WEARABLE RFID READER AND COMPACT FRACTAL PATCH ANTENNA DESIGN

By

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A THESIS PRESENTED TO THE GRADUATE SCHOOL
OF THE UNIVERSITY OF FLORIDA IN PARTIAL FULFILLMENT
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To my mom, dad, sister, brother, grandparents and friends

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Abstract of Thesis Presented to the Graduate School
of the University of Florida in Partial Fulfillment of the
Requirements for the Degree of Master of Engineering

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The purpose of this thesis was to develop a compact antenna for Wearable RFID (Radio Frequency Identification) Reader applications with a proof of concept prototype. The intended antenna should provide similar properties, compared to a patch antenna resonating at UHF frequency, with a smaller size. The antenna should be integrated into a prototype Wearable RFID Reader and should be able to read RFID tags attached to a box during package handling process.

The process of designing a compact antenna was started with analyzing microstrip patch antennas. A probe feed square patch antenna was designed and tested based on transmission line model. A low cost patch antenna prototype was manufactured using simulation parameters and tested with a Network Analyzer. Software for fractal patch calculations was written and used for generating four iterations of the initiator. Iteration factor values of 0.20 and 0.25 were chosen to be simulated and two substrates, FR4 and AD1000 with 4.6 and 10.2 dielectric constant values, were used.

Probe feed simulation results were validated with the measured results of the prototype antenna. Although the probe feed patch antenna provided good performance for most of the RFID applications, it had no use case for Wearable RFID Reader

application due to size limitations. It is shown that the fractal patch antenna resonant frequency decreases with an increase on the iteration factor and number. It is also observed that iteration factor has more effect on resonant frequency than iteration number. Antenna size miniaturization was achieved with a maximum value of 58.94% for 4^{th} iteration fractal and 0.25 iteration factor.

A prototype Wearable RFID Reader constructed using a fractal patch antenna with an iteration factor of 0.20 and iteration number of 1 was also presented in this thesis work. It is concluded that antenna miniaturization can be achieved by using fractal patch antennas which can be integrated into Wearable RFID Readers.

CHAPTER 1
INTRODUCTION

Radio Frequency Identification (RFID) is one of the automatic identification and data capturing technologies which has been widely used in many applications for identifying objects remotely. Based on RF signals, object identification and sensor data can be captured in a variety of ways. This technology is mainly divided into groups based on energy source of the transponder. While in passive systems the transponder harnesses the energy from the interrogator, in active RFID systems transponders use their own energy source.

With the improvement of semi-conductor technology, the manufacturing cost of passive RFID tags has been reduced to an acceptable level for supply chain applications. Especially in the supply chain in which warehouse management is one of the fundamental steps, efficiency can be improved by using RFID systems instead of barcode systems which have a line of sight requirement. This research focuses on passive RFID systems for supply chain applications.

Problem Description

While RFID promises fast, reliable, non-line of sight requirement for case level package handling in a warehouse management system, it’s still an external device used for reading the ID on a package. Having a handheld RFID device in one hand and carrying a box at the same time would be difficult when it’s desired to be as fast as possible. To solve this problem, an RFID reader device has to be designed to allow the package handler to work without interrupting his package handling process.

The device that would be used in package handling should be compact and easy to use. The device has to have an integrated battery, a RFID reader module, a compact

RFID reader antenna and a communication interface for communicating with the host system which runs the desired application.

The main goal of this thesis is to design a compact antenna with a prototype “Wearable RFID Reader” which can be used in package handling operations.

Organization of Thesis

In Chapter 2 a general overview of RFID Technology, patch antennas, fractal patch antennas is presented. In Chapter 3, detailed information about patch antenna design and fractal patch antenna design is given and design considerations are presented in detail. A prototype patch antenna and fractal patch antennas are also presented with the Wearable RFID reader concept prototype. In Chapter 4, results are given for antenna simulations and measurements. A discussion is presented in Chapter 5 followed by the conclusion and future work given in Chapter 6.

CHAPTER 2
LITERATURE REVIEW

History of RFID

The fundamentals of RFID technology are based on electromagnetic energy studies, originating with Michael Faraday's explanation of light and radio waves as forms of electromagnetic energy back in 1846. James Clerk Maxwell's theory of electromagnetism in 1864 was confirmed by Rudolf Hertz in 1887 who is also known as the first to be able to transmit and receive radio waves. In 1896 Guglielmo Marconi is the first scientist to have successful RF transmission over the Atlantic [1].

One of the primary papers explaining the theory of RFID systems is "Communication by Means of Reflected Power," which was published by Stockman in 1948 [2]. During those years a form of RF identification system which is called IFF (Identification Friend or Foe) was used in World War II.

RFID's first known commercial usage which dates back to the 1960's was called EAS (Electronic Article Surveillance). These systems were used in applications which require 1-bit information; i.e. the presence or absence of a tag in observed RF field [1].

In 1975, the publication of "Short range Radio Telemetry for Electronic Identification Using Modulated Backscatter" [3] resulted in the beginning of commercialization of passive RFID systems.

For the last two decades RFID tags have been used in many applications with CMOS (Complementary metal oxide semiconductor) integrated circuit chips. Improvements in semiconductor technology resulted in increased affordability of the RFID tags, which sped up the industrial applications of RFID.

RFID Technology Overview

RFID Technology can be divided into subcategories according to the energy source of the tags and operating frequencies.

According to source of energy in an RFID system, transponders can be categorized as;

1. Passive tags
2. Semi-passive tags
3. Active tags

Passive Tags: Passive RFID tags have no internal power source. In inductively coupled systems; when the tags are present in the RF field of an RFID interrogator, the energy induced on the tag circuitry is used for transmitting back the ID of the tag. In UHF systems, electromagnetic backscatter coupling is used at the tag circuitry for changing the impedance of the tag antenna according to its ID.

Semi-passive Tags*:* Semi-passive systems have internal batteries and are not beaconing signals in a defined period. In the presence of the RF field of an interrogator, the tag wakes up and starts to transmit its ID to the interrogator; using integrated battery supply. The trade off for energy efficiency is to have reduced response time caused by the time slot needed to wake up the transponder.

As proposed by Auto-ID labs Class-3 categorization; Semi-passive tags use their integrated power source for increased communication range, in contrast to fully passive tags, and also perform on tag functionality such as sensor data logging. These tags have been proposed to be able to send their ID even when they are out of internal battery power [6].

Active Tags: Active Tags are beaconing in a defined period of time by using integrated power supplies. These tags are commonly used in RTLS (Real Time Location Systems) in which the tag continuously reports its ID to the receiver units and location of the tag is usually calculated by using RSS (Received Signal Strength) information and triangulating between different receivers.

RFID Frequencies

Low frequency (LF): Common LF systems operate at either 125 kHz or 134 kHz, the power supply to the transponder is generated by inductive coupling. RF signals at lower frequencies can penetrate through the body better than higher frequencies, that is one of the main reasons for using LF systems in animal identification applications. ISO 11785 defines the standard for animal tracking applications using LF RFID systems.

High frequency (HF): High frequency RFID systems operate at 13.56 MHz frequency. Passive 13.56 MHz systems also operate with the inductive coupling principle, in which magnetic fields are playing the major role for energy transfer. That is why 13.56 MHz performs better in the presence of water and metallic surfaces in short range. ISO 15693 defines the standard for “Vicinity Cards” in HF systems.

Ultra-high frequency (UHF): The most common passive RFID tags used in supply chain applications operate at 915 MHz in US and 868 MHz in Europe. The accepted standard for passive UHF frequency is ISO 18000-6C (aka UHF Gen2). Active or semi-active RFID systems in UHF frequencies operate at 433 MHz. ISO 18000-7 is the accepted standard for parameters of active air interface communications at 433 MHz.

Microwave frequency: Typical microwave operating frequency is either at 2.45 GHz or 5.8 GHz in the ISM band [5]. Microwave systems can be either passive or semi-passive and provide the fastest data communication rates compared to the other frequencies. Read range performance for passive systems in the presence of water and metallic surfaces is very poor because of the higher signal attenuation at higher frequency.

Microstrip Patch Antennas

Patch antennas are widely used in commercial applications mostly because they are simple and inexpensive to fabricate, they can be integrated into printed circuit boards and are conformable to planar surfaces. The resonant frequency, polarization, radiation pattern and impedance properties can be easily configured by using a particular patch shape and adding loads between the radiating plate and the ground plane. These low profile antennas consist of mainly two parts: a radiating patch and a ground plane. Patch geometrical shapes can vary, but the most common forms are square, rectangle, ellipse, circle and rectangle with truncated corners [7, 8].

Different substrates can be used in Microstrip antennas with dielectric constant values varying between $2.2 \leq \varepsilon_r \leq 12$. Thick substrates with lower dielectric constant values are preferred because of their efficiency and larger bandwidth. Although thin substrates with higher dielectric constants are less efficient and have smaller bandwidths they can be manufactured in smaller element sizes with minimum undesired radiation and coupling [8, 9].

The radiating patch can be fed by using one of the methods below:

- Microstrip line feed
- Probe feed
- Aperture-coupled feed
- Proximity-coupled feed

The microstrip line is connected directly to the edge of the microstrip patch, and impedance matching can be done by controlling the inset position. In probe feed patch antennas, coax is attached to the radiation patch and the outer conductor is connected to the ground plane. Controlling the feeding point is used for impedance matching. Both microstrip line feed and probe feed methods can be categorized as contacting methods. Aperture coupling and proximity coupling feed techniques can be categorized as non-contacting methods. The major disadvantage of these techniques is that they are not easy to fabricate; while aperture coupled feed requires a proper slot on the radiating patch, proximity coupled feed requires proper alignment between two substrates [10].

Fractal Antennas

Fractals are complex geometric shapes with space filling and self-similarity properties. Space filling contours result in electrically large features which can be efficiently packed into small areas. Antenna miniaturization can be achieved by using the space filling properties of fractals that lead to curves that are electrically very long but fit into a compact physical space [26-29].

Researchers have been working on developing efficient RFID reader antennas and using different methods to achieve smaller sizes, using a vertical ground is one of the options which can reduce the resonant frequency by about 25% in comparison to no vertical ground [21,22]. Others worked on corner truncated square patch antennas for creating circular polarization which is crucial when the orientation of the tag is not known [23,24]. Although circular polarization gives orientation independency, the trade off is having a lower gain antenna which will affect the battery life time of the wearable RFID reader. A short pin and a high-permittivity substrate can also be used for miniaturization, but these will lead to a sharp deterioration of the antenna performance

[25]. In this thesis, design and simulation of fractal patch antennas was performed for size miniaturization.

CHAPTER 3
MATERIALS AND METHODS

Analysis of Patch Antenna Design

Microstrip patch antennas can be analyzed in various methods; the most common methods are as follows:

- Transmission-line method
- Cavity method
- Full-wave method

Although the transmission line model has the least accuracy and is the most difficult one to model coupling, it is the easiest method to implement and gives good physical insight [11]. The cavity model is more accurate, compared to the transmission line method, but more complex to implement. Full-wave method is the most complex, accurate and versatile method but gives less physical insight [7].

The transmission-line method will be described in detail as it is used in this thesis to design patch antennas for RFID applications.

Transmission-line Model. According to Balanis [7], microstrip patch antennas can be explained by the transmission line model representing two slots with a width of W and separated by transmission line of length L.

As it’s seen in Figures 3-2 and 3-3, most of the field lines are inside the substrate and some of them are extended to outer space. Since this is a non-homogenous line of two dielectrics, an effective dielectric constant (ε_r) has to be taken into consideration for fringing and the wave propagation in the line. The assumption of embedding the center conductor of the microstrip line into a dielectric material with a uniform dielectric constant (ε_{reff}) is shown in Figure 3-4.

ε_{reff} can be calculated from [7];

$$\varepsilon_{reff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2} \times \left[1 + 12\frac{h}{W}\right]^{-1/2}$$

(3.1)

Where, $\frac{W}{h} > 1$ and;

ε_{reff} : Effective dielectric constant

ε_r: Dielectric constant of the substrate

W: Width of the radiating patch

h: Height of the substrate

As shown in Figure 3-5, fringing field lines extends physical antenna Length L on each end by a distance ΔL, which is a function of the effective dielectric constant ε_{reff} and the width to height ratio (W/h). This is given in [12] as;

$$\frac{\Delta L}{h} = 0.412 \times \frac{\left(\varepsilon_{reff} + 0.3\right) \times \left(\frac{W}{h} + 0.264\right)}{\left(\varepsilon_{reff} - 0.258\right) \times \left(\frac{W}{h} + 0.8\right)}$$

(3.2)

Effective length of the patch turned into;

$$L_{eff} = L + 2\Delta L$$

(3.3)

Effective length of the patch can also be described as [13];

$$L_{eff} = \frac{\delta}{2\sqrt{\varepsilon_{reff}}}$$

(3.4)

Width of the radiating patch can be calculated as follows for a good efficiency [14-17].

$$W = \frac{\delta}{2}\sqrt{\frac{2}{\varepsilon_r + 1}}$$

(3.5)

UHF RFID Patch Antenna Design

Step 1: Design considerations:

RFID antenna design process basically starts with defining the operating frequency, desired bandwidth, materials intended to be used by considering antenna dimensions and manufacturing cost. Other requirements can be summarized as; defining maximum gain, 3dB beam width, polarization and axial ratio.

Operating Frequency*:* Although operating frequencies of RFID systems are all in ISM bands because of local regulations they can slightly change in different regions. Operating frequencies can be summarized as follows;

- North America: 902 - 928 MHz
- Europe: 866 - 869 MHz
- South Korea: 908-914 MHz
- Japan: 950-956 MHz

In this thesis work, the North American zone will be covered with an antenna resonating frequency of 915 MHz.

$$f_r = 915\ MHz$$

Dielectric Material: For the purpose of making a low cost and easy to manufacture proof of concept antenna, air gap was used as the dielectric substrate between the radiating patch and the ground plane which has a dielectric constant of 1.0006.

$$\varepsilon_r = 1.0006$$

Plastic spacers were used between the radiating patch and the ground plane. The most common spacers are half inch nylon spacers which can be easily found in most local hardware stores, so the height of the substrate was chosen to be half inch.

$$h = 12.72\ mm$$

Step 2: Calculating width of the radiating patch:

As described in the transmission line model section, radiating patch width can be calculated from equation (3.5) as given by;

$$W = \frac{\delta}{2}\sqrt{\frac{2}{\varepsilon_r + 1}}$$

(3.6)

δ can be calculated as;

$$\delta = \frac{c}{f_r}$$

(3.7)

where, speed of light $c = 3x10^8\ m/s$

and using $f_r = 915\ MHz$; $\varepsilon_r = 1.0006$

we can calculate $\delta = 0.32m$

substituting all into equation (3.6) will give;

$W = 163.9\ mm$

Step 3: Calculating maximum height of the substrate:

According to Bancroft [13], if we increase the substrate thickness too much, undesired surface waves can be generated. Maximum substrate height can be found using the equation below;

$$h \leq \frac{0.3c}{2\pi f_r \sqrt{\varepsilon_r + 1}}$$

(3.8)

Using the Equation (3.8) leads to $h \leq 15.64\ mm$, which means our initial choice of $h = 12.72\ mm$ is acceptable.

