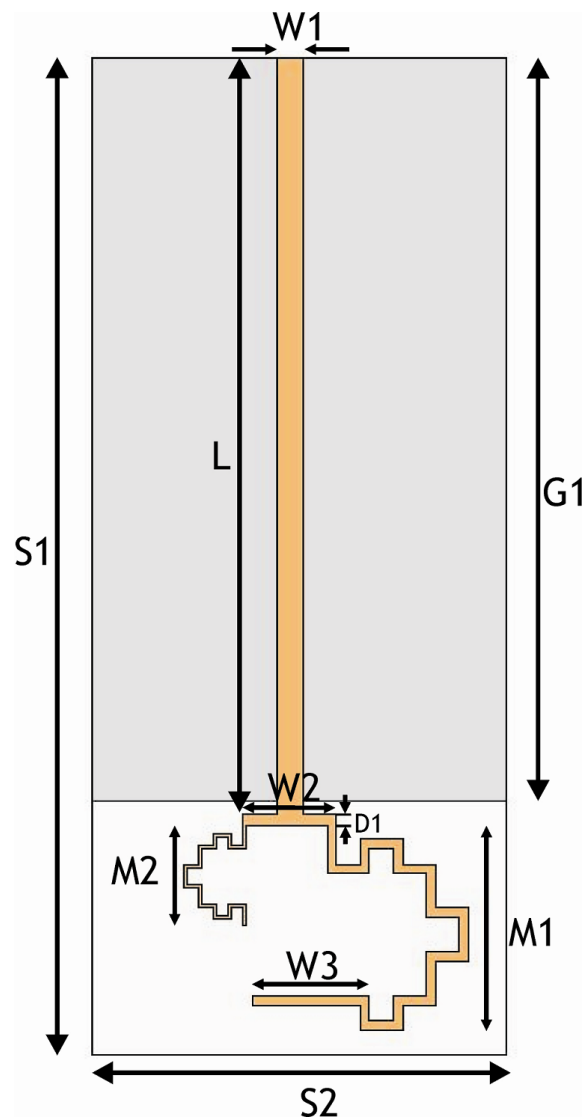


Figure 4.3: Antenna A schematic

Table 4.1: Antenna A dimensions

Parameter	Measure
S1	53mm
S2	22mm
G1	39.5mm
L	40.2mm
W1	1.4mm
W2	5mm
W3	6.25mm
M1	11mm
M2	5.5mm
D1	0.6mm

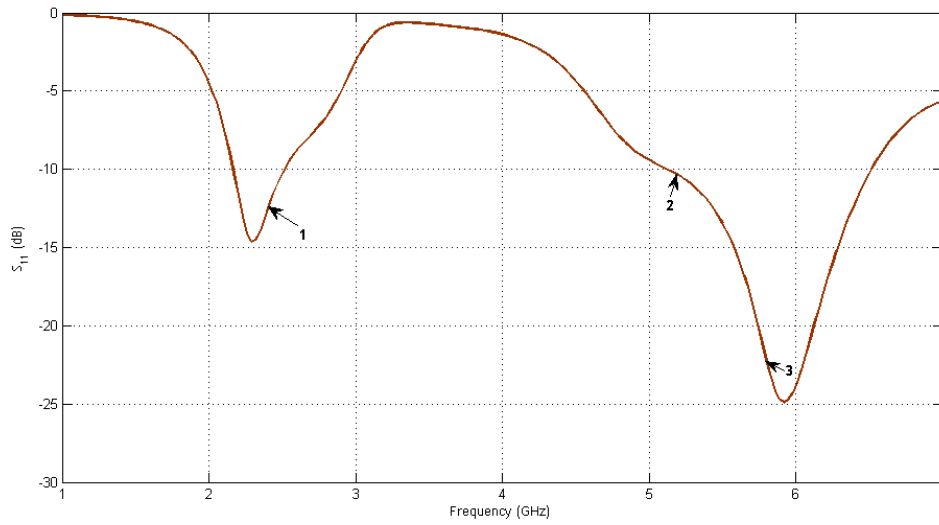


Figure 4.4: Simulated reflection coefficient antenna A

Table 4.2: Simulated reflection coefficient values for figure 4.4

#	Frequency (GHz)	S_{11} (dB)
1	2.41	-12.31
2	5.2	-10.56
3	5.8	-22.22

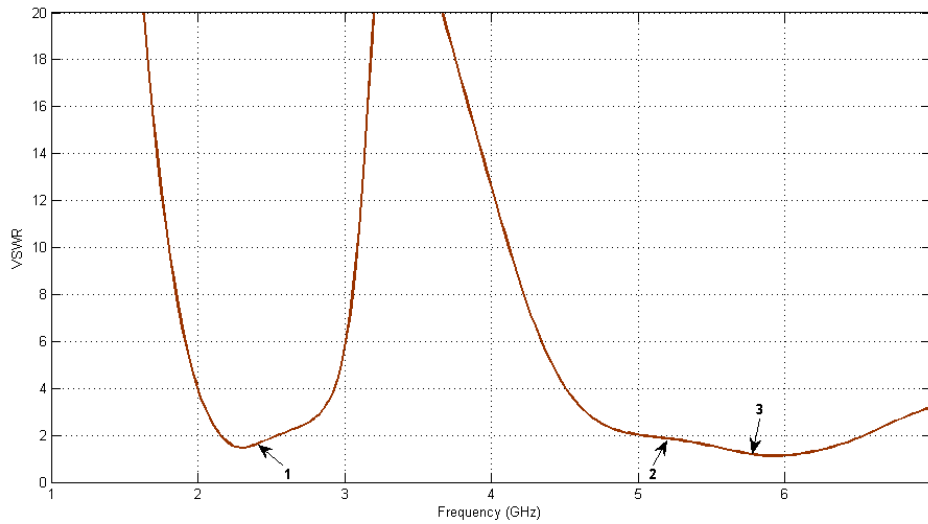


Figure 4.5: Simulated VSWR for antenna A

As it would be expected the VSWR is excellent at 5.8 GHz but at 5.2 GHz it is very close to the operating margin (2:1). We conclude that this antenna will have a good performance at 2.41 GHz

Table 4.3: VSWR values for figure 4.5

#	Frequency (GHz)	VSWR
1	2.41	1.640
2	5.2	1.868
3	5.8	1.168

and 5.8 GHz.

