DESIGN AND FABRICATION OF MINIATURIZED MICROSTRIP ANTENNAS AT 900 MHZ FOR INDUSTRIAL REMOTE CONTROLLERS

A THESIS SUBMITTED TO
THE GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES
OF
ATILIM UNIVERSITY

BY

VADİ SU YILMAZ

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR
THE DEGREE OF MASTER OF SICIENCE
IN
ELECTRICAL AND ELECTRONICS ENGINEERING

APRIL 2019

Approval of the Graduate School of Natural and Applied Sciences, Atilim University.

Prof. Dr. Ali KARA
Director

I certify that this thesis satisfies all the requirements as a thesis for the degree of **MASTER OF SICIENCE in Electrical and Electronics Engineering Department, Atilim University**.

Assoc. Prof. Dr. Efe ESELLER
Head of Department

This is to certify that we have read the thesis DESIGN AND FABRICATION OF MINIATURIZED MICROSTRIP ANTENNAS AT 900 MHZ FOR INDUSTRIAL REMOTE CONTROLLERS submitted by VADİ SU YILMAZ and that in our opinion it is fully adequate, in scope and quality, as a thesis for the degree of MASTER OF SICIENCE.

Prof. Dr. Elif AYDIN
Co-Supervisor

Prof. Dr. Ali KARA
Supervisor

Examining Committee Members:

Assist Prof. Dr. Mehmet ÜNLÜ

Prof. Dr. Ali KARA

Prof. Dr. Elif AYDIN

Prof. Dr. Çiğdem Seçkin GÜREL

Assoc. Prof. Dr. Kemal Efe ESELLER

Date: April 30, 2019

I declare and guarantee that all data, knowledge and information in this document has been obtained, processed and presented in accordance with academic rules and ethical conduct. Based on these rules and conduct, I have fully cited and referenced all material and results that are not original to this work.

Name, Last Name : VADİ SU YILMAZ

Signature :

ABSTRACT

DESIGN AND FABRICATION OF MINIATURIZED MICROSTRIP ANTENNAS AT 900 MHZ FOR INDUSTRIAL REMOTE CONTROLLERS

Yılmaz, Vadi Su

M.S., Department of Electrical and Electronics Engineering

Supervisor : Prof. Dr. Ali KARA

Co-Supervisor : Prof. Dr. Elif AYDIN

APRIL 2019, 52 pages

This thesis explores the efficiency of miniaturization techniques for sub-GHz band remote control applications through simulations and measurements. First, the theory of microstrip antenna is studied and introduced at the beginning of the thesis. For the design process, a finite element method based simulation tool is used, multiple patches are designed accordingly. The miniaturization techniques are applied on the designed antennas. The antennas that satisfy the desired criteria are produced. The necessary measurements are subsequently made on the fabricated antennas, validity of the techniques is discussed. The effects of the box in which the antenna to be placed were examined as most of such antennas are enclosed by plastic boxes. Finally, a polyamide box with appropriate size was fabricated, and the designed antenna was placed inside the box and the measurements were conducted. The measurement results show that the designed antenna provides resonance at the targeted license-free band with appropriate size for industrial remote controllers.

Keywords: Miniaturization, Microstrip Antenna, Operating at sub-GHz, Remote Control, Slot Antenna