Step 4: Calculating effective dielectric constant ($\boldsymbol{\varepsilon_{reff}}$)

Using equation (3.1):

$$\varepsilon_{reff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2} \times \left[1 + 12\frac{h}{W}\right]^{-1/2}$$

(3.9)

And substituting $\varepsilon_r = 1.0006$, $h = 12.72\ mm$, $W = 163.9\ mm$

We get, $\varepsilon_{reff} = 1.000516$

Step 5: Calculating length extension of the patch (ΔL)

Using equation (3.2)

$$\frac{\Delta L}{h} = 0.412 \times \frac{(\varepsilon_{reff} + 0.3) \times \left(\frac{W}{h} + 0.264\right)}{(\varepsilon_{reff} - 0.258) \times \left(\frac{W}{h} + 0.8\right)}$$

(3.10)

And substituting $\varepsilon_{reff} = 1.000516$ into (3.10), ΔL can be calculated as;

$$\Delta L = 8.81mm$$

Step 6: Calculating effective length of the patch (L_{eff})

By using equation (3.4)

$$L_{eff} = \frac{\delta}{2\sqrt{\varepsilon_{reff}}}$$

(3.11)

L_{eff} can be calculated as;

$L_{eff} = 163.89mm$

Step 7: Calculating physical length of the patch

By using equation (3.3)

$$L_{eff} = L + 2\Delta L$$

(3.12)

And substituting $L_{eff} = 163.89mm$ and $\Delta L = 8.81mm$

L can me calculated as;

$L = 146.25mm$

Step 8: Calculating feed point location:

After deciding patch length and width, we needed to determine the best feed point location in order to have a good impedance match between the RFID reader and the antenna. The feed point can be selected on any location along the patch width [19], it is therefore selected as; $y_f = {}^{W}\!/_{2}$.

Determining exact feed point location requires an iterative approach and Kara [20] suggested a starting point for x_f as follows;

$$x_f = \frac{L}{2\sqrt{\varepsilon_{reff}(L)}}$$

(3.13)

Where;

$$\varepsilon_{reff}(L) = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2} \times \left[1 + 12\frac{h}{L}\right]^{-1/2}$$

(3.14)

Substituting $\varepsilon_{reff}(L)$ from (3.14) to (3.13) gives us x_f which is;

$$x_f = 86.17mm$$

Step 9: Calculating ground plane size:

Infinite ground planes are widely used in antenna simulations due to the fact that finite size ground plane simulations requires more calculation time. It's stated that when the size of the ground plane is $\delta/20$ bigger on each side of the patch, then it can be assumed to be an infinite ground plane [19].

$$d = \delta/20$$

(3.14)

$L_g = L + d$ and $W_g = W + d$

This gives us a minimum ground plane size of;

$L_g = 179mm$ and $W_g = 196mm$

Step 10: Final antenna design decisions and summary:

According to calculations based on transmission line model, below are the minimum requirements for an antenna resonating at 915 MHz with a dielectric constant 1.0006 and height of 12.72mm

L: $146.25mm$

$W: 163.91mm$

$L_g: 179mm$

$W_g: 196mm$

Simulation

The software called CAD FEKO (Feko, Hampton, VA, USA) was used for simulating the antenna designs throughout this thesis work. FEKO is an electromagnetic field analysis simulator software based on Method of Moments technique.

We have chosen to simulate and manufacture a square patch antenna with the parameters given below. According to Kumar [18], the width of the patch can be taken smaller with the tradeoff of having smaller bandwidth and decreased gain.

Patch dimensions:

$L: 146.25mm$

$W: 146.25mm$

Ground plane dimensions:

$L_g: 250mm$

$W_g: 250mm$

Calculated antenna design parameters were integrated into FEKO for optimum feed point location iterations and antenna simulation.

Prototype Manufacturing of Designed Patch Antenna

By using the simulation results, a prototype low cost RFID reader antenna was manufactured from materials that can be found from local hardware stores:

Table 3-1. Bill of materials for UHF RFID Reader Antenna

1	Galvanized Steel Sheet 1’ x 2’	$8.49
2	SMA connector + 1foot coax cable	$4.00
3	Nylon spacer 1/2Inch	$1.2
	Total:	$13.69

Fractal Patch Antenna Design for Wearable RFID Readers

Koch Island fractals can be constructed by forming polygon with the Koch curves on each side. As shown in Figure 3-8, each segment of the geometry is replaced with the generator. The iteration factor is defined as the ratio of indentation width to the generator. The initiator, which is shown in Figure 3-8, is the 0^{th} iteration fractal antenna where other antennas on are named 1^{st}, 2^{nd} and 3^{rd} iterations respectively.

Fractal Geometry Calculator Software: A piece of code was written in C# for calculating the 1^{st}, 2^{nd}, 3^{rd} and 4^{th} iteration geometries with the coordinates of each individual corner. The 0^{th} iteration patch size and the iteration factor value should be given as inputs to the software and four separate text files would be generated in the folder, these text files can be imported to CAD FEKO software to generate the geometry without giving coordinates of each corner of a polygon manually. It would be almost impossible to create 4^{th} iteration geometries by manually entering the coordinates. Software code can be found in Appendix A.

Fractal Antenna Designs and Simulations: Transmission line model was used for calculating dimensions of 0^{th} iteration square patch antenna. Two different substrates with different dielectric constant values and heights were chosen for simulations. Antenna simulations were performed in CAD FEKO as stated in previous chapter.

Substrates:

- FR4 with $\varepsilon_r = 4.6$ and $h = 1.57mm$
- AD1000 with $\varepsilon_r = 10.2$ and $h = 1.49mm$

Table 3-2. Patch Antenna Design Parameters

Resonant Frequency (f_r)	(ε_r)	(h) *mm*
915 MHz	4.6	1.57
915 MHz	10.2	1.49

Table 3-3. Calculated parameters according to transmission line model

$Substrate$	W	$max\ h$	ε_{reff}	ΔL	L_{eff}	L	W_g	L_g
FR4	97.97mm	7.3mm	4.45	0.73mm	77.73mm	76.27mm	114.36mm	92.67mm
AD1000	69.27mm	4.9mm	9.7	0.64mm	52.63mm	51.35mm	85.67mm	67.74mm

Table 3-4. 0^{th} iteration square patch antenna dimensions

Substrate	Patch Length (L)	Patch Width (W)
FR4	76.27mm	76.27mm
AD1000	51.35mm	51.35mm

By using Fractal Geometry Calculator Software 1^{st}, 2^{nd}, 3^{rd} and 4^{th} iterations were generated to be imported into CAD FEKO, as shown in the figures below with Iteration Factor 0.20 and 0.25 respectively.

Also, an iterative approach was taken for finding the appropriate patch size to be able to resonate at 915 MHz at different iteration number and factor.

Wearable RFID Reader Prototype

A wearable RFID reader prototype was build throughout this thesis work with a prototype fractal patch antenna. The main purpose of this prototype was to show the concept of a wearable RFID reader with minimum capabilities. Size miniaturization of the antenna with fractal geometry was also implemented in this prototype. Main parts of the reader can be summarized as;

- UHF RFID Reader Module – Skyetek M9 (Skyetek, Denver, CO,USA)
  - Operating Frequency: 862-955 MHz
  - Supported Protocols: EPC C1G1/G2, ISO-18000 6C/6B, EM4122,EM4444, IP-X
  - Power consumption
    - 800mA at 27 dBm
    - 500mA at 21 dBm
  - Supply Voltage: 4.5V-5.5V
  - Host Communication Interface: UART, SPI, USB 2.0, I2C
- Bluetooth Module (Roving Network RN-41)(Roving Networks, Las Gatos, CA, USA)
  - Bluetooth 2.1/2.0/1.2/1.1 module
  - Bluetooth v2.0+EDR support
  - Class 1 high power amplifier
  - Power consumption
    - 30mA when connected
    - 250 uA sleep mode
  - Supply Voltage: 3.3V
  - Host Communication Interface: UART, USB
- Voltage Regulator
  - 5V Voltage regulator – LP3963
  - 3.3V Voltage regulator – LT1963
- Battery (3.7V – 2000mAh Polymer Lithium Ion)

Full list of Bill of Materials can be found in Appendix D.

Printed Circuit Board and Schematic design were done by using free version of Cadsoft EAGLE software (Cadsoft, Pines, FL, USA). Schematic of the board can be found in Appendix B and Printed Circuit Board design can be found in Appendix C.

The Fractal patch antenna used in the prototype has the following properties:

- AD1000 substrate
- Iteration factor:0.20
- Iteration number:1

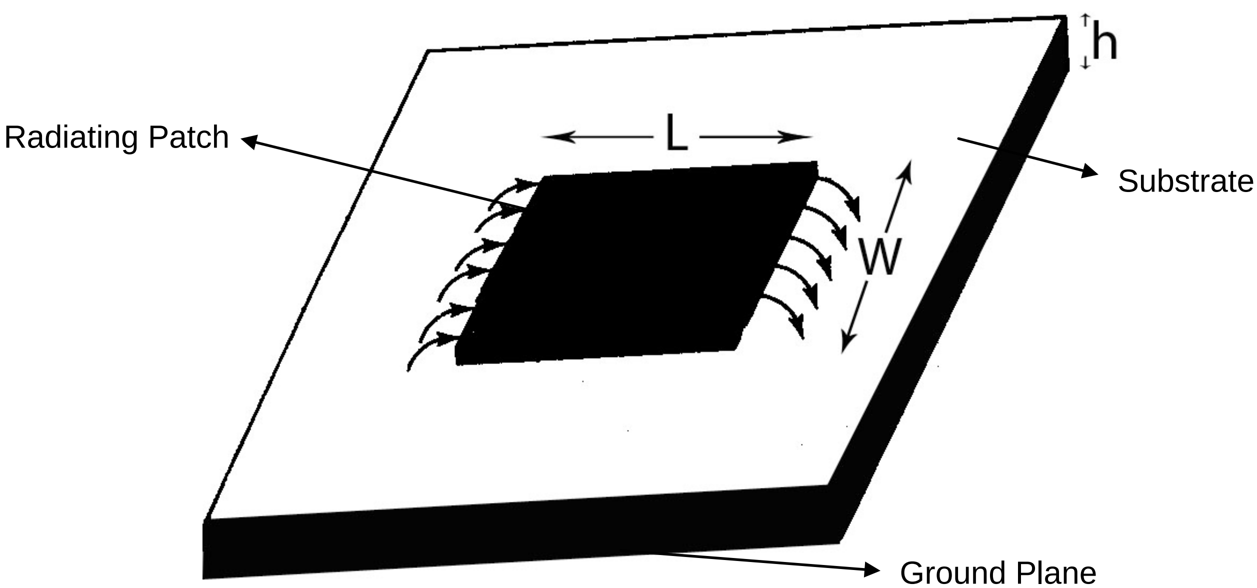


Figure 3-1. Patch antenna components

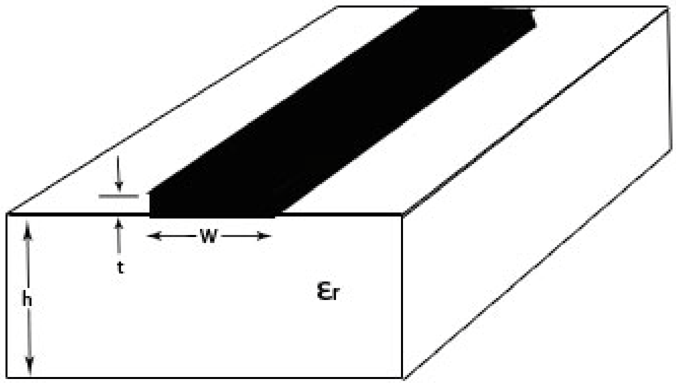


Figure 3-2. Microstrip Line

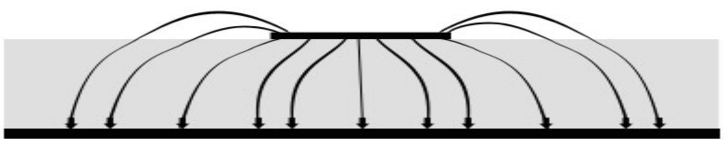


Figure 3-3. Electric Field Lines

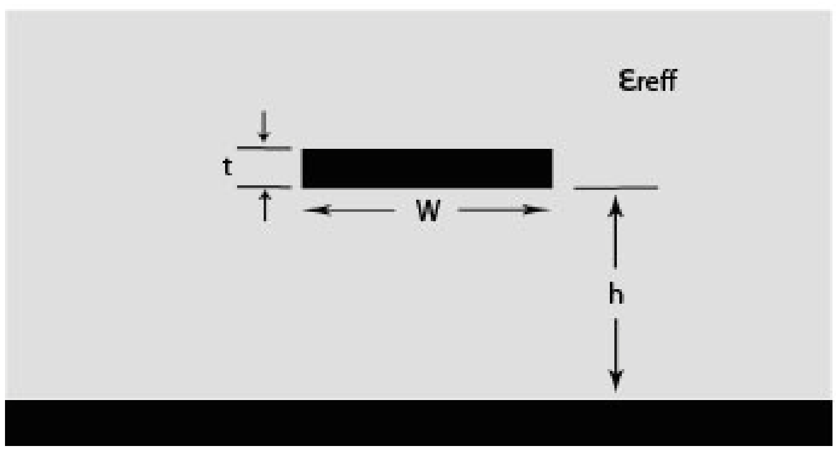


Figure 3-4. Effective Dielectric Constant (ε_{reff})