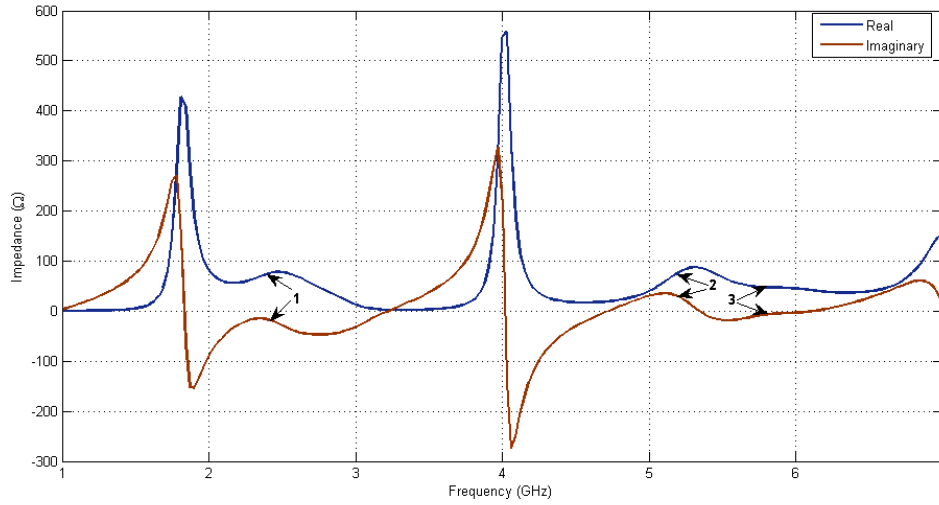


Figure 4.6: Simulated input impedance antenna A

Table 4.4: Simulated input impedance values for figure 4.6

#	Frequency (GHz)	Impedance (Ω)
1	2.41	$74.9 - j17.75$
2	5.2	$76.66 + j28.9$
3	5.8	$47.8 - j7.05$

The input impedance is presented in table 4.4. As we can see at 5.8 GHz the impedance is close to 50Ω , which explains the deep value on the reflection coefficient and VSWR presented before. Impedance matching could be performed to achieve better results on the other two frequencies but this would only improve one band and not in all of them.

In figure 4.7 the radiation pattern at 2.41 GHz is presented. The E plane is represented in blue and the H plane in brown. We observe that the antenna has a maximum gain of almost $2.83dB@186^\circ$. This radiation pattern has two major lobes, at 356° and the other at 182° (E - Plane).

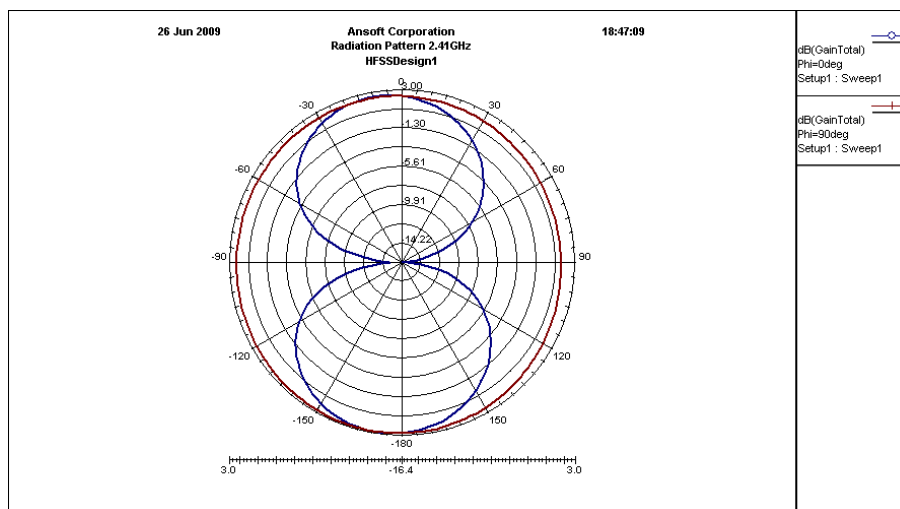


Figure 4.7: Simulated radiation pattern at 2.4 GHz

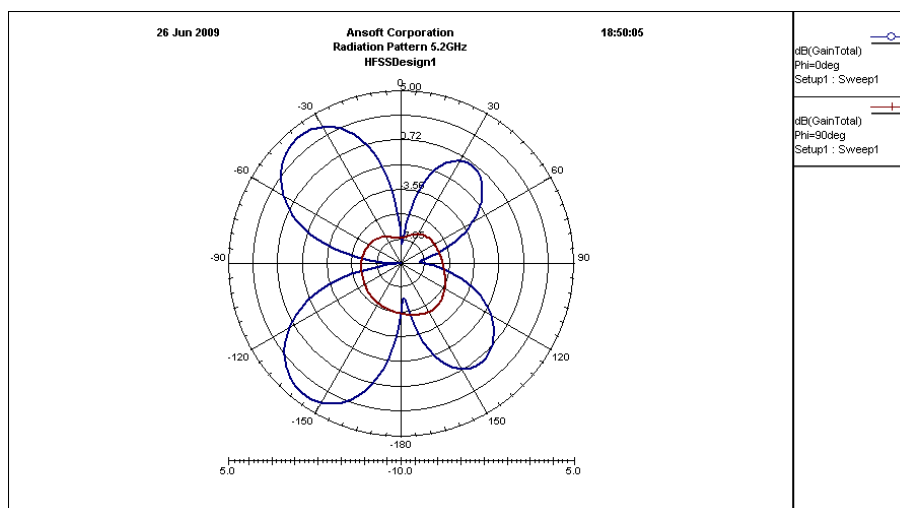


Figure 4.8: Simulated radiation pattern at 5.2 GHz

In figure 4.8 the radiation pattern at 5.2GHz is presented. The E plane is represented in blue and the H plane in brown. We observe that the antenna has a maximum gain of almost $4.1dB@216^\circ$. This radiation pattern has two major lobes, at 218° and the other at 320° also has two back lobes at 36° and a 140° (E - Plane).

In figure 4.9 the radiation pattern at 5.8GHz is presented. The E plane is represented in blue and the H plane in brown. We observe that the antenna has a maximum gain of almost $3.5dB@322^\circ$. This radiation pattern has two major lobes at 218° and 318° and a side lobe at 90° (E - Plane).

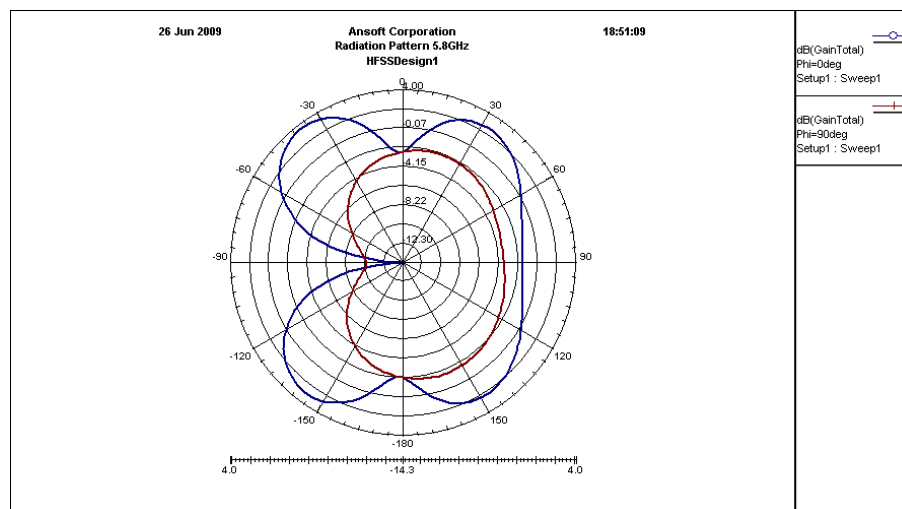


Figure 4.9: Simulated radiation pattern at 5.8GHz

4.3.5 Simulation of antenna B

This antenna could be considered an optimization of antenna A due to the fact that the procedure of making this antenna is the same. The process of optimization is held by HFSS, which has a feature called OPTIMETRICS. In this feature variables can be added and the start, stop and step points can be chosen so an optimization can be done with precision. These variables are defined when the antenna is designed.

The difference between the two antennas is that this antenna works on the three desired bands while antenna A only has good performance at 2.4 GHz and 5.8 GHz still this antenna shows good results on these bands.

Both antennas could be used for different applications.

Table 4.5: Antenna B dimensions

Parameter	Measure
S1	45mm
S2	22mm
G1	33mm
L	33.3mm
W1	1mm
W2	5.27mm
W3	7.05mm
M1	10.5mm
M2	6mm
D1	0.5mm

Trace line thickness for M1 is 0.5mm and M2 is 0.27mm.

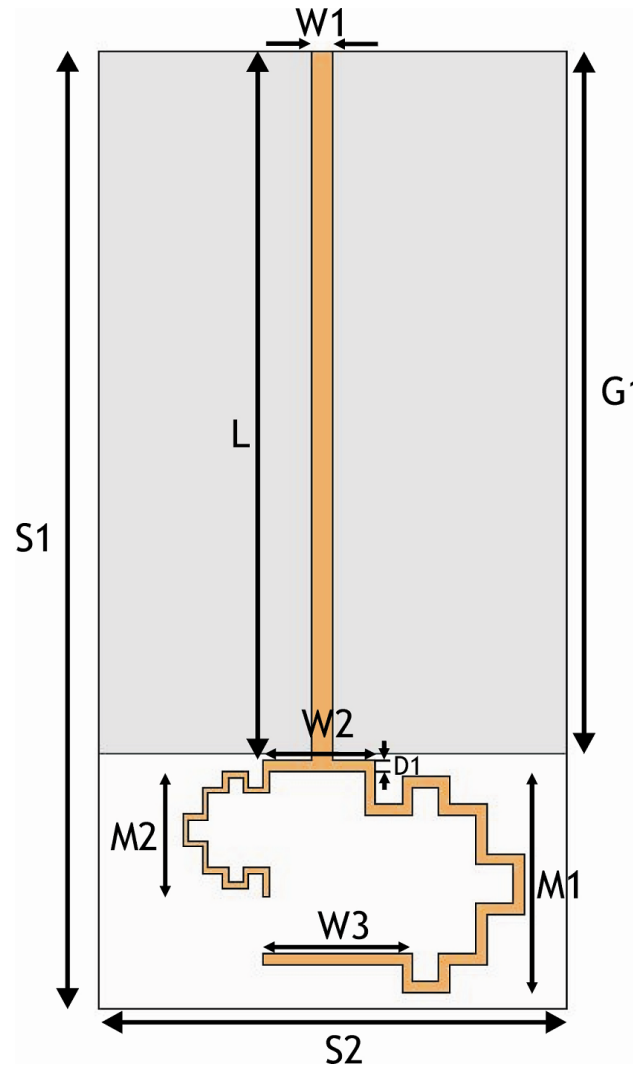


Figure 4.10: Antenna B schematic

Table 4.6: Simulated reflection coefficient values for figure 4.11

#	Frequency (GHz)	$S_{11}(dB)$
1	2.41	-27.32
2	5.2	-11.97
3	5.8	-20.11

Figure 4.11 represents the S_{11} plot and analyzing its results presented in table 4.6 we conclude that this antenna has a good performance on the desired frequencies. At 2.4 GHz we got very good S_{11} result of $-27.32dB$, at 5.2 GHz $-11.97dB$ and at 5.8GHz $-20.11dB$. All return loss values are under $-10dB$ which dictates that this antenna is triband performer.

Consequently the VSWR is always under 2:1 with a deep of 1.090 at 2.41 GHz.

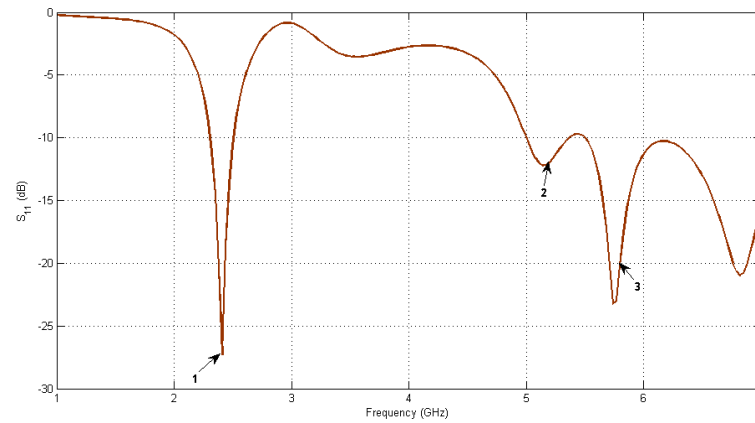


Figure 4.11: Simulated reflection coefficient antenna B

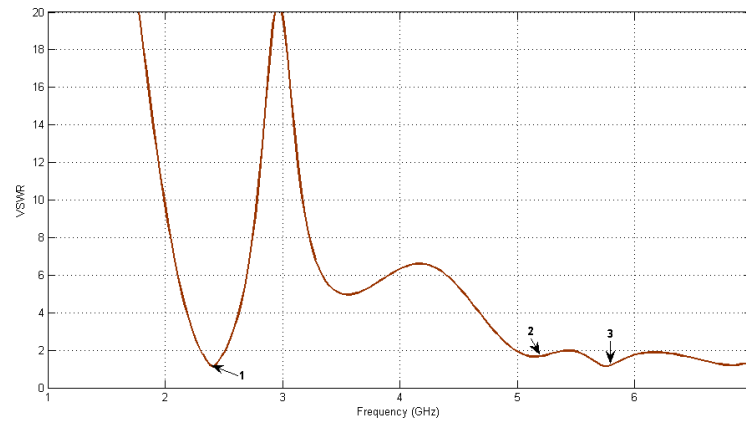


Figure 4.12: Simulated VSWR antenna B

Table 4.7: VSWR values for figure 4.12

#	Frequency (GHz)	VSWR
1	2.41	1.090
2	5.2	1.674
3	5.8	1.219

A bandwidth of 8.3%, 7.1% and 11.1% were calculated at 2.41 GHz, 5.2 GHz and 5.8 GHz, respectively.

Table 4.8 presents the impedance values for 2.41 GHz, 5.2 GHz and 5.8 GHz, respectively. We can conclude that at 2.4 GHz and 5.8 GHz the impedance is close to 50Ω with an imaginary part close to zero.