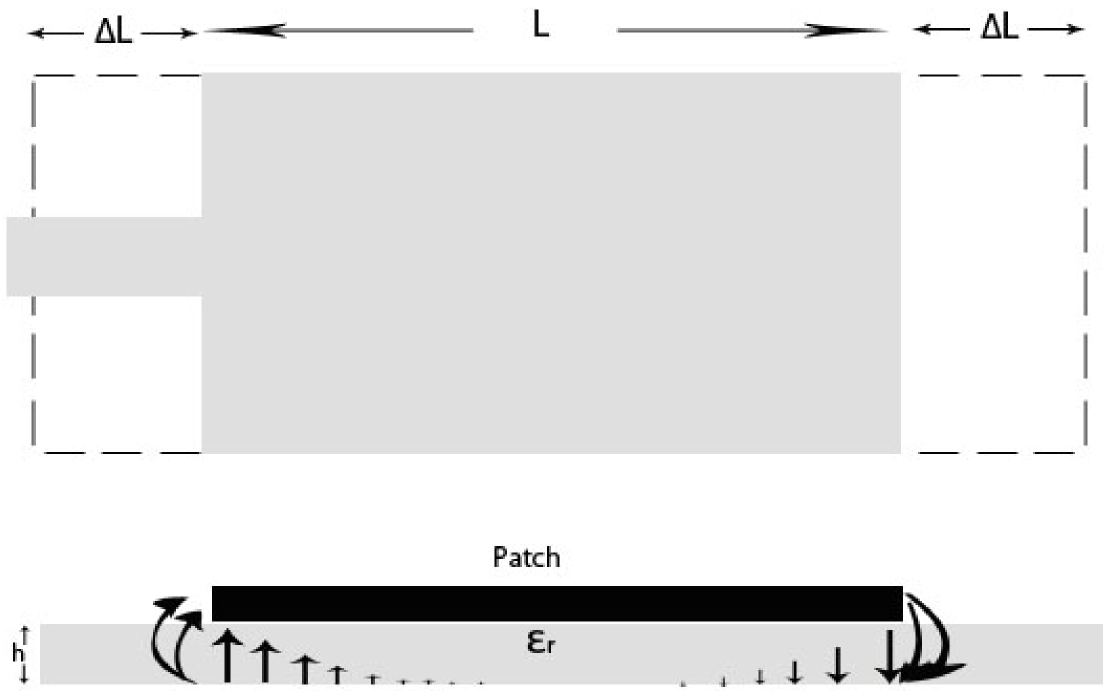


Figure 3-5. Rectangular microstrip patch antenna top and side views

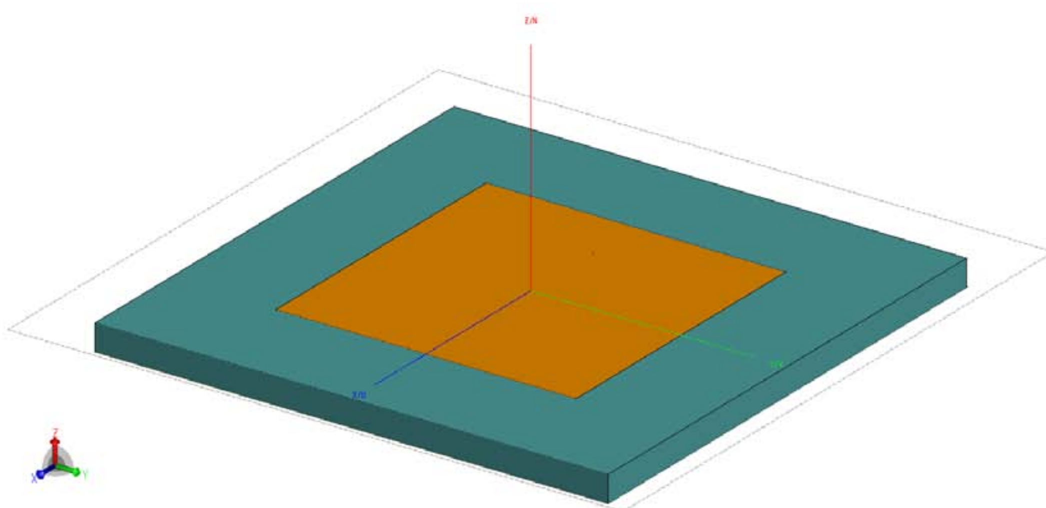


Figure 3-6. Patch antenna design in FEKO

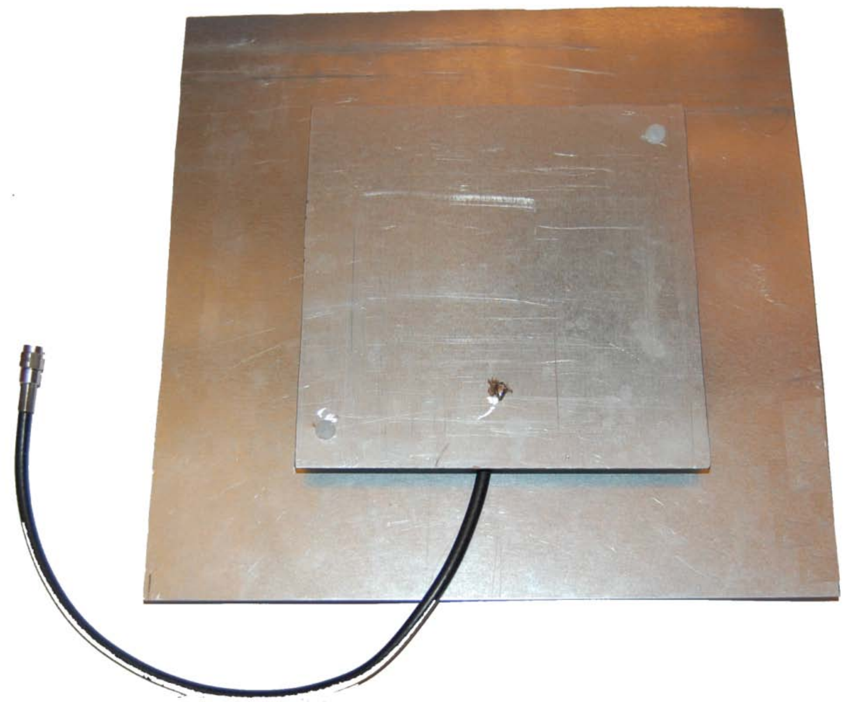


Figure 3-7. Prototype UHF Patch RFID Reader Antenna

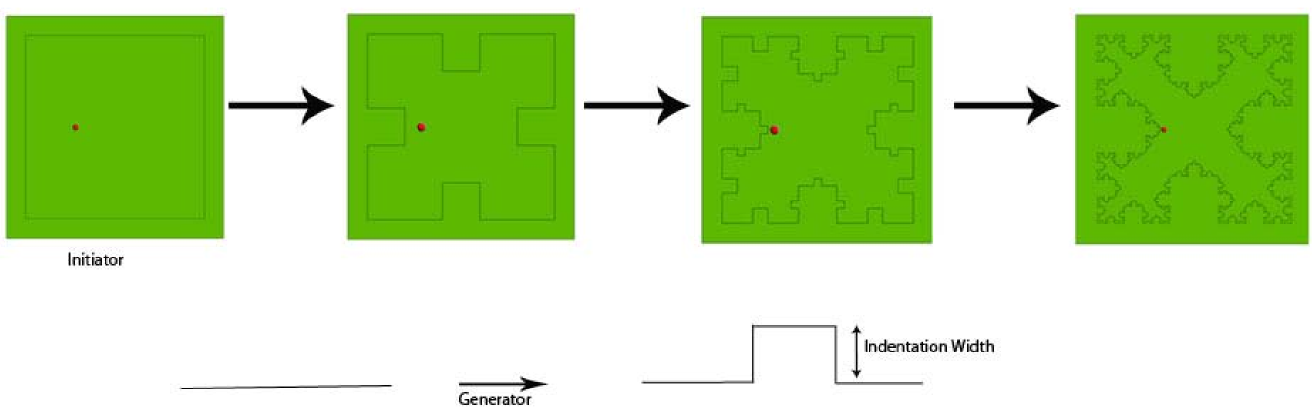


Figure 3-8. Fractal geometry iteration technique

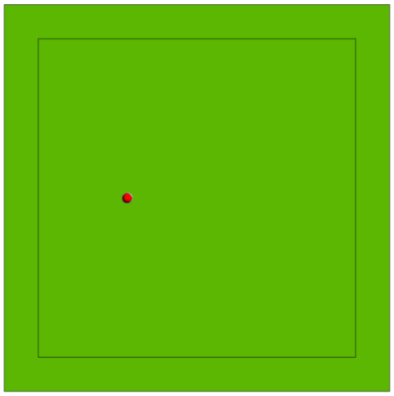


Figure 3-9. 0th iteration fractal patch antenna

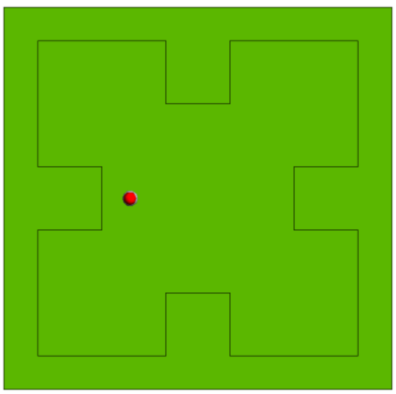


Figure 3-10. 1th iteration fractal patch antenna

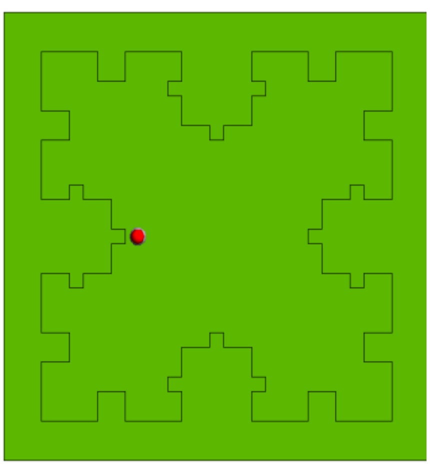


Figure 3-11. 2nd iteration fractal patch antenna

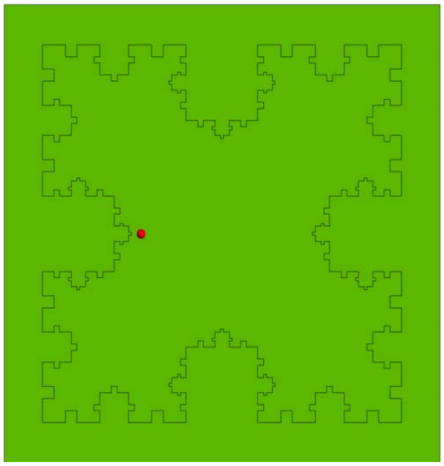


Figure 3-12. 3rd iteration fractal patch antenna

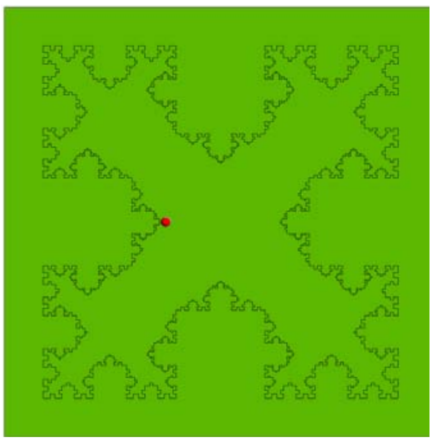


Figure 3-13. 4th iteration fractal patch antenna

CHAPTER 4
RESULTS

Square Patch Antenna Simulation and Measurement Results

Simulation:

Simulation results for square patch antenna design were given in this section.

Table 4-1 gives a summary of the antenna design parameters calculated in Chapter 3,

Table 4-2 represents simulated results of the patch antenna.

Table 4-1. Square Patch Antenna Design Parameters

(L) *mm*	(W) *mm*	(L_g) *mm*	(W_g) *mm*	(ε_r)	(h) *mm*
146.25	146.25	250	250	1.0001	12.7

Table 4-2. Square Patch Antenna Simulation Results

Resonance Frequency	*Max Gain*	*Return Loss (S11)*	*-10 dB Bandwidth*	*3dB Beam Width*	*Feed Location*(x_f)
915.19 MHz	9.05 dBi	-32.6 dB	45 MHz	$60.5°$	(-30,0)mm

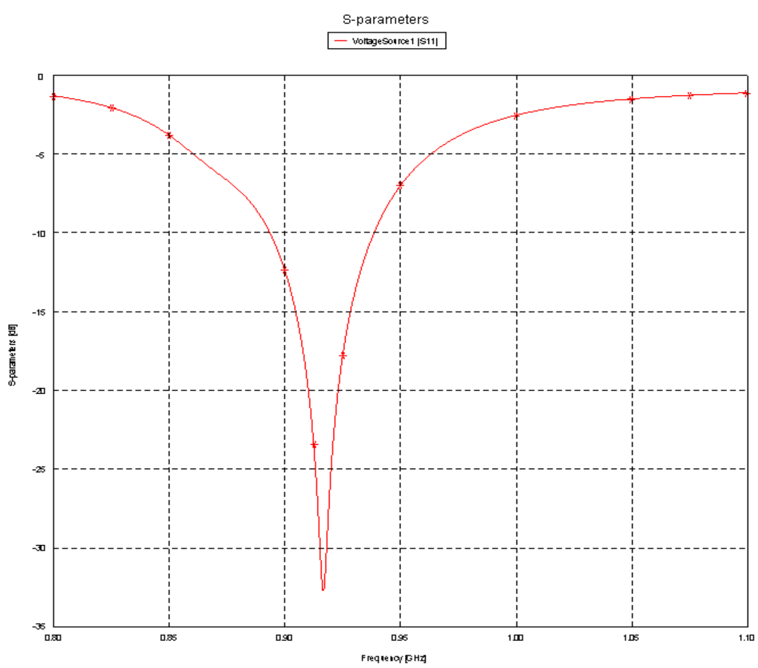


Figure 4-1. Return Loss (S11) simulation result

As shown in Figure 4-1, bandwidth for -10 dB return loss value can be calculatedfrom two resonant frequencies at each end, which are 894 MHz and 939 MHz respectively and can be calculated as 45 MHz

Radiation pattern simulations are performed by plotting elevation patterns for $\varphi = 0°$ and $\varphi = 90°$ as a function of θ.

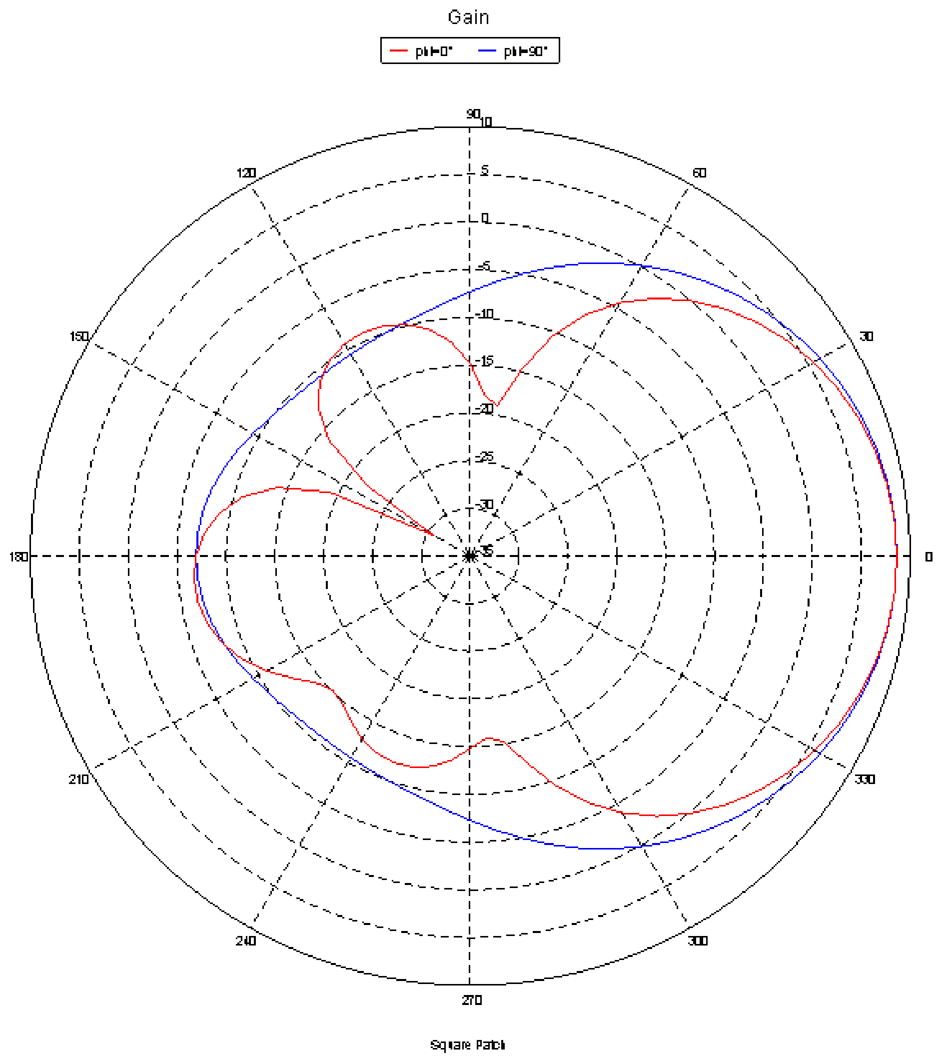


Figure 4-2. 2D radiation pattern for square patch antenna

The maximum gain of 9.05 dBi was achieved at the broadside of the antenna, the 3dB beam width can be calculated from angles on which the antenna gain decreases 3dB below of its max value, which are $29.9°$ and $329.4°$. Therefore 3dB beam width is $60.5°$

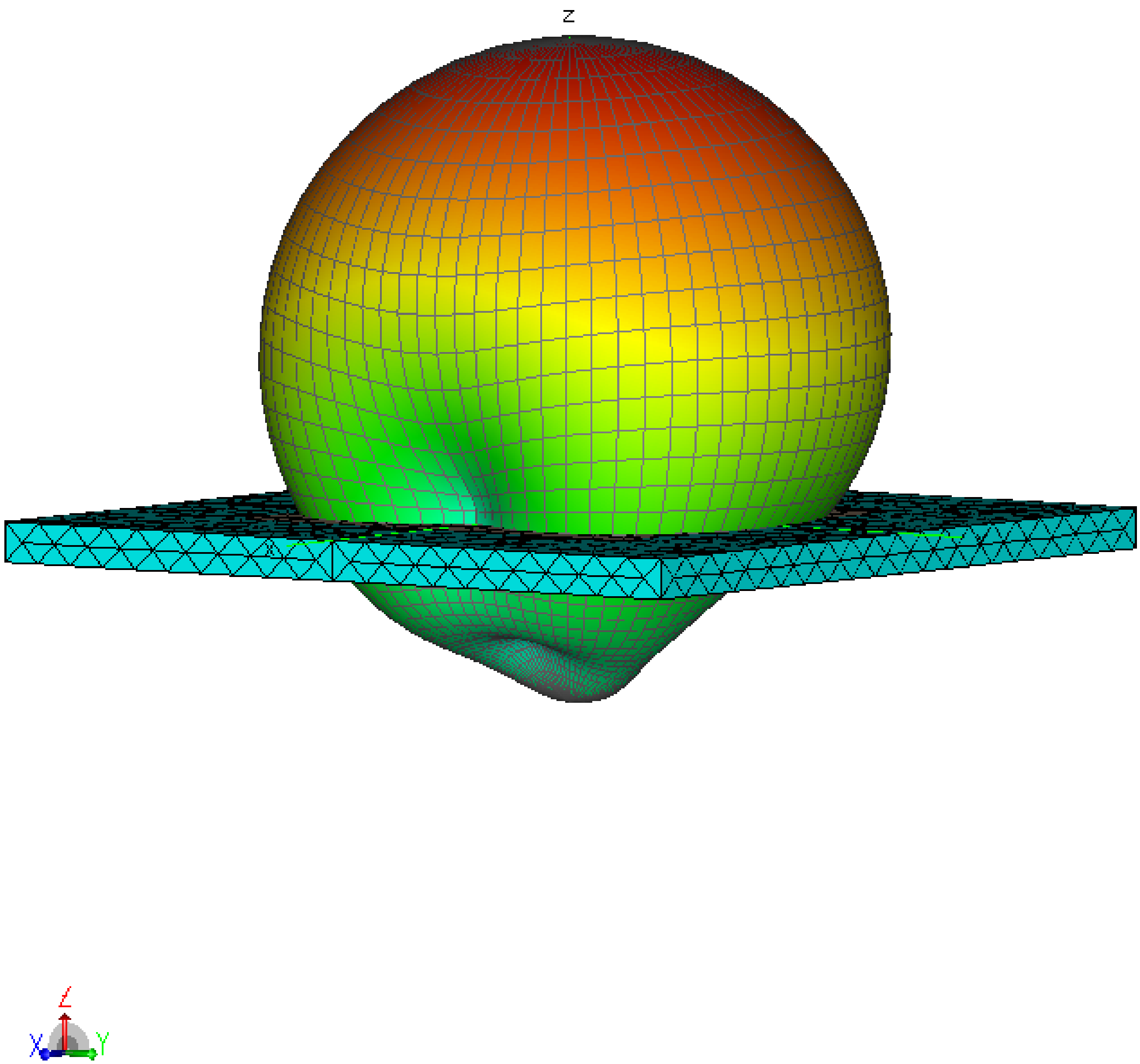
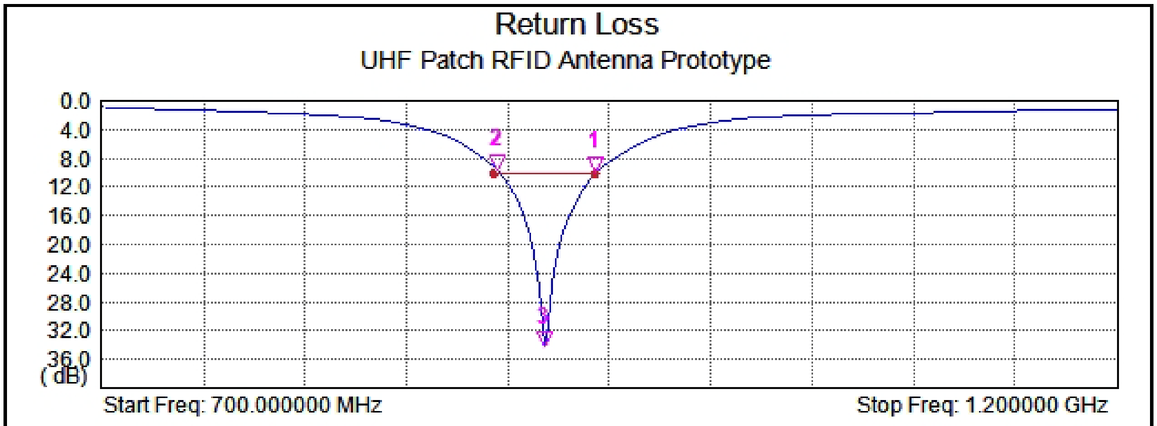


Figure 4-3. 3D radiation pattern for square patch antenna

Measurement:

Measurements are performed by using Anritsu (Anritsu, Richardson, TX, USA), MS2024A Vector Network Analyzer.



Mkr	Ref	Delta	Ref Freq	Ref Amp	Delta Freq	Delta Amp
1	☐	☐	943.6364 MHz	9.9342 dB	- -	- -
2	☐	☐	894.5455 MHz	9.6230 dB	- -	- -
3	☐	☐	918.1818 MHz	34.2837 dB	- -	- -
4	☐	☐	- -	- -	- -	- -
5	☐	☐	- -	- -	- -	- -
6	☐	☐	- -	- -	- -	- -

Measurement Parameters

Calibration Status	On	Ref. Plane Length	0
Cal Mode	Standarad		
Data Points	551	Serial Number	926068
Output Power	High	Base Ver.	V2.01
Start Frequency	700.000000 MHz	App Ver.	V1.76
Stop Frequency	1.200000 GHz	Date	1/22/2010 4:33:38 AM
Smoothing %	0	Device Name	

Figure 4-4. Measured return loss for the UHF Patch RFID Antenna prototype

Table 4-3. Comparison between Simulated and Measured results

	Simulated	*Measured*
Resonance Frequency	915.19 MHz	918.18 MHz
Return Loss (S11)	-32.6 dB	-34.28 dB
-10 dB bandwidth	45 MHz	49 MHz

With a commercially available RFID reader at 30dBm output power, we had 11m read range with this prototype antenna.

Fractal Patch Antenna Simulation Results

Table 4-4. Fractal Patch Antenna Simulation Results – FR4 substrate – IF:0.20

Antenna ID	*iteration #*	*iteration factor*	*Center frequency (MHz)*	*Max Gain (dBi)*	*Return Loss (RL) (dB)*	*BW(RL> -9.5dB)(MHz)*	*εr*	*h(mm)*	*L=W*
1	0	0	915	4.71	-45.00	12.00	4.60	1.57	76.27
3	1	0.20	762	1.52	-27	8.00	4.60	1.57	76.27
4	2	0.20	726	-3.7	-49	8.00	4.60	1.57	76.27
5	3	0.20	721	-	-31.2	6.00	4.60	1.57	76.27

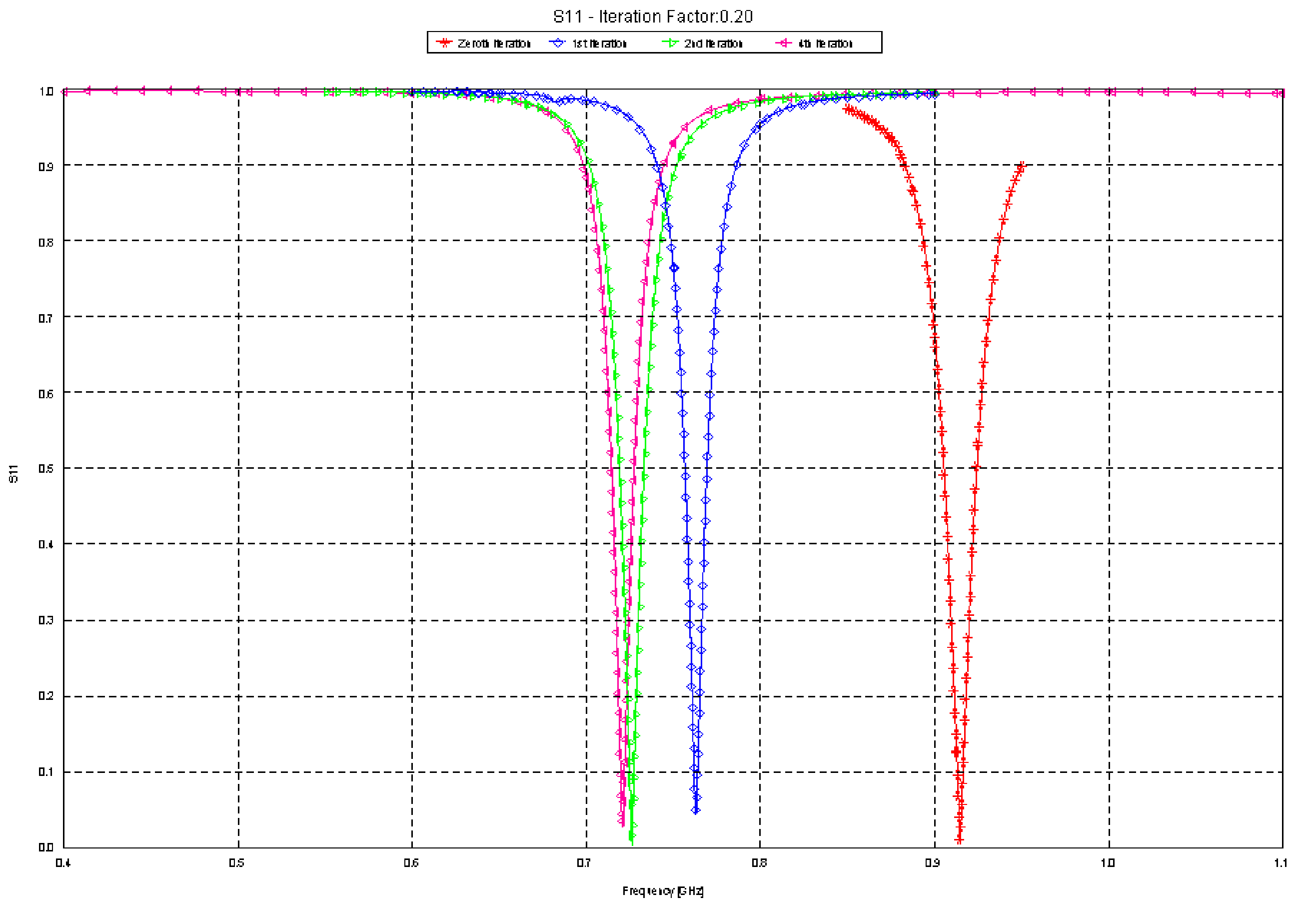


Figure 4-5. Simulated return loss of 0th, 1st, 2nd, 3rd and 4th iteration fractal antenna FR4 substrate - IF:0.20

Table 4-5. Fractal Patch Antenna Simulation Results – FR4 substrate – IF:0.25

Antenna ID	*iteration #*	*iteration factor*	*Center frequency (MHz)*	*Max Gain (dBi)*	*Return Loss (RL) (dB)*	*BW(RL> -9.5dB)(MHz)*	*εr*	*h(mm)*	*L=W*
1	0	0	915	4.71	-45.00	12.00	4.60	1.57	76.27
6	1	0.25	682	2.85	-9.4	-	4.60	1.57	76.27
7	2	0.25	635	-9.3	-10.5	-	4.60	1.57	76.27
8	3	0.25	620	-	-7.8	-	4.60	1.57	76.27
9	4	0.25	568	-	-13	6.00	4.60	1.57	76.27

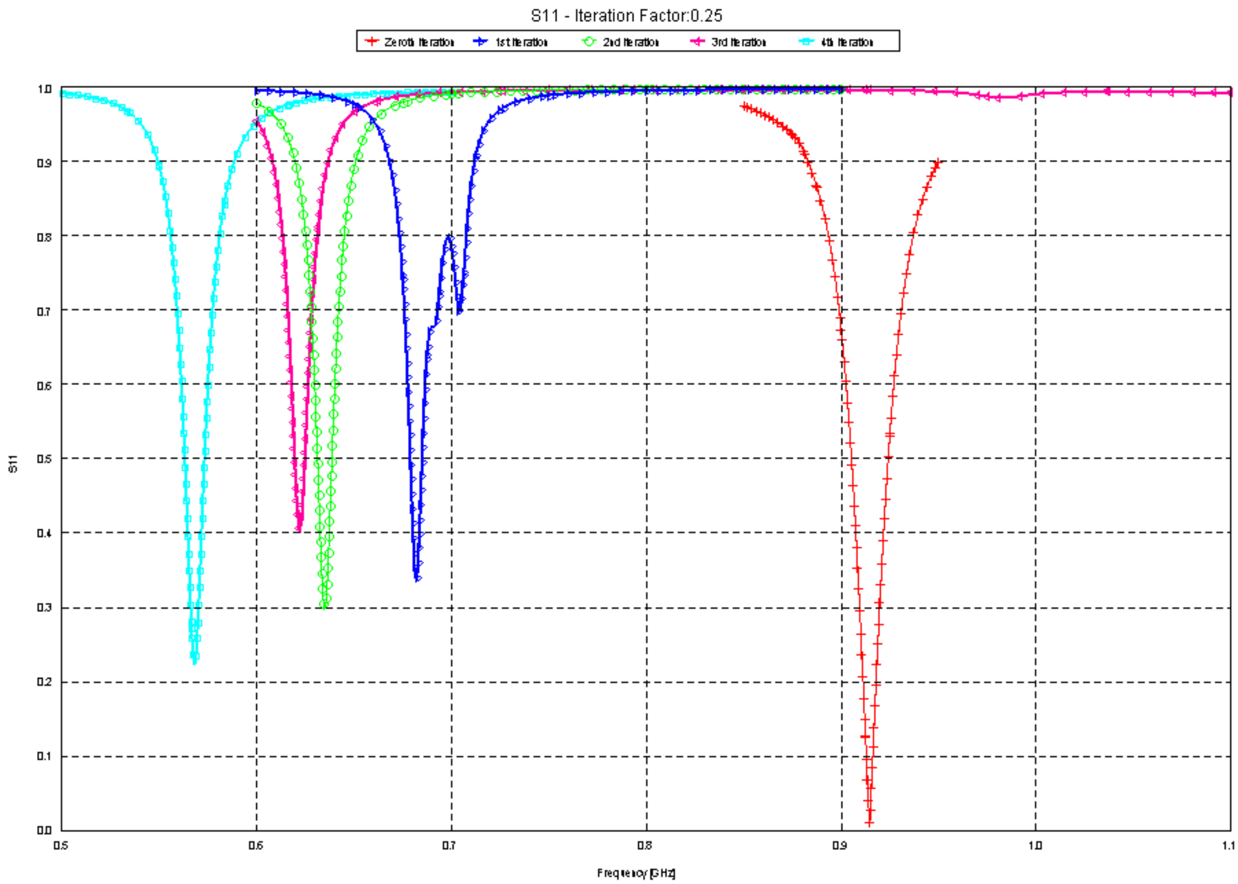


Figure 4-6. Simulated return loss of 0th, 1st, 2nd, 3rd and 4th iteration fractal antenna FR4 substrate - IF:0.25