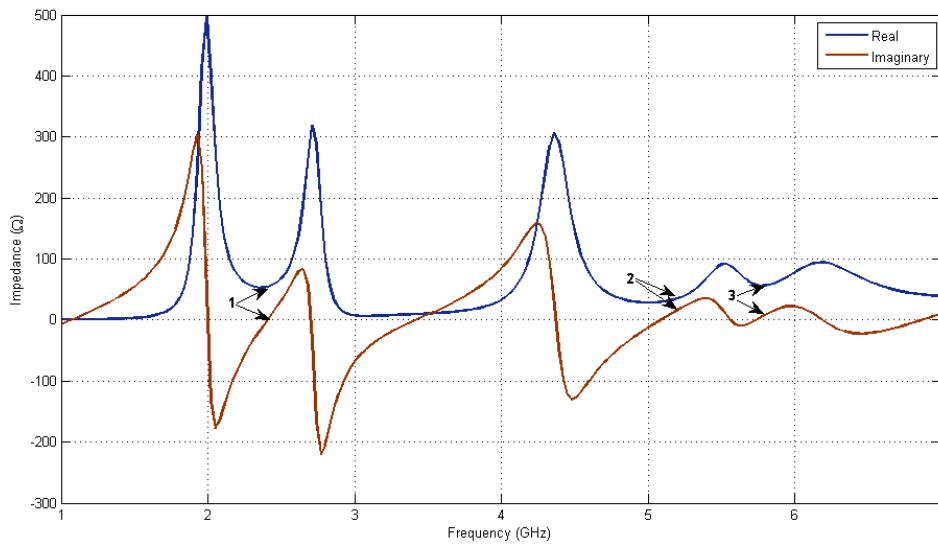


Figure 4.13: Simulated input impedance antenna B

Table 4.8: Simulated input impedance values for figure 4.13

#	Frequency (GHz)	Impedance (Ω)
1	2.41	$54.49 + j0.36$
2	5.2	$34.95 + j15.74$
3	5.8	$56.37 + j8.39$

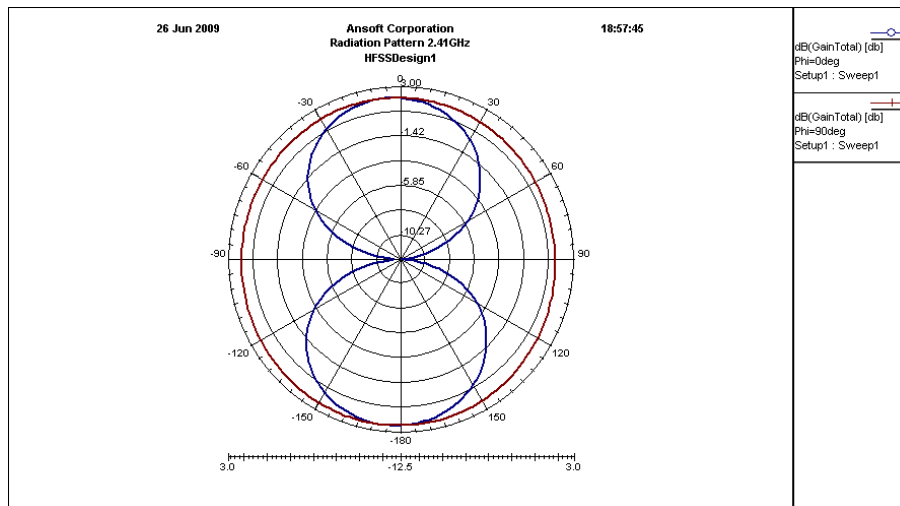


Figure 4.14: Simulated radiation pattern at 2.4 GHz

In figure 4.14 the radiation pattern at 2.41 GHz is presented. The E plane is represented in blue and the H plane in brown. We observe that the antenna has a maximum gain of almost $2.39\text{dB}@184^\circ$. This radiation pattern has two major lobes, at 354° and the other at 180° (E -

Plane).

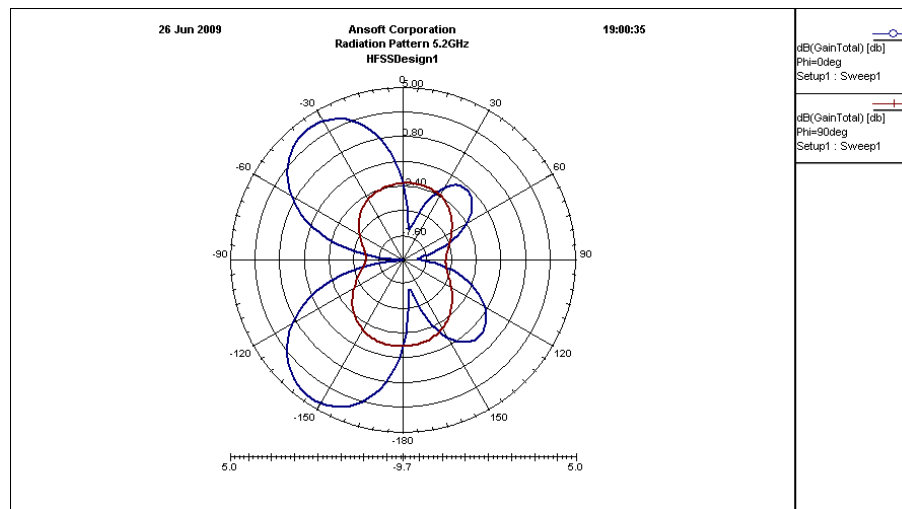


Figure 4.15: Simulated radiation pattern at 5.2 GHz

In figure 4.15 the radiation pattern at 5.2 GHz is presented. The E plane is represented in blue and the H plane in brown. We observe that the antenna has a maximum gain of almost 4.4dB at 214° . This radiation pattern has two major lobes, at 212° and the other at 324° also has two back lobes at 44° and a 134° (E - Plane).

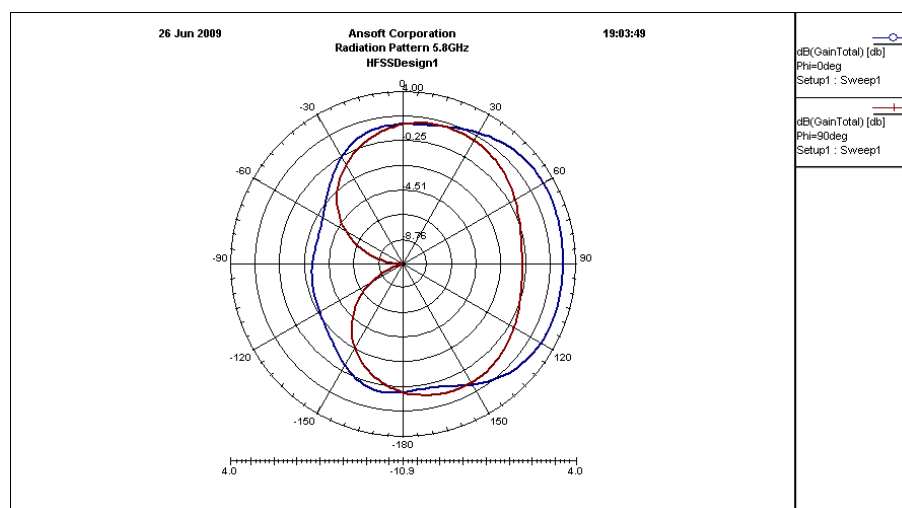


Figure 4.16: Simulated radiation pattern at 5.8 GHz

In figure 4.16 the radiation pattern at 5.8 GHz is presented. The E plane is represented in blue and the H plane in brown. We observe that the antenna has a maximum gain of almost 3dB at 62° .

This radiation pattern has a major lobe at 90° (E - Plane).

4.4 Summary

In this chapter the Cohen-Minkowski geometry was presented together with its affine transformations. Then the software used to design the antennas was briefly described. A comparison between FR4 and RO4003 substrates is also given in this chapter.

Finally the simulation of two antennas with the Cohen-Minkowski geometries is presented focusing on the S_{11} , VSWR, input impedance and radiation patterns.

Next chapter will focus on the implementation of both antennas and the simulated vs measured results.