Table 4-6. Fractal Patch Antenna Simulation Results – AD1000 substrate – IF:0.20

Antenna ID	*iteration #*	*iteration factor*	*Center frequency (MHz)*	*Max Gain (dBi)*	*Return Loss (RL) (dB)*	*BW(RL> -9.5dB)(MHz)*	*εr*	*h(mm)*	*L=W*
10	0	0	914	2.2	-37.6	10	10.20	1.49	51.35
11	1	0.20	718	-7.7	-24	9.00	10.20	1.49	51.35
12	2	0.20	695	-	-20	10	10.20	1.49	51.35
13	3	0.20	687	-	-17	10.00	10.20	1.49	51.35

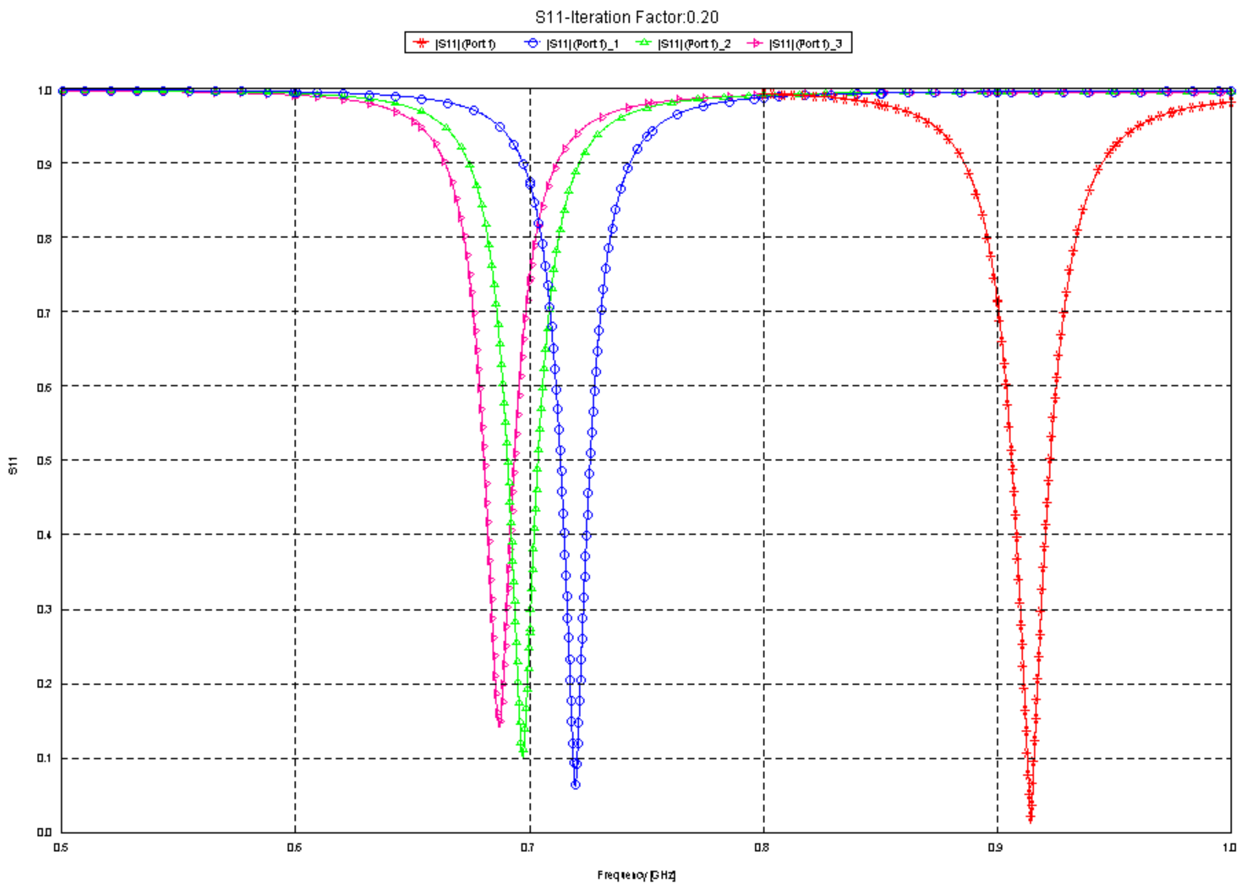


Figure 4-7. Simulated return loss of 0th, 1st, 2nd, 3rd and 4th iteration fractal antenna AD1000 substrate - IF:0.20

Table 4-7. Fractal Patch Antenna Simulation Results – AD1000 substrate – IF:0.25

Antenna ID	*iteration #*	*iteration factor*	*Center frequency (MHz)*	*Max Gain (dBi)*	*Return Loss (RL) (dB)*	*BW(RL> -9.5dB)(MHz)*	*εr*	*h(mm)*	*L=W*
10	0	0	914	2.2	-37.6	10	10.20	1.49	51.35
14	1	0.25	618	-21	-23	8.00	10.20	1.49	51.50
15	2	0.25	580	-17	-15	-	10.2	1.49	51.35
16	3	0.25	566	-	-11.50	-	10.20	1.49	51.35
17	4	0.25	632		-6	-	10.20	1.49	51.50

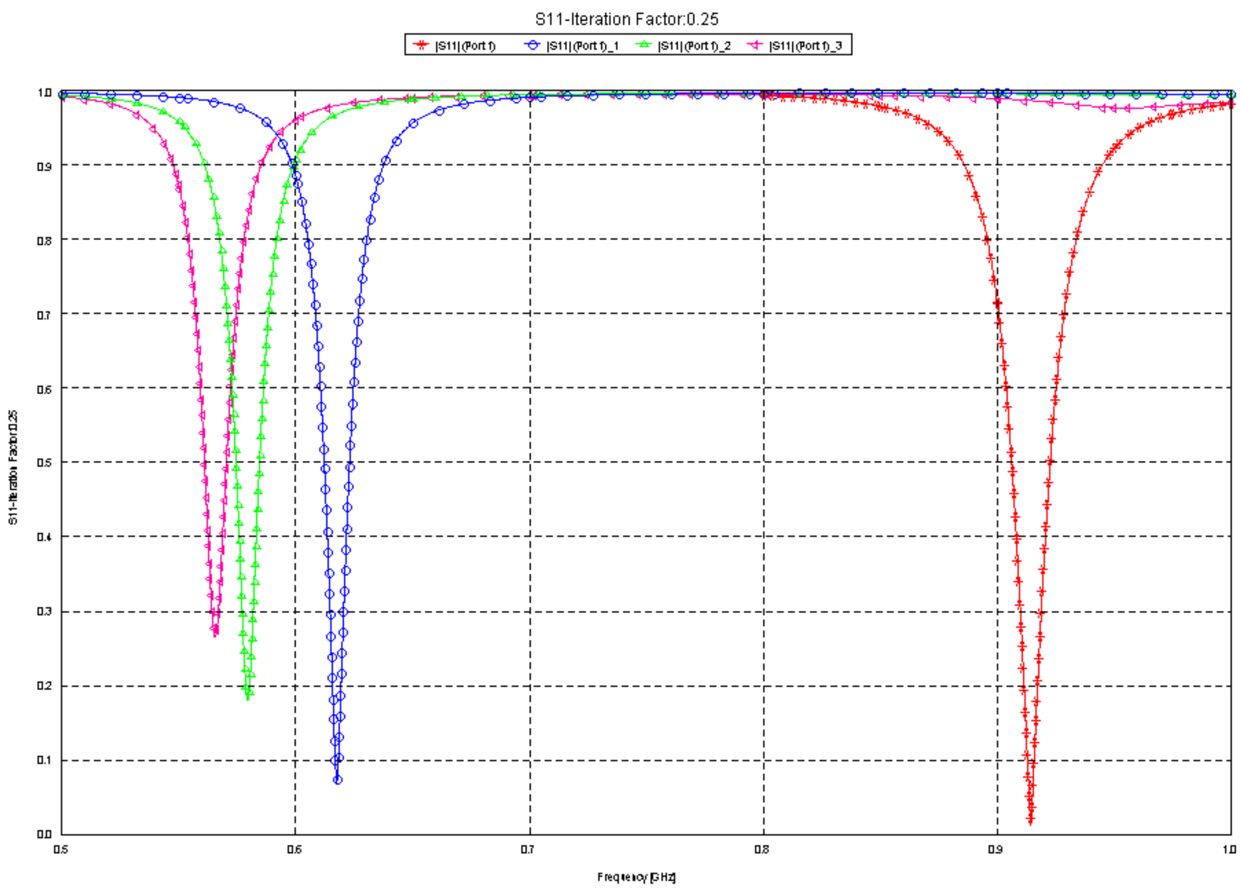


Figure 4-8. Simulated return loss of 0th, 1st, 2nd, 3rd and 4th iteration fractal antenna AD1000 substrate - IF:0.25

Size Miniaturization (FR4 Substrate)

Table 4-8. Fractal Patch Antenna Simulation Results – FR4 substrate – IF:0.20

Antenna ID	*iteration #*	*iteration factor*	*Center frequency (MHz)*	*Max Gain (dBi)*	*Return Loss (RL) (dB)*	*BW(RL> -9.5dB)(MHz)*	*εr*	*h(mm)*	*L=W*
1	0	0	915	4.71	-45.00	12.00	4.60	1.57	76.27
18	1	0.20	915	1.87	-19	9.00	4.60	1.57	63.00
19	2	0.20	911	3.4	-42	10.00	4.60	1.57	60.60
20	3	0.20	913	3.14	-34.9	10.00	4.60	1.57	60.00

Table 4-9. Fractal Patch Antenna Simulation Results – FR4 substrate – IF:0.25

Antenna ID	*iteration #*	*iteration factor*	*Center frequency (MHz)*	*Max Gain (dBi)*	*Return Loss (RL) (dB)*	*BW(RL> -9.5dB)(MHz)*	*εr*	*h(mm)*	*L=W*
1	0	0	915	4.71	-45.00	12.00	4.60	1.57	76.27
21	1	0.25	916	4.7	-29.7	10.00	4.60	1.57	57.80
22	2	0.25	921	3.48	-20	9.00	4.60	1.57	51.00
23	3	0.25	924	2.7	-16.8	8.00	4.60	1.57	50.00

Table 4-10. Fractal Patch Antenna Dimensions - FR4 (all sizes are in mm)

	L x W IF=0.2	*area(mm2)*	*size*	*L x W IF=0.25*	*area(mm2)*	*size*
Square patch	76x76	5776	100.00	76x76	5776	100.00
Fractal 1st iteration	63x63	3969	68.72	57.8x57.8	3341	57.84
Fractal 2nd iteration	60.6x60.6	3672	63.58	51x51	2601	45.03
Fractal 3rd iteration	60x60	3600	62.33	50x50	2500	43.28

Size Miniaturization (AD1000 Substrate)

Table 4-11. Fractal Patch Antenna Simulation Results – AD1000 substrate – IF:0.20

Antenna ID	*iteration #*	*iteration factor*	*Center frequency (MHz)*	*Max Gain (dBi)*	*Return Loss (RL) (dB)*	*BW(RL> -9.5dB)(MHz)*	*εr*	*h(mm)*	*L=W*
10	0	0	914	2.2	-37.6	10	10.20	1.49	51.35
24	1	0.20	915	0.84	-23	11.00	10.20	1.49	42.50
25	2	0.20	923	-1.4	-24.6	-	10.2	1.49	40.5
26	3	0.20	937	-0.8	-20.20	9.00	10.20	1.49	39.90

Table 4-12. Fractal Patch Antenna Simulation Results – AD1000 substrate – IF:0.25

Antenna ID	*iteration #*	*iteration factor*	*Center frequency (MHz)*	*Max Gain (dBi)*	*Return Loss (RL) (dB)*	*BW(RL> -9.5dB)(MHz)*	*εr*	*h(mm)*	*L=W*
10	0	0	914	2.2	-37.6	10	10.20	1.49	51.35
27	1	0.25	916	0.86	-25.7	10	10.2	1.49	37.5
28	2	0.25	915	-2.2	-11.6	-	10.2	1.49	34
29	3	0.25	921	-4.9	-10	-	10.2	1.49	33

Table 4-13. Fractal Patch Antenna Dimensions – AD1000 (all sizes are in mm)

	L x W IF=0.2	*area(mm2)*	*size*	*L x W IF=0.25*	*area(mm2)*	*size*
Square patch	51.3X51.3	2632	100	51.5x51.5	2652	100.00
Fractal 1st iteration	42.5*42.5	1806	69	37.5x37.5	1406	53.02
Fractal 2nd iteration	40.5x40.5	1640	62	34x34	1156	43.59
Fractal 3rd iteration	39.9x39.9	1592	60	33x33	1089	41.06

Fractal Patch Antenna for Wearable RFID Reader Prototype

Simulation:

Simulation results for fractal patch antenna, used in Wearable RFID Reader prototype, were given in this section.

Antenna with ID number of 24, as shown in Table 4-11, was used in the Wearable RFID Reader prototype. Design parameters are given in Table 4-14.

Table 4-14. Antenna ID:24 Design Parameters

(L) mm	*(W) mm*	*(ε_r)*	*(h) mm*	*Iteration #*	*Iteration Factor*
42.50	42.50	10.2	1.49	1	0.20

Table 4-15 represents simulated results of the fractal antenna used in prototype

Table 4-15. Fractal Patch Antenna (ID:24) Simulation Results

Resonance Frequency	*Max Gain*	*Return Loss (S11)*	*-10 dB Bandwidth*	*Feed Location(x_f)*
915 MHz	0.84	-23 dB	11 MHz	(-7.6,0)mm

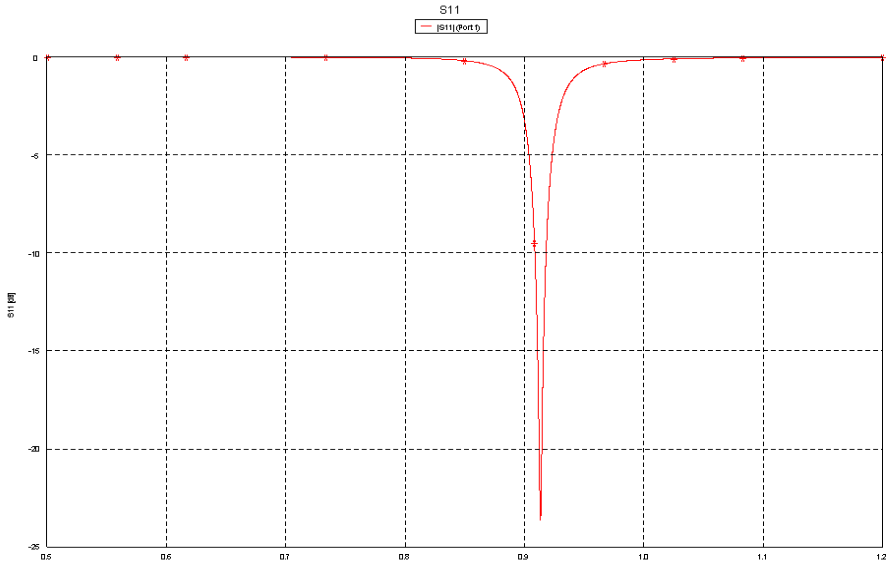


Figure 4-9. Return loss (S11) simulation result

Radiation pattern simulations are performed by plotting elevation patterns for $\varphi = 0°$ and $\varphi = 90°$ as a function of θ.

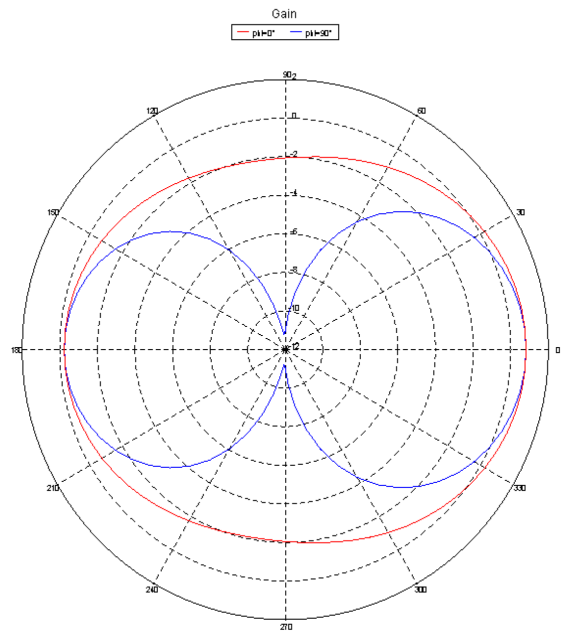


Figure 4-10. 2D radiation pattern for fractal patch antenna

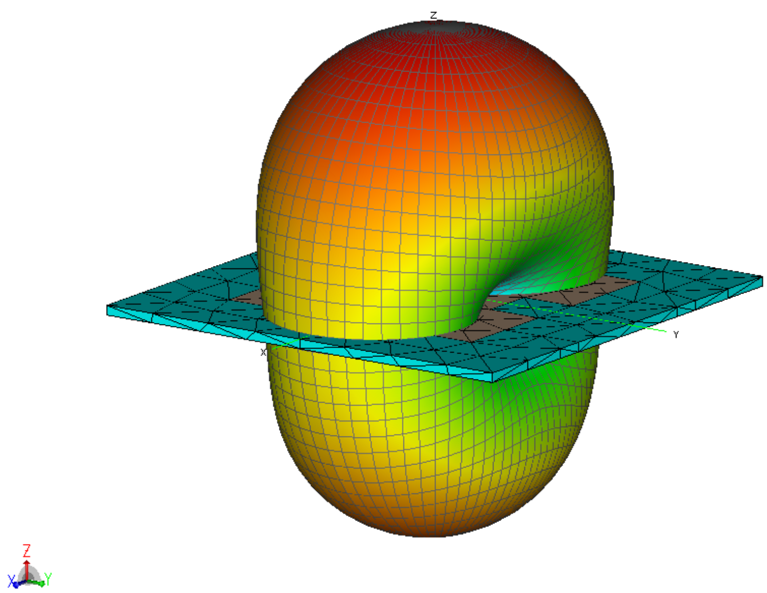
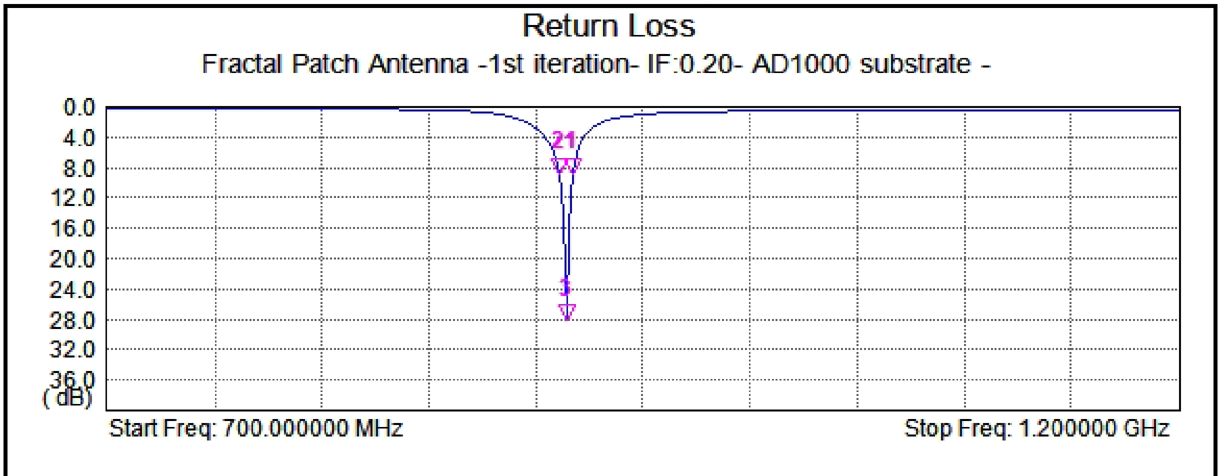


Figure 4-11. 3D radiation pattern for fractal patch antenna

Measurement:



Mkr	Ref	Delta	Ref Freq	Ref Amp	Delta Freq	Delta Amp
1	☐	☐	917.2727 MHz	8.8575 dB	--	--
2	☐	☐	910.9091 MHz	8.9477 dB	--	--
3	☐	☐	914.5455 MHz	28.2149 dB	--	--
4	☐	☐	--	--	--	--
5	☐	☐	--	--	--	--
6	☐	☐	--	--	--	--

Measurement Parameters

Calibration Status	On	Ref. Plane Length	0
Cal Mode	Standarad		
Data Points	551	Serial Number	926068
Output Power	High	Base Ver.	V2.01
Start Frequency	700.000000 MHz	App Ver.	V1.76
Stop Frequency	1.200000 GHz	Date	1/25/2010 7:34:50 PM
Smoothing %	0	Device Name	

Figure 4-12. Measured return loss for the fractal patch antenna used in Wearable RFID Reader prototype

Table 4-16. Comparison between Simulated and Measured results

	Simulated	*Measured*
Resonance Frequency	915.19 MHz	917.27 MHz
Return Loss (S11)	-23 dB	-28 dB
-10 dB bandwidth	11 MHz	7 MHz

CHAPTER 5
DISCUSSION

Square Patch Antenna

A square patch antenna with air substrate made of galvanized steel metal sheet was designed and manufactured because of its simplicity and ease of comparison between simulation results and measurement results.

Antenna design process relies on the simulation results due to its flexibility to change parameters and evaluate antenna efficiently. To do so, we decided to manufacture an antenna which will be easy to manufacture and will give us enough information to validate our simulated results.

Simulation

Simulations performed in CAD FEKO described in the previous chapter shows that our antenna perfectly resonates at the desired frequency which is 915 MHz. Although it’s easy to manufacture pin feed patch antennas, the best feed point location, which impacts antenna impedance for proper matching, was hard to find by using an iterative approach. Multiple simulations had to be run for each antenna design to determine the best location.

Antenna gain of 9.05 dBi is generally adequate for most of the RFID applications. Due to the allowed output power regulations in different countries, RFID readers should be configured to output at most 0.5W in US with this simulated antenna. Although, these values are half of the allowed output powers in US, readers cannot exceed more due to the fact that, with this high gain antenna, the allowed Equivalent Isotropic Radiated Power (EIRP) of 4W would be exceeded.

Bandwidth of 45MHz is enough for covering US frequencies of 902 MHz-928 MHz with this antenna. This antenna has to be adjusted to allow use in different regions. For example to be able to use this antenna in EU, the resonant frequency should be lowered down to 868 MHz, which can be done by enlarging the patch length.

This linearly polarized patch antenna shows good directivity for RFID applications in which zone differentiation would be crucial. A 3dB beam width of $60.5°$ should be taken into consideration when installing an RFID system for better performance.

As can be seen from Figures 4-2 and 4-3, the back lobe of the antenna is fairly small. This is acceptable for RFID applications where it is likely to have another antenna attached to the same reader.

Measurements and Comparison with Simulation

Results presented in Figure 4-4 show a good match between simulation and measurement. Although imperfection of hand manufacturing the prototype antenna might have caused the 3 MHz shift in resonance frequency, this should not affect antenna performance.

Measured return loss and -10dB return loss bandwidth values are also close enough with simulations. Measured 4 MHz wider bandwidth gives more flexibility to the prototype antenna. Read range measurement at 30dBm shows great performance of this antenna and this antenna can be used where linearly polarized directional antennas are needed.

Up to this point our measured results showed good agreement with simulated results, so fractal antenna measurements are decided to be based on simulations.

Fractal Patch Antenna

The antenna is one of the most crucial components of an RFID system, especially in battery powered systems, due to the fact that an inefficient antenna requires more output power from the reader which will decrease the battery life. Although the prototype antenna developed in a previous chapter performs well enough to be used in most RFID applications, it’s not realistic to have an antenna with a 146mm radiating patch and 250mm ground plane attached to a human arm for wearable RFID applications. Therefore, a compact fractal antenna was developed for wearable RFID applications.

Since fractal geometries get smaller when iteration number increases, it’s very difficult to obtain good results with bench made fractal antennas, so we based our fractal antenna design on simulation results.

Two different substrates, FR4 and AD1000 with different dielectric constant values and very similar heights were used for fractal designs. The higher dielectric constant substrate AD1000 provided smaller patch sizes as expected.

Effect of Iteration Factor and Iteration Number on Resonant Frequency

Considering Figures 4-5 to 4-8 individually, it’s seen that as iteration number increases, resonant frequency of the antenna becomes lower than that of the 0^{th} iteration. After the 1^{st} iteration, the resonant frequency change is not significant. Comparing figures within the same substrate, it’s observed that as iteration factor changes from 0.20 to 0.25 resonant frequency dramatically decreases. It’s concluded that iteration factor has more effect on resonant frequency than iteration number while both substrates behaved similarly.

Antenna Size Miniaturization with Fractals

It's shown that the square patch dimension reduced 37.67% at IF:0.20 and 56.72% at IF:0.25 for the FR4 substrate. Also for the AD1000 substrate, similar results are observed as follows; 40% at IF:0.20 and 58.94% at IF:0.25. Although similar behaviors are observed between different substrates, it's shown that higher iteration factor results in better antenna size miniaturization.

Fractal Patch Antenna for Wearable RFID Reader Prototype

Prototype fractal patch antenna decision was based on measurement results of manufactured antennas. Bench made manufacturing of small size fractals was resulted with poor measurement results. Potential causes of this problem would be summarized as follows:

- Press and peel technique used for manufacturing fractals is not as precise as machines
- Smaller patch size with higher iteration number, factor requires more precision.
- Probe feed location effects on impedance matching

Although most of the antennas showed poor results, the fractal patch antenna (Antenna ID:24) with the iteration factor of 0.20 generated from 1st iteration of a square patch antenna performed well enough for integrating into Wearable RFID Reader prototype. Results presented in Table 4-16 show a close match between the measurement and the simulation.

CHAPTER 6
CONCLUSION

The aim of this research is to design a compact RFID antenna with a prototype "Wearable RFID Reader". This objective was achieved by designing, simulating and measuring microstrip patch antennas as well as fractal patch antennas for size miniaturization. A prototype Wearable RFID Reader was also presented with an integrated fractal patch antenna.

Analysis of the microstrip patch antennas was performed by using transmission line model and simulation results were validated with the measurement results. Although designed patch antenna performed well enough for general RFID applications, it was still not small enough for a Wearable RFID Reader application. Further research on fractal patch antennas resulted with a significant size reduction. Maximum size reduction of 58.94% was achieved with a fractal patch antenna at 4^{th} iteration and Iteration Factor of 0.25. The prototype Wearable RFID Reader was manufactured with an integrated fractal patch antenna. Fractal patch antenna used in the prototype was generated from the 1^{st} iteration of a square patch antenna resonating at 915MHz with iteration factor of 0.20.

Results of this research can be used in developing complex Wearable RFID Readers with integrated compact antennas. Future work can be summarized as; manufacturing and testing fractal antennas by using precise manufacturing techniques and also designing Wearable RFID Readers with integrated microprocessors and sensors for standalone applications. To sum up, this thesis work proves that antenna miniaturization can be achieved by using fractal patch antennas for Wearable RFID Readers.