Chapter 5

Implementation and Measurement

5.1 Introduction

In this chapter the fabrication process of the Cohen-Minkowski monopole will be described. The procedure and equipment for measuring the antennas will then be referred and finally an analysis of the simulated vs measured results will be presented.

5.2 Fabrication process

The fabrication process can be described in five phases:

- **First phase:** Use ADS to create the Top and Bottom views of the antenna. ADS allows the files to be exported as Gerber extension. The gerber files are then converted into fpf extension using FPF software, which is the only extension that the photo plotter accepts. After printing the transparency in actual size it goes into a revealing chemical for 30 to 60 seconds. A second chemical, that will act as a retainer, will be applied for twice the time of the revealing chemical. After the transparency has been in the chemicals, it needs to dry naturally.
- **Second phase:** The substrate plaque is cut with a certain margin and is intensely sanded with a rubber that has metallic particles. After sanding the substrate it is cleaned with dish-washing detergent to guarantee there are no metallic particles. Then Positiv 20 is applied to one side of the substrate and it dries for 20 minutes at maximum of 70 Celcius. The same procedure is done for the other side of the substrate.
- **Third phase:** The photo lites are aligned with the substrate plaque guaranteeing that the side which was printed is in direct contact with the Positiv 20, this will prevent any reflection or refraction. Then it goes into the UV chamber for 120 seconds. After going into the

UV chamber the plaque is immersed into sodium hydroxide 15%, known as caustic soda to remove the Positiv 20 that was exposed to the UV light.

- **Fourth phase:** After cleaning the substrate plaque with water it goes into hydrochloric acid, distilled water and some hydrogen peroxide 140 volumes. Last step is to clean with water and clean the Positiv 20 from the microstrip lines.
- **Fifth phase:** An SMA connector [5.1](#), which is a coaxial RF connector, was used due to its excellent frequency response from DC up to 18 GHz. However, there are some customized versions of this connector that are rated as high as 26.5 GHz.



Figure 5.1: SMA connector

5.3 Measuring procedure

- **Why calibrate the network analyser:** all measuring instruments have imperfections, these imperfections lead to errors.
- **Types of calibration:**
 - **Response calibration:** Removes frequency response errors for transmission or reflection measurements. Suitable for devices with good matching and low in attenuation. It is the most simple calibration and the less precise.
 - **Response and isolation calibration:** Removes frequency response and crosstalk errors in the transmission measurements. Removes frequency response and directivity errors in the reflection measurements. Suitable for good matching and with high attenuation devices.
 - **One-port calibration:** Corrects frequency response and directivity errors for the reflection measurements (S_{11} , S_{22}). Suitable to measure reflections from one port devices only.
 - **Full two-port calibration:** Corrects all systematic errors in both directions. All S parameters are measured and it is the most complex calibration method.

- **Calibration procedure:**

- **One-port calibration:** After going into the calibrate menu we place an Open into port 1, after this we place a Short into port 1 finally we place a Load into port 1.
- **Full two-port calibration:** After going into the calibrate menu and chose Reflection, we place an Open into port 1, after this we place a Short into port 1 finally we place a Load into port 1. After repeating this process in port 2 the Reflection calibration is done. Now we choose Transmission calibration and we place a Thru between port 1 and 2. After this we place a 50Ω load between the two ports.

The reflection coefficient (S_{11}) was measured using an Agilent 8703B network analyzer.



Figure 5.2: Agilent 8703B

This can be obtained by using a single port calibration. The range frequencies chosen to analyse were the same as the simulations, from 1 GHz to 7 GHz. Due to the fact that the network analyzer only has type N connectors, an SMA to type N adaptor had to be used in order to connect the antenna to the network analyzer. A very short 50Ω coax cable was also used to keep the antenna away from the analyzer so there would be no interference.

The radiation pattern was only measured at 2.41 GHz due to the fact that the log-periodic antenna used in the anechoic chamber (see figure 5.3) at FEUP (Faculdade de Engenharia da Universidade do Porto) works as far as 3.6 GHz. The network analyser used was the Hewlett Packard HP8753A. A two-port calibration was accomplished before starting the measurements.

The configurations made in the network analyser were, center frequency set to 2.41 GHz, the span 200 MHz and the number of points 201. The power injected in the log-periodic antenna was 20dBm.

The gain of the antenna was calculated according to the Friis equation:

$$\frac{P_r}{P_t} = G_r G_T \left(\frac{\lambda}{4\pi R} \right)^2 \quad (5.1)$$

where P_r/P_t represents the S parameter $|S_{21}|^2$. R is the distance between antennas. $\left(\frac{\lambda}{4\pi R} \right)^2$ represents the free space attenuation. The calculated free space attenuation, with $R = 4.8m$ is 3.8×10^{-6} and the log-periodic antenna gain is 7dBi.

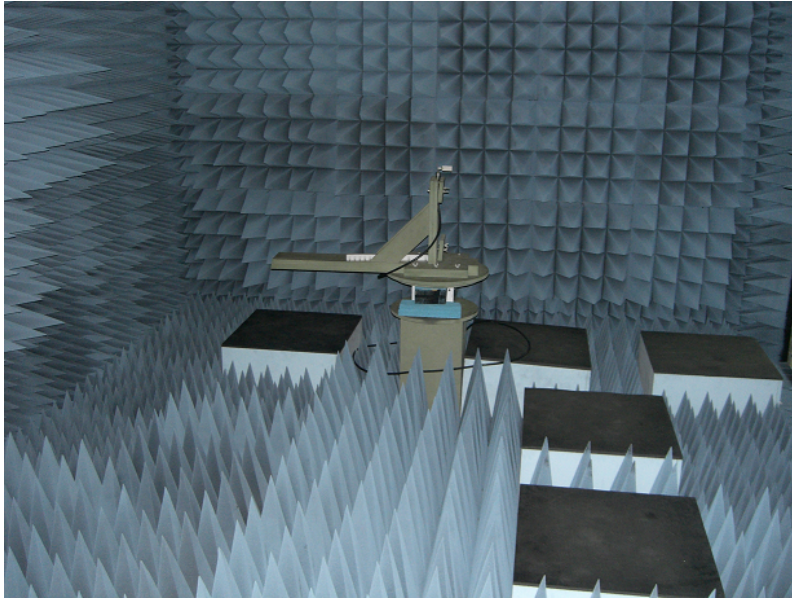


Figure 5.3: Anechoic chamber

5.4 Results Cohen-Minkowski Monopole

5.4.1 Antenna A

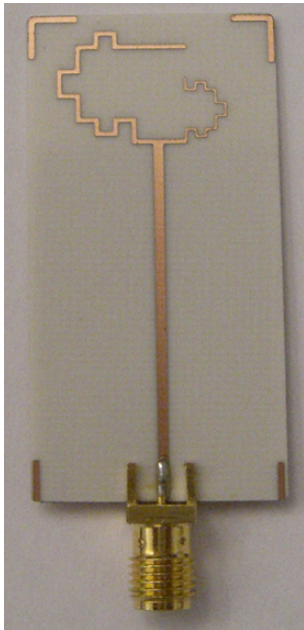


Figure 5.4: Top view of the antenna A



Figure 5.5: Bottom view of the antenna A

Figures 5.4 and 5.5 show the implemented antenna A, bottom and top views, respectively. In table 5.1 the values for the measured vs simulated. Analysing these results we conclude that at 2.4 GHz the S_{11} is almost the same, just a $0.25dB$ difference. At 5.8 GHz the results are better

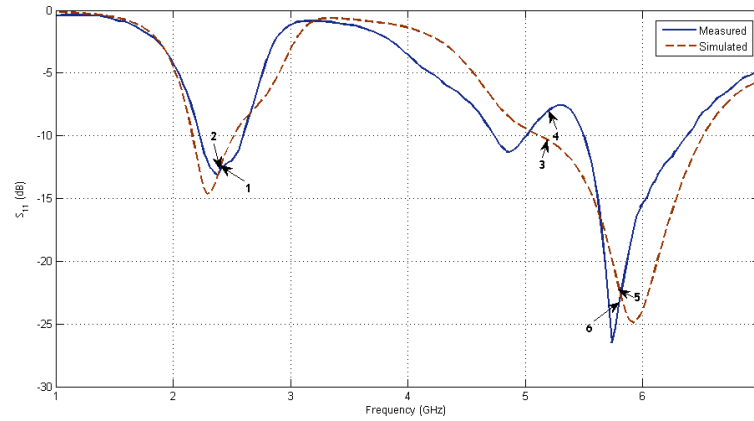


Figure 5.6: Coefficient reflection simulated vs measured antenna A

Table 5.1: Coefficient reflection simulated vs measured for figure 5.6

#	Frequency (GHz)	$S_{11}(dB)$
1	2.41	-12.31
2	2.41	-12.56
3	5.2	-10.38
4	5.2	-7.99
5	5.8	-22.22
6	5.8	-23.41

by 1.19dB difference from measured to simulated. At 5.2 GHz the results are not so good with a 2.39dB difference from simulation to measurement. With these results we conclude that this antenna is capable of operating at 2.4 and 5.8 GHz with good performance while at 5.2 GHz the results are not so promising.

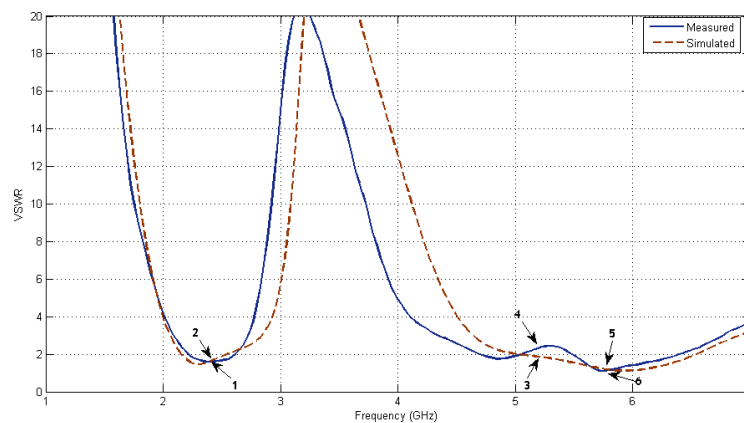


Figure 5.7: VSWR simulated vs measured antenna A

Table 5.2: VSWR simulated vs measured for figure 5.7

#	Frequency (GHz)	VSWR
1	2.41	1.640
2	2.41	1.588
3	5.2	1.868
5	5.2	2.329
5	5.8	1.168
6	5.8	1.141

A bandwidth of 14.9% and 14.6% were calculated at 2.41 GHz and 5.93 GHz, respectively. As expected the VSWR is below the 2:1 margin at 2.4 GHz and 5.8 GHz. Usually devices are limited to a 2:1 VSWR in order to avoid any malfunction.

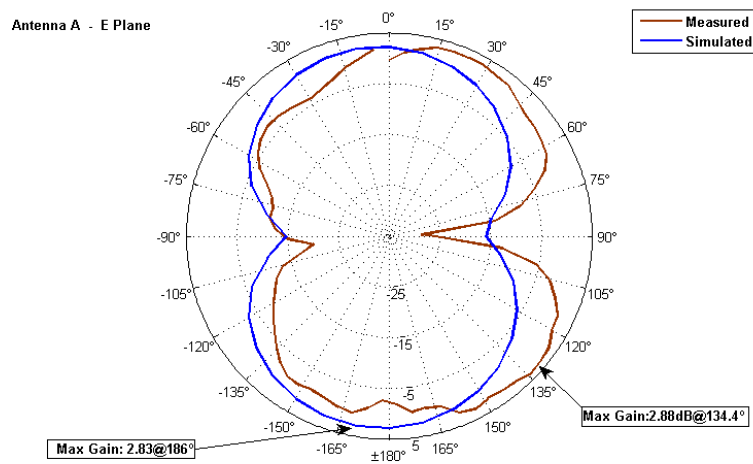


Figure 5.8: E plane radiation pattern at 2.41 GHz

Figure 5.8 represents the measured E plane of antenna A at 2.41 GHz. Analyzing the image there are two major lobes, one at 0° and the other at 165°. There is a maximum gain at 134.4° with 2.88dB. Comparing this result with the simulated in 4.14 we conclude that results are very similar.

Figure 5.9 represents the measured H plane of antenna A at 2.41 GHz. The H plane shown has a max gain of 2.18dB@77.8°.

5.4.2 Antenna B

Figures 5.10 and 5.11 show the implemented antenna B, bottom and top views, respectively. Analysing table 5.3 the values taken from figure 5.12, we conclude that this antenna has good performance in all three desired bands. At 2.4 GHz there is a 11.29dB difference from simulated

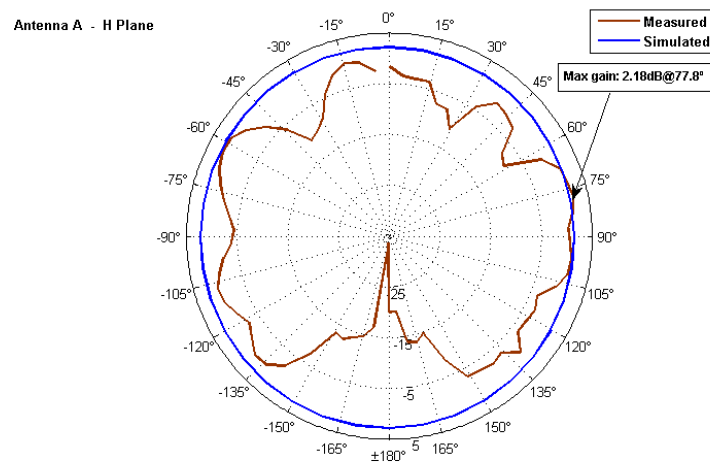


Figure 5.9: H plane radiation pattern at 2.41 GHz

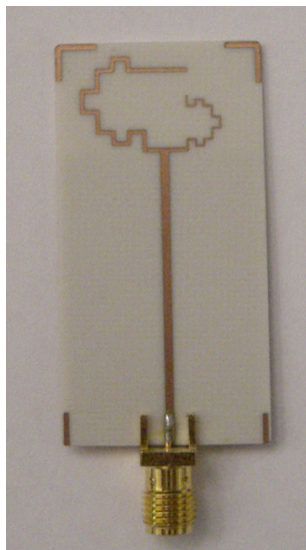


Figure 5.10: Top view of antenna B

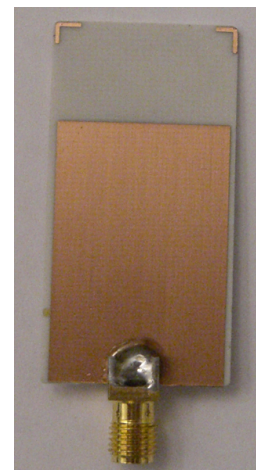


Figure 5.11: Bottom view of antenna B

Table 5.3: Coefficient reflection simulated vs measured for figure 5.12

#	Frequency (GHz)	$S_{11}(dB)$
1	2.41	-27.32
2	2.41	-15.71
3	5.2	-11.97
4	5.2	-27.91
5	5.8	-20.11
6	5.8	-14.71

to measured but the measured value is still acceptable for good performance. At 5.2 GHz we see the opposite from 2.4 GHz with an $15.94dB$ difference from measured to simulated, this dictated