APPENDIX A
FRACTAL GEOMETRY CALCULATOR CODE

```
namespace Fractal Calculator
{
    public class SquareCoordinates
    {
        public double patch_l = 50;
        public double patch_w = 50;
        public double IterationFactor = 0.25;

        public double a0;
        public double a11, a13;
        public double a12;
        public double b;

        public int t = 0;
        public int size;


        double[] CoordinateX = new double[5];
        double[] CoordinateY = new double[5];

        double[] iterCoordinateX = new double[5000];
        double[] iterCoordinateY = new double[5000];


        double[] TobeiterCoordinateX = new double[1000];
        double[] TobeiterCoordinateY = new double[1000];


        public SquareCoordinates()
        {
            CoordinateX[0] = patch_l / 2;
            CoordinateY[0] = patch_w / 2;
            CoordinateX[1] = -patch_l / 2;
            CoordinateY[1] = patch_w / 2;
            CoordinateX[2] = -patch_l / 2;
            CoordinateY[2] = -patch_w / 2;
            CoordinateX[3] = patch_l / 2;
            CoordinateY[3] = -patch_w / 2;
        }

        public void FirstIteration()
        {
            Array.Copy(CoordinateX, TobeiterCoordinateX, 4);
            Array.Copy(CoordinateY, TobeiterCoordinateY, 4);

            a0 = (Math.Abs((TobeiterCoordinateX[1] -
TobeiterCoordinateX[0])));
            a12 = a0 * IterationFactor;
            b = a12;
            a13 = (a0 - a12) / 2;
```

```
            a11 = a13;
            t = 0;//1

            size = 4;
        }

        public void SecondIteration()
        {
            Array.Copy(iterCoordinateX, TobeiterCoordinateX, 20);
            Array.Copy(iterCoordinateY, TobeiterCoordinateY, 20);

            a0 = (Math.Abs((TobeiterCoordinateX[1] -
TobeiterCoordinateX[0])));
            a12 = a0 * IterationFactor;
            b = a12;
            a13 = (a0 - a12) / 2;
            a11 = a13;
            t = 0;//1

            size = 20;
        }

        public void ThirdIteration()
        {
            Array.Copy(iterCoordinateX, TobeiterCoordinateX, 100);
            Array.Copy(iterCoordinateY, TobeiterCoordinateY, 100);

            a0 = (Math.Abs((TobeiterCoordinateX[1] -
TobeiterCoordinateX[0])));
            a12 = a0 * IterationFactor;
            b = a12;
            a13 = (a0 - a12) / 2;
            a11 = a13;
            t = 0;//1

            size = 100;
        }

        public void ForthIteration()
        {
            Array.Copy(iterCoordinateX, TobeiterCoordinateX, 500);
            Array.Copy(iterCoordinateY, TobeiterCoordinateY, 500);

            a0 = (Math.Abs((TobeiterCoordinateX[1] -
TobeiterCoordinateX[0])));
            a12 = a0 * IterationFactor;
            b = a12;
            a13 = (a0 - a12) / 2;
            a11 = a13;
            t = 0;//1

            size = 500;
        }
```

```
        public void Iteration()
        {

            for (int i = 0; i < size; i++)
            {
                iterCoordinateX[t] = TobeiterCoordinateX[i];
                iterCoordinateY[t] = TobeiterCoordinateY[i];


                if ((Math.Abs((TobeiterCoordinateX[i + 1] -
TobeiterCoordinateX[i]))) > 0)
                {
                    a0 = (Math.Abs((TobeiterCoordinateX[i + 1] -
TobeiterCoordinateX[i])));

                }
                else
                {
                    a0 = (Math.Abs((TobeiterCoordinateY[i + 1] -
TobeiterCoordinateY[i])));
                }

                a12 = a0 * IterationFactor;
                b = a12;
                a13 = (a0 - a12) / 2;
                a11 = a13;



                if (i == (size - 1))
                {
                    if ((Math.Abs((TobeiterCoordinateX[0] -
TobeiterCoordinateX[i]))) > 0)
                    {
                        a0 = (Math.Abs((TobeiterCoordinateX[0] -
TobeiterCoordinateX[i])));

                    }
                    else
                    {
                        a0 = (Math.Abs((TobeiterCoordinateY[0] -
TobeiterCoordinateY[i])));
                    }

                    a12 = a0 * IterationFactor;
                    b = a12;
                    a13 = (a0 - a12) / 2;
                    a11 = a13;




                    t++;//2
                    iterCoordinateX[t] = iterCoordinateX[t - 1];
                    iterCoordinateY[t] = iterCoordinateY[t - 1] + a11;
                    t++;//3
                    iterCoordinateX[t] = iterCoordinateX[t - 1] - b;
```

```
                    iterCoordinateY[t] = iterCoordinateY[t - 1];
                    t++;//4
                    iterCoordinateX[t] = iterCoordinateX[t - 1];
                    iterCoordinateY[t] = iterCoordinateY[t - 1] + a12;
                    t++;//5
                    iterCoordinateX[t] = iterCoordinateX[t - 1] + b;
                    iterCoordinateY[t] = iterCoordinateY[t - 1];
                    //t++;//6
                    //iterCoordinateX[t] = iterCoordinateX[t - 1];
                    //iterCoordinateY[t] = iterCoordinateY[t - 1] + a13;
                    t++;


                }

                else
                {

                    if (TobeiterCoordinateX[i] > TobeiterCoordinateX[i + 1])
                    {
                        t++;//2
                        iterCoordinateX[t] = iterCoordinateX[t - 1] - a13;
                        iterCoordinateY[t] = iterCoordinateY[t - 1];
                        t++;//3
                        iterCoordinateX[t] = iterCoordinateX[t - 1];
                        iterCoordinateY[t] = iterCoordinateY[t - 1] - b;
                        t++;//4
                        iterCoordinateX[t] = iterCoordinateX[t - 1] - a12;
                        iterCoordinateY[t] = iterCoordinateY[t - 1];
                        t++;//5
                        iterCoordinateX[t] = iterCoordinateX[t - 1];
                        iterCoordinateY[t] = iterCoordinateY[t - 1] + b;
                        //t++;//6
                        ////iterCoordinateX[t] = iterCoordinateX[t - 1] -
a11;
                        ////iterCoordinateY[t] = iterCoordinateY[t - 1];

                        t++;
                    }

                    if (TobeiterCoordinateX[i] < TobeiterCoordinateX[i + 1])
                    {
                        t++;//2
                        iterCoordinateX[t] = iterCoordinateX[t - 1] + a11;
                        iterCoordinateY[t] = iterCoordinateY[t - 1];
                        t++;//3
                        iterCoordinateX[t] = iterCoordinateX[t - 1];
                        iterCoordinateY[t] = iterCoordinateY[t - 1] + b;
                        t++;//4
                        iterCoordinateX[t] = iterCoordinateX[t - 1] + a12;
                        iterCoordinateY[t] = iterCoordinateY[t - 1];
                        t++;//5
                        iterCoordinateX[t] = iterCoordinateX[t - 1];
                        iterCoordinateY[t] = iterCoordinateY[t - 1] - b;
                        //t++;//6
                        //iterCoordinateX[t] = iterCoordinateX[t - 1] + a13;
                        //iterCoordinateY[t] = iterCoordinateY[t - 1];
```

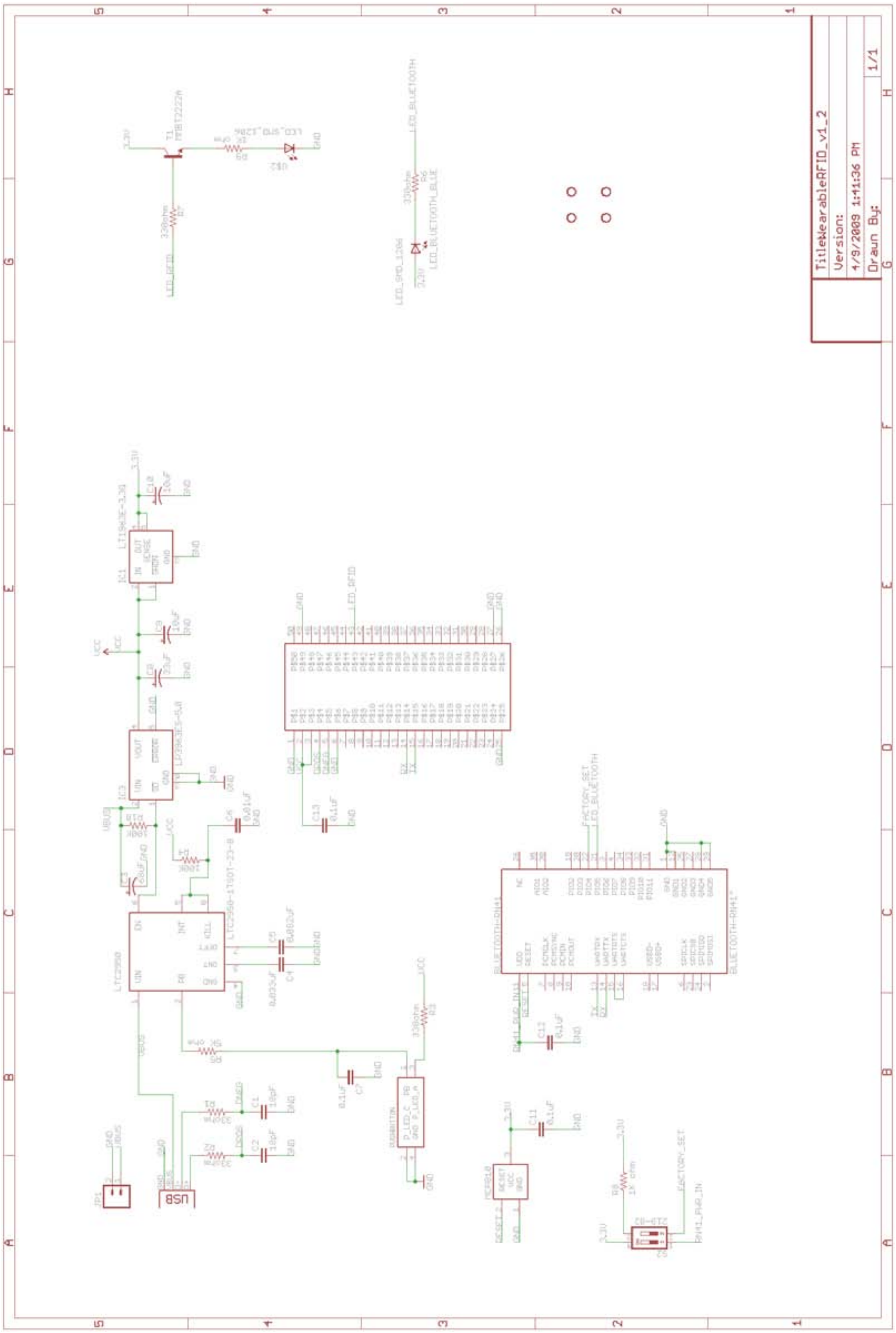
```
                t++;
            }

            if (TobeiterCoordinateY[i] > TobeiterCoordinateY[i + 1])
            {
                t++;//2
                iterCoordinateX[t] = iterCoordinateX[t - 1];
                iterCoordinateY[t] = iterCoordinateY[t - 1] - a11;
                t++;//3
                iterCoordinateX[t] = iterCoordinateX[t - 1] + b;
                iterCoordinateY[t] = iterCoordinateY[t - 1];
                t++;//4
                iterCoordinateX[t] = iterCoordinateX[t - 1];
                iterCoordinateY[t] = iterCoordinateY[t - 1] - a12;
                t++;//5
                iterCoordinateX[t] = iterCoordinateX[t - 1] - b;
                iterCoordinateY[t] = iterCoordinateY[t - 1];
                //t++;//6
                //iterCoordinateX[t] = iterCoordinateX[t - 1];
                //iterCoordinateY[t] = iterCoordinateY[t - 1] - a13;
                t++;
            }

            if (TobeiterCoordinateY[i] < TobeiterCoordinateY[i + 1])
            {
                t++;//2
                iterCoordinateX[t] = iterCoordinateX[t - 1];
                iterCoordinateY[t] = iterCoordinateY[t - 1] + a11;
                t++;//3
                iterCoordinateX[t] = iterCoordinateX[t - 1] - b;
                iterCoordinateY[t] = iterCoordinateY[t - 1];
                t++;//4
                iterCoordinateX[t] = iterCoordinateX[t - 1];
                iterCoordinateY[t] = iterCoordinateY[t - 1] + a12;
                t++;//5
                iterCoordinateX[t] = iterCoordinateX[t - 1] + b;
                iterCoordinateY[t] = iterCoordinateY[t - 1];
                //t++;//6
                //iterCoordinateX[t] = iterCoordinateX[t - 1];
                //iterCoordinateY[t] = iterCoordinateY[t - 1] + a13;
                t++;
            }
        }

    }

}




public void ShowPoints()
{
    Console.WriteLine("Coordinates of the square");
    for (int i = 0; i < 4; i++)
    {
```

```
                Console.WriteLine("X{0} = {1}", i, CoordinateX[i]);
                Console.WriteLine("Y{0} = {1}", i, CoordinateY[i]);
            }


        }

        public void ShowPointsIter()
        {

            // Specify file, instructions, and privelegdes
            FileStream file = new FileStream("iterDataPoints.txt",
FileMode.OpenOrCreate, FileAccess.Write);

            // Create a new stream to write to the file
            StreamWriter sw = new StreamWriter(file);

            // Write a string to the file
            //sw.WriteLine("Iteration coordinates");


            Console.WriteLine("Coordinates of the square");
            for (int i = 0; i < size * 5; i++)
            {
                sw.WriteLine("{0},{1},0", iterCoordinateX[i],
iterCoordinateY[i]);
                Console.WriteLine("X{0} = {1}", i, iterCoordinateX[i]);
                Console.WriteLine("Y{0} = {1}", i, iterCoordinateY[i]);
            }

            // Close StreamWriter
            sw.Close();

            // Close file
            file.Close();

        }

        public void ShowPointsIter2()
        {

            // Specify file, instructions, and privelegdes
            FileStream file = new FileStream("iterDataPoints2.txt",
FileMode.OpenOrCreate, FileAccess.Write);

            // Create a new stream to write to the file
            StreamWriter sw = new StreamWriter(file);

            // Write a string to the file
            //sw.WriteLine("Iteration coordinates");


            Console.WriteLine("Coordinates of the square");
            for (int i = 0; i < size * 5; i++)
            {
                sw.WriteLine("{0},{1},0", iterCoordinateX[i],
iterCoordinateY[i]);
```