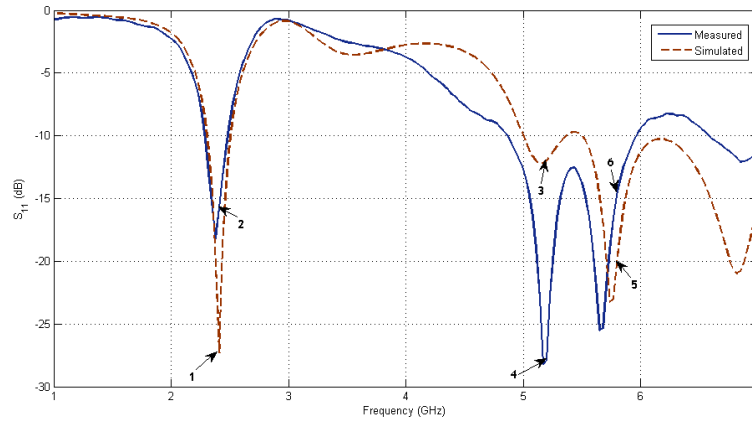


Figure 5.12: Coefficient reflection simulated vs measured antenna B

that this antenna is performs best at 5.2 GHz with an S_{11} value of $-27.91dB$. At 5.8 GHz the value of $-14.71dB$ is achieved.

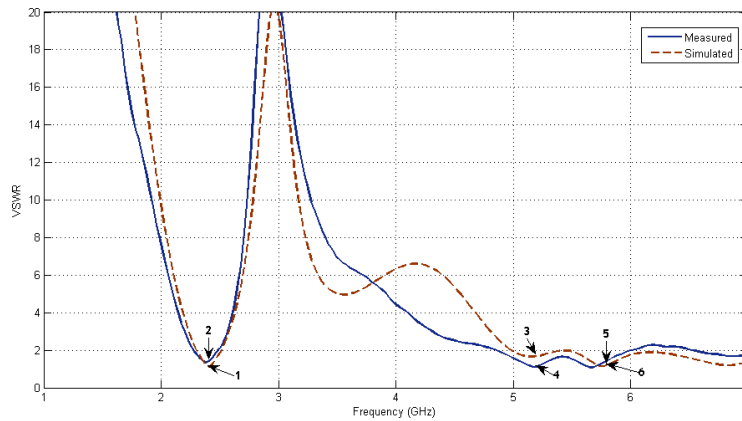


Figure 5.13: VSWR simulated vs measured antenna B

Table 5.4: VSWR simulated vs measured for figure 5.13

#	Frequency (GHz)	VSWR
1	2.41	1.090
2	2.41	1.418
3	5.2	1.674
5	5.2	1.117
5	5.8	1.219
6	5.8	1.220

A bandwidth of 8.3% and 20% were calculated at 2.41 GHz and 5.4 GHz, respectively. As

expected the VSWR is below the 2:1 margin in all the three bands with a minimum of 1.117 at 5.2 GHz.

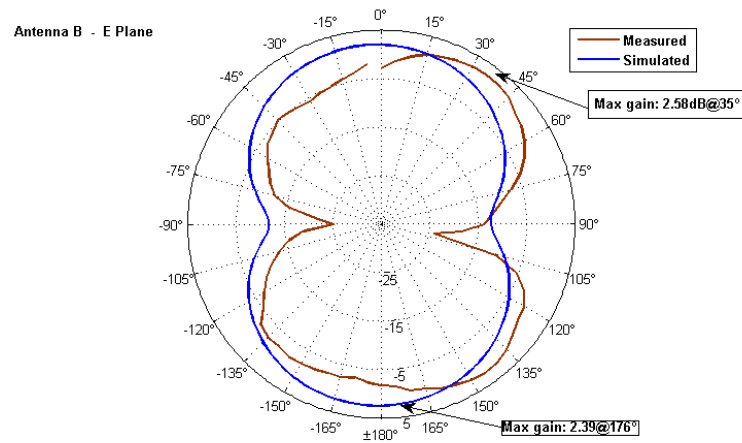


Figure 5.14: E plane radiation pattern at 2.41 GHz

Figure 5.14 represents the measured E plane of antenna A at 2.41 GHz versus the Simulated. Analyzing the image there are two major lobes, one at 0° and the other at 180° . There is a maximum gain at 35° with 2.58dB . Comparing this result with the simulated in 4.14 we conclude that results are very similar.

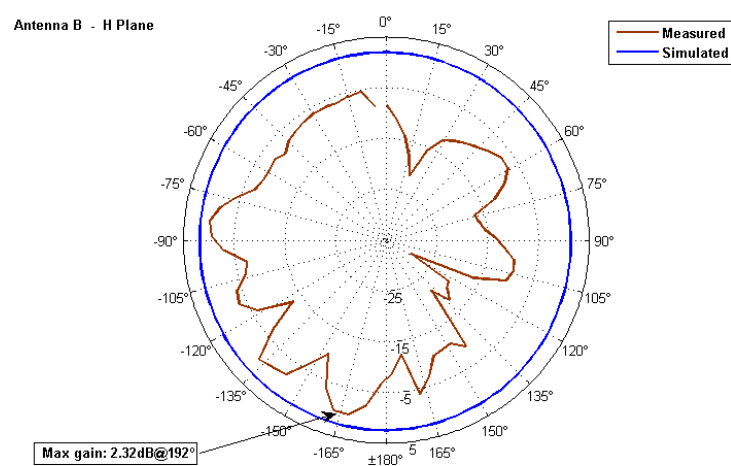


Figure 5.15: H plane radiation pattern at 2.41 GHz

Figure 5.15 represents the measured H plane of antenna A at 2.41 GHz. The H plane shown has a max gain of $2.32\text{dB}@192^\circ$.

5.5 Summary

This chapter presents the implementation and measurement results. The fabrication process is described as well as the measuring procedure. A detailed description of both procedures can be found. The return loss, VSWR and radiation patterns for both antenna A and B are presented and discussed. The results for both antennas are very promising especially for antenna B, as it shows good results on the three bands.

Chapter 6

Final Conclusions

The main goal of this project was to make an antenna capable of operating at 2.4 GHz, 5.2 GHz and 5.8 GHz and would be suitable for Wireless USB applications. As we can observe in the simulations this was achieved. First the size of the antennas is suitable for such applications, then the antennas properties are very promising. The input impedances are very close to 50Ω or 75Ω , the return loss is below $-10dB$ which is our margin, consequently the VSWR is always under 2, the radiation patterns show that these antennas have good gain. We conclude that antenna A is capable of operating at 2.41 GHz and 5.8 GHz while antenna B has a better performance allowing operation at 2.4 GHz, 5.2 GHz and 5.8 GHz with good results.