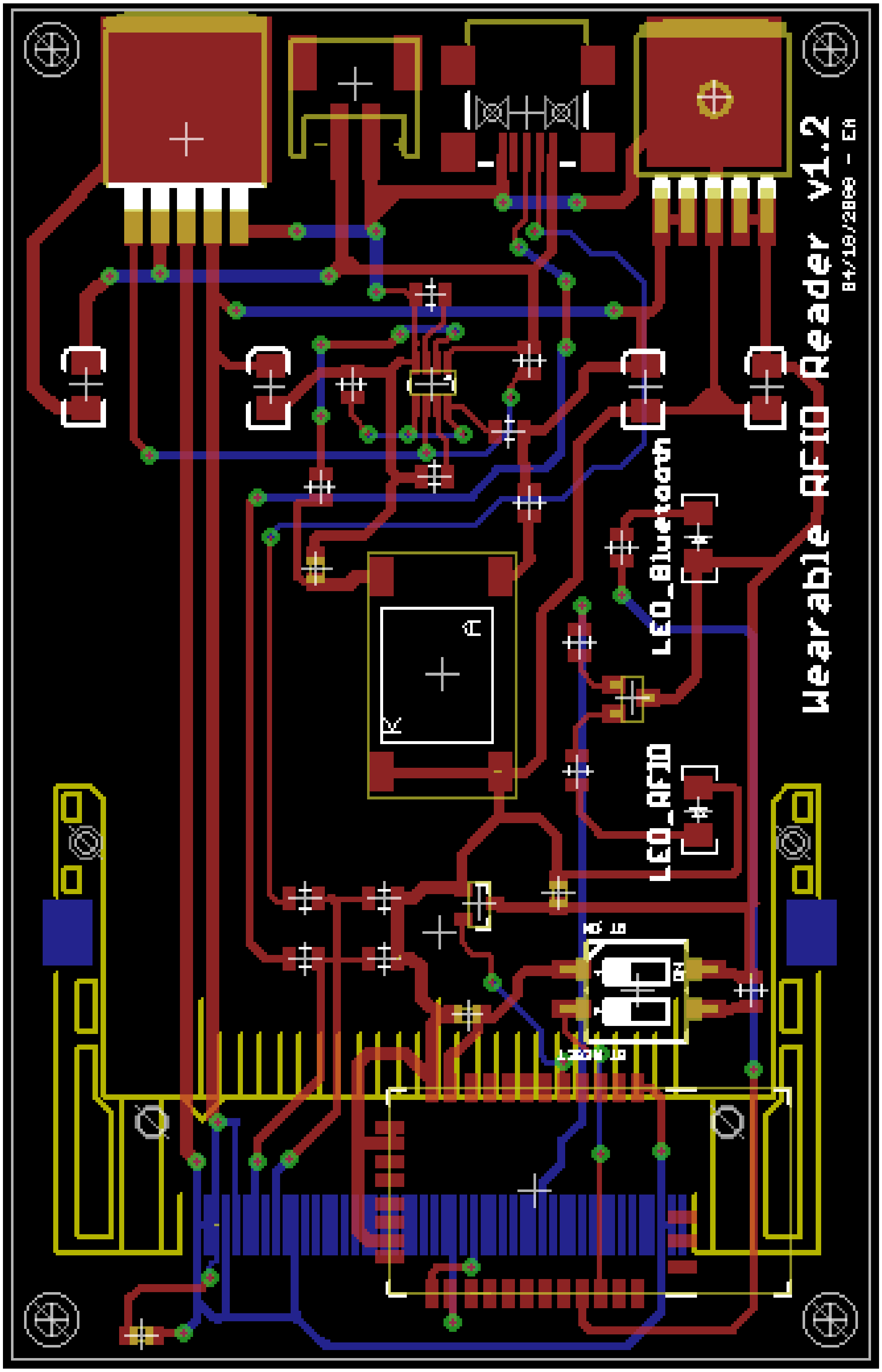
```
                Console.WriteLine("X{0} = {1}", i, iterCoordinateX[i]);
                Console.WriteLine("Y{0} = {1}", i, iterCoordinateY[i]);
            }

            // Close StreamWriter
            sw.Close();

            // Close file
            file.Close();

        }

        public void ShowPointsIter3()
        {

            // Specify file, instructions, and privelegdes
            FileStream file = new FileStream("iterDataPoints3.txt",
FileMode.OpenOrCreate, FileAccess.Write);

            // Create a new stream to write to the file
            StreamWriter sw = new StreamWriter(file);

            // Write a string to the file
            //sw.WriteLine("Iteration coordinates");


            Console.WriteLine("Coordinates of the square");
            for (int i = 0; i < size * 5; i++)
            {
                sw.WriteLine("{0},{1},0", iterCoordinateX[i],
iterCoordinateY[i]);
                Console.WriteLine("X{0} = {1}", i, iterCoordinateX[i]);
                Console.WriteLine("Y{0} = {1}", i, iterCoordinateY[i]);
            }

            // Close StreamWriter
            sw.Close();

            // Close file
            file.Close();

        }

        public void ShowPointsIter4()
        {

            // Specify file, instructions, and privelegdes
            FileStream file = new FileStream("iterDataPoints4.txt",
FileMode.OpenOrCreate, FileAccess.Write);

            // Create a new stream to write to the file
            StreamWriter sw = new StreamWriter(file);

            // Write a string to the file
            //sw.WriteLine("Iteration coordinates");
```

```
            Console.WriteLine("Coordinates of the square");
            for (int i = 0; i < size * 5; i++)
            {
                sw.WriteLine("{0},{1},0", iterCoordinateX[i],
iterCoordinateY[i]);
                Console.WriteLine("X{0} = {1}", i, iterCoordinateX[i]);
                Console.WriteLine("Y{0} = {1}", i, iterCoordinateY[i]);
            }

            // Close StreamWriter
            sw.Close();

            // Close file
            file.Close();

        }


        class Program
        {


            static void Main(string[] args)
            {
                SquareCoordinates Square0 = new SquareCoordinates();



                Square0.FirstIteration();
                Square0.Iteration();
                Square0.ShowPoints();
                Square0.ShowPointsIter();


                Square0.SecondIteration();
                Square0.Iteration();
                Square0.ShowPoints();
                Square0.ShowPointsIter2();

                Square0.ThirdIteration();
                Square0.Iteration();
                Square0.ShowPoints();
                Square0.ShowPointsIter3();

                Square0.ForthIteration();
                Square0.Iteration();
                Square0.ShowPoints();
                Square0.ShowPointsIter4();


            }
        }
    }
                                  }
```

APPENDIX B
WEARABLE RFID READER PROTOTYPE SCHEMATIC



APPENDIX C
WEARABLE RFID READER PROTOTYPE PRINTED CIRCUIT BOARD



APPENDIX D
WEARABLE RFID READER BILL OF MATERIALS

Bill of Materials (BOM):
Project: Wearable RFID reader v1.0
Date: 04/09/2009
Digikey

1. RFID READER MODULE M9 CF FORMAT
   Part Number: 753-1014-ND
   Package: Compact Flash
   http://search.digikey.com/scripts/DkSearch/dksus.dll?Detail&name=753-1014-ND
   Price: $274.00

2. MODULE BLUETOOTH W/ANT CLASS1
   Part Number: 740-1007-ND
   Package: Module
   http://search.digikey.com/scripts/DkSearch/dksus.dll?Detail&name=740-1007-ND
   Price: (Price break: 10) Unit: $26.95 Total: $269.50

3. Push Button On/OFF controller IC
   Part Number: LTC2950CTS8-1#TRMPBFCT-ND
   Package: TSOT23-8
   http://search.digikey.com/scripts/DkSearch/dksus.dll?Detail&name=LTC2950CTS8-1%23TRMPBFCT-ND
   Price: $4.17

4. Voltage Regulator 5V output
   Part Number: LP3963ES-5.0-ND
   Package: TO-263-5
   http://search.digikey.com/scripts/DkSearch/dksus.dll?Detail&name=LP3963ES-5.0-ND
   Price: $3.70

5. Voltage Regulator 3.3V output
   Part Number: LT1963AEQ-3.3#PBF-ND
   Package: D^2Pak
   http://search.digikey.com/scripts/DkSearch/dksus.dll?Detail&name=LT1963AEQ-3.3%23PBF-ND
   Price: $5.50

6. Reset IC
   Part Number: MCP810T-485I/TTCT-ND
   Package: SOT-23-3

http://search.digikey.com/scripts/DkSearch/dksus.dll?Detail&name=MCP810T-485I/TTCT-ND
Price: 0.48

7. LED
    a. LED 3.2X1.6MM 570NM GRN CLR SMD-50°
    Part Number: 754-1152-1-ND
    http://search.digikey.com/scripts/DkSearch/dksus.dll?Detail&name=754-1152-1-ND
    Price: $0.30

    b. LED 3.2X1.6MM 470NM BLUE CLR SMD - 50°
    Part Number: 754-1155-1-ND
    http://search.digikey.com/scripts/DkSearch/dksus.dll?Detail&name=754-1155-1-ND
    Price: $0.56

8. SMD DIP Switch
Part Number: CT2192MST-ND
http://search.digikey.com/scripts/DkSearch/dksus.dll?Detail&name=CT2192MST-ND
Price: $0.49

9. Mini USB
Part Number: A31727CT-ND
http://search.digikey.com/scripts/DkSearch/dksus.dll?Detail&name=A31727CT-ND
Price: $1.62

10. Capacitor
    a. C1-C2 : 18pF Ceramic
    Package: 0805 SMD
    Part Number: PCC180CNCT-ND
    Price: $0.48
    http://search.digikey.com/scripts/DkSearch/dksus.dll?Detail&name=PCC180CNCT-ND
    b. C3: 68uF Tantalum Capacitor
    Package: 3216-10 (EIA) 1206 SMD
    Part Number: 493-2912-1-ND
    Price: (Price break:10) Unit: $0.92 Total: $9.24
    http://search.digikey.com/scripts/DkSearch/dksus.dll?Detail&name=493-2912-1-ND
    c. C4: 0.033uF
    Package: 0805 SMD
    Part Number: PCC1834CT-ND
    Price: $0.31
    http://search.digikey.com/scripts/DkSearch/dksus.dll?Detail&name=PCC1834CT-ND
    d. C5: 0.082uF
    Package: 0805 SMD

Part Number: PCC1811CT-ND
Price: $0.40
http://search.digikey.com/scripts/DkSearch/dksus.dll?Detail&name=PCC1811CT-ND

e. C6: 0.01uF
Package: 0805 SMD
Part Number: PCC103BNCT-ND
Price: $0.25
http://search.digikey.com/scripts/DkSearch/dksus.dll?Detail&name=PCC103BNCT-ND

f. C7-C11-C12-C13: 0.1uF Ceramic Decoupling Capacitor
Package: 0603 SMD
Part Number: 709-1004-1-ND
Price: (Price break:10) Unit: $0.771 Total: $7.71
http://search.digikey.com/scripts/DkSearch/dksus.dll?Detail&name=709-1004-1-ND
Quantity: 80

g. C8: 33uF Tantalum Capacitor
Package: 3216-10 (EIA) 1206 SMD
Part Number: 493-2906-1-ND
Price: (Price break:10) Unit: $0.655 Total: $6.55
http://search.digikey.com/scripts/DkSearch/dksus.dll?Detail&name=493-2906-1-ND

h. C9-C10: 10uF Tantalum Capacitor
Package: 3216-10 (EIA) 1206 SMD
Part Number: 511-1446-1-ND
Price: $0.33
http://search.digikey.com/scripts/DkSearch/dksus.dll?Detail&name=511-1446-1-ND

11. Resistor

a. R1-R2: 33ohm Thick Film Chip Resistor
Package: 0805 SMD
Part Number: P33ACT-ND
Price: (Price break:10) Unit: $0.07 Total: $0.77
http://search.digikey.com/scripts/DkSearch/dksus.dll?Detail&name=P33ACT-ND

b. R3-R6-R7: 330 ohm
Package: 0805 SMD
Part Number: P330ACT-ND
Price: (Price break:10) Unit: $0.07 Total: $0.77
http://search.digikey.com/scripts/DkSearch/dksus.dll?Detail&name=P330ACT-ND

c. R4: 10K ohm
   Package: 0805 SMD
   Part Number: P100KACT-ND
   Price: (Price break:10) Unit: $0.07 Total: $0.77
   http://search.digikey.com/scripts/DkSearch/dksus.dll?Detail&name=P100KACT-ND

d. R8-R9: 1K ohm
   Package: 0805 SMD
   Part Number: P1.0KACT-ND
   Price: (Price break:10) Unit: $0.07 Total: $0.77
   http://search.digikey.com/scripts/DkSearch/dksus.dll?Detail&name=P1.0KACT-ND

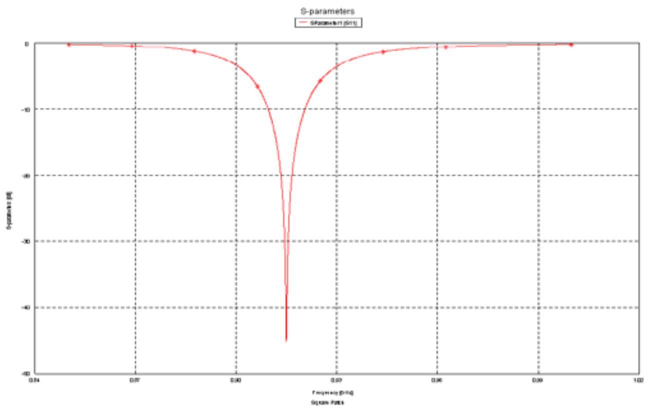
12. Transistor
    a. T1
       Part Number: MMBT2222AFSCT-ND
       http://search.digikey.com/scripts/DkSearch/dksus.dll?Detail&name=MMBT2222AFSCT-ND
       Price: $0.09

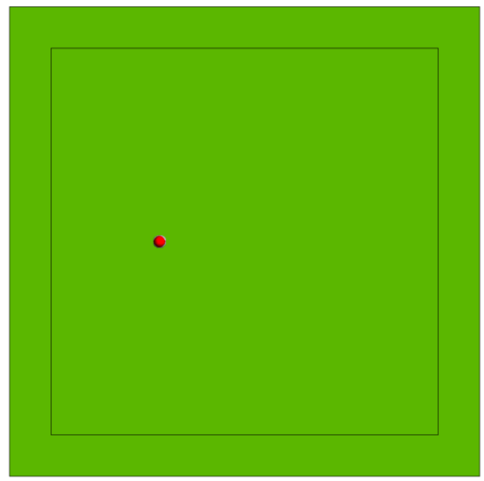
Heilind Electronics

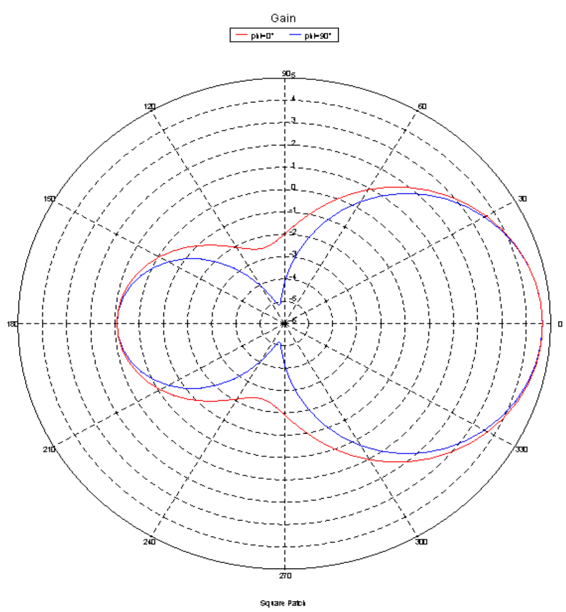
13. Compact Flash:
    http://www.hirose.co.jp/cataloge_hp/e64070010.pdf
    Part Number: MI20-50PD-SF(71)
    http://estore.heilind.com/partdetail.asp?pn=MI20-50PD-SF(71)&dp=HIRMI20-50PD-SF(71)&cp=
    Price: $4.4
    Quantity: 20

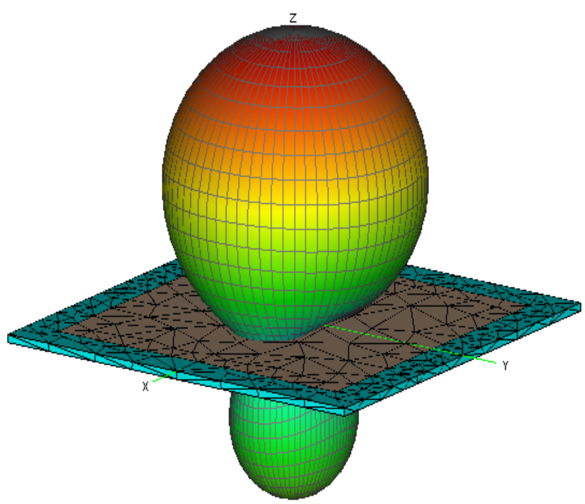
APPENDIX E
RETURN LOSS AND RADIATION SIMULATIONS FOR FRACTALS

Antenna ID	*iteration #*	*iteration factor*	*Center frequency (MHz)*	*Max Gain (dBi)*	*Return Loss (RL) (dB)*	*BW(RL> -9.5dB)(MHz)*	*εr*	*h(mm)*	*L=W*
1	0	0	915	4.71	-45.00	12.00	4.60	1.57	76.27









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BIOGRAPHICAL SKETCH

Ahmet Erdem Altunbas was born in Trabzon, Turkey in 1982. He received his bachelor's degree in Telecommunication Engineering from Istanbul Technical University, Turkey. He has been working on Radio Frequency Identification area since 2004 and involved with numerous projects with RFID technology. His research interest mainly includes RFID, Electronic hardware design, antenna design, microcontrollers and RF propagation.

In his spare time he enjoys outdoor activities and spending time with family and friends.