We conclude that the goals of this assignment were successfully accomplished.

6.1 Discussed future work

The first thing that needs to be done in the future is to measure the radiation pattern of both antennas at 5.2 GHz and 5.8 GHz because as previously mentioned the log-periodic antenna in the anechoic chamber only works as far as 3.6 GHz. Matching techniques could also be used to try to reduce the return loss in antenna A at 5.2 GHz.

For this project the Cohen-Minkowski geometry was used, but other structures could be used. Other geometries could be simulated and described and finally compared so the best geometry for a certain application could be found. Usually the size of the antenna is very important, mainly for wireless applications so other fractal geometries need to be tested to achieve a reduced size with the best performance.

Appendix A

Sorce codes

```
1
2 function [y]=cohen (length , iteration , h)
3
4 w1 = [1/3 0 0; 0 1/h 0; 0 0 1];
5 w2 = [0 -1/h 1/3; 1/3 0 0; 0 0 1];
6 w3 = [1/3 0 1/3; 0 1/h 1/3; 0 0 1];
7 w4 = [0 1/h 2/3; -1/3 0 1/3; 0 0 1];
8 w5 = [1/3 0 2/3; 0 1/h 0; 0 0 1];
9
10 v1 = [0 1;0 0;1 1];
11
12 % Generate the fractal geometry to an iteration number specified before
13 for i = 1:iteration
14     y1a = w1* v1 ;
15     y2a = w2* v1 ;
16     y3a = w3* v1 ;
17     y4a = w4* v1 ;
18     y5a = w5*v1;
19     y = [ y1a y2a y3a y4a y5a] ;
20     v1 = y ;
21 end
22 %plot the geometry
23 y = length*y(1:2,:);
24 plot(y(1,:),y(2,:))
25 return

1
2 function cohen_hfss
3
4 hfssScriptFile = 'C:\Documents and Settings\Filipe\Ambiente de trabalho\HFSS.vbs';
5
6 fid = fopen(hfssScriptFile , 'wt');
7
8 %Header of the .vbs file
9
10 fprintf(fid , 'Dim oHfssApp\n');
11 fprintf(fid , 'Dim oDesktop\n');
12 fprintf(fid , 'Dim oProject\n');
13 fprintf(fid , 'Dim oDesign\n');
14 fprintf(fid , 'Dim oEditor\n');
15 fprintf(fid , 'Dim oModule\n');
16 fprintf(fid , 'Set oHfssApp = CreateObject("AnsoftHfss.HfssScriptInterface")\n');
17 fprintf(fid , 'Set oDesktop = oHfssApp.GetAppDesktop()\n');
18 fprintf(fid , 'oDesktop.RestoreWindow\n');
19 fprintf(fid , 'oDesktop.NewProject\n');
20 fprintf(fid , 'Set oProject = oDesktop.GetActiveProject\n');
21 fprintf(fid , 'oProject.InsertDesign "HFSS", "design1", "DrivenModal", ""\n');
22 fprintf(fid , 'Set oDesign = oProject.SetActiveDesign("design1") \n');
23 fprintf(fid , 'Set oEditor = oDesign.SetActiveEditor("3D Modeler") \n');
24
25 fprintf(fid , 'oDesign.ChangeProperty Array("NAME: AllTabs", Array("NAME: LocalVariableTab", Array("NAME: PropServers",_'\n');
26 fprintf(fid , '" LocalVariables", Array("NAME: NewProps",_'\n');
27 fprintf(fid , 'Array("NAME: sizeh", "PropType:=", " VariableProp", " UserDef:=",_'\n');
28 fprintf(fid , 'true , "Value:=", "%f%s")))\n',35,'mm');
29
```

```

30 fprintf(fid, 'oDesign.ChangeProperty Array("NAME: AllTabs", Array("NAME: LocalVariableTab", Array("NAME: PropServers", _\n');
31 fprintf(fid, '"LocalVariables"', Array("NAME: NewProps", _\n');
32 fprintf(fid, 'Array("NAME: width", "PropType:=", "VariableProp", "UserDef:=", _\n');
33 fprintf(fid, 'true, "Value:=", "%f%s")\n', 0.5, 'mm');
34
35 fprintf(fid, '\n');
36
37 %specify the number of iterations, the length and the high of the third
38 %section of the structure
39
40 length=1;
41 iteration=2;
42 h=4;
43 [x]=cohen (length , iteration , h);
44
45
46 ny = size(x);
47
48 % Enter the Points and draw its corresponding rectangular
49 fprintf(fid, '\n');
50
51 for i = 1:ny(2)-1,
52     fprintf(fid, 'oEditor.CreateRectangle Array("NAME: RectangleParameters", "CoordinateSystemID:=", _\n');
53     fprintf(fid, '-1, "IsCovered:=", true, _\n');
54
55     if x (1,i) == x (1,i+1) % Vertical part
56
57         fprintf(fid, '"XStart:=", "%s%f", _\n', 'sizeh*', x(1,i), '- width/2');
58         fprintf(fid, '"YStart:=", "%s%f", _\n', 'sizeh*', x(2,i));
59         fprintf(fid, '"ZStart:=", "%.4f%s", _\n', 0, 'mm');
60
61         fprintf(fid, '"Width:=", "%s", _\n', 'width');
62
63
64         if x (2,i) > x (2,i+1)
65
66             fprintf(fid, '"Height:=", "%s%f%s", _\n', 'sizeh*', x(2,i+1)-x(2,i), '- width/2');
67
68         else
69
70             fprintf(fid, '"Height:=", "%s%f%s", _\n', 'sizeh*', x(2,i+1)-x(2,i), '+ width/2');
71
72         end
73
74     else % Horizontal part
75
76         fprintf(fid, '"XStart:=", "%s%f", _\n', 'sizeh*', x(1,i));
77         fprintf(fid, '"YStart:=", "%s%f%s", _\n', 'sizeh*', x(2,i), '- width/2');
78         fprintf(fid, '"ZStart:=", "%.4f%s", _\n', 0, 'mm');
79
80
81         if x (1,i) > x (1,i+1)
82
83             fprintf(fid, '"Width:=", "%s%f%s", _\n', 'sizeh*', x(1,i+1)-x(1,i), '- width/2');
84
85         else
86
87             fprintf(fid, '"Width:=", "%s%f%s", _\n', 'sizeh*', x(1,i+1)-x(1,i), '+ width/2');
88
89         end
90
91
92         fprintf(fid, '"Height:=", "%s", _\n', 'width');
93
94     end
95
96     fprintf(fid, '"WhichAxis:=", "Z"', Array("NAME: Attributes", "Name:=", _\n');
97     fprintf(fid, '"Rectangle1", "Flags:=", "", "Color:=", "(132 132 193)", "Transparency:=", 0, _\n');
98     fprintf(fid, '"PartCoordinateSystem:=", _\n');
99     fprintf(fid, '"Global", "MaterialName:=", "vacuum", "SolveInside:=", true)_\n');
100
101     fprintf(fid, '\n');
102 end
103 fclose (fid);

```

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