ÖZ

ENDÜSTRİYEL UZAKTAN KONTROL SİSTEMLERİ İÇİN 900 MHz'de ÇALIŞAN MİNYATÜR ANTEN TASARIMI VE ÜRETİMİ

Yılmaz, Vadi Su

Yüksek Lisans, Elektrik & Elektronik Mühendisliği Bölümü

Tez Yöneticisi : Prof. Dr. Ali KARA

Ortak Tez Yöneticisi : Prof. Dr. Elif AYDIN

Nisan 2019, 52 sayfa

Bu tez, GHz altı bantlarda çalışan antenler için minyatürizasyon tekniklerine ışık tutarken, uzaktan kontrol sistemleri için anten tasarımları yaparak, minyatürizasyon tekniklerinin analizlerini gerçekleştirmeyi hedeflemiştir. Bu evrede birçok tasarım gerçekleştirilmiş ve incelemeler yapılmıştır. Kullanılan FEM tabanlı tasarım araçlarının sonuçlarını, anten teorisini kavramadan anlamak mümkün olmadığından, mikroşerit anten teorisi üzerinde durulmuştur. Anten yamasının tasarımı yapılmış, birçok model belirlenmiş, belirlenen modeller üzerinden, kullanılan tekniklerin geçerlilikleri saptanmıştır. İstenilen değerlere ulaşan antenlerin üretimi ve ölçümleri gerçekleştirilmiştir. Uzaktan kontrol uygulamalarında kullanılan kutu malzemesi üzerine de çalışmalar yapılmıştır. Kutu malzemesi, anten performansını etkilemeyecek şekilde, iyileştirilmeler yapılarak tanımlanmış ve üretimi gerçekleştirilmiştir. Anten kutu içerisine yerleştirilerek, ölçüm ve tasarım sonuçları karşılaştırılmıştır.

Anahtar Kelimeler: Minyatür Anten, Mikroşerit Anten, GHz-altı Bant Operasyonu, Uzaktan kontrol, Yarık Anten

To Universe

ACKNOWLEDGMENTS

Firstly, I would like to express my sincere gratitude to my advisor Prof. Dr. Ali Kara and my co-advisor Prof. Dr. Elif Aydın for the continuous support of my Master study and related research, for their patience, motivation, and immense knowledge. Their guidance helped me in all the time of research and writing of this thesis. I would also like to thank them for including me in the Tübitak Ardeb-1005 project with grant number 116E216. I could not have imagined having a better advisor and mentor for my master study.

Besides, I would like to thank the rest of my thesis committee: Assist. Prof. Dr. Mehmet Ünlü, Prof. Dr. Çiğdem Seçkin Gürel, and Assoc. Prof. Dr. Efe Eseller, for their insightful comments and encouragement, but also for the hard question which incented me to widen my research from various perspectives.

Last but not the least, I would like to thank my family and my friends for supporting me spiritually throughout writing this thesis and my life in general..

The financial support of The Scientific and Technical Research Council of Turkey (TÜBİTAK) is also acknowledged for supporting this project under Ardeb-1005 with project number 116E216.

TABLE OF CONTENTS

LIST OF TABLES

TABLES

LIST OF FIGURES

FIGURES

LIST OF SYMBOLS

λ_0	:	Free space wavelength
ϵ_r	:	Relative Permittivity
$\mathbb{Q}$	:	Quality Factor
ϵ_{eff}	:	Effective dielectric Constant
$\mathbb{U}_{max}$	:	Max Radiation Intensity
$\mathbb{B}W$	:	Bandwidth of Antenna Return Loss
Γ	:	Refelection Coefficient
$\mathbb{V}SWR$	:	Standing Wave Ratio

CHAPTER 1

INTRODUCTION

Antennas are essential to many applications and they are one of the most important components of wireless communication and there are many variations depending on the application area. Microstrip antennas are one of the most widely used antenna types in the microwave frequency range [1]. Therefore, they are frequently used in many, especially mobile and wireless communication systems. The microstrip antennas are superior in terms of features such as being lightweight, inexpensive, low-profile and easy to integrate [2]. In addition, they are very versatile in terms of resonance frequency, polarization, radiation pattern and impedance. However, microstrip antennas are inferior in some respects, for example they have low gain, poor performance, undesired radiation due to feeding and narrow bandwidth which cause them to be restricted to certain application areas. High gain is important for wireless communication systems (such as cellular communication and WiMAX system) that require long range [3]. In those cases, the problem can be solved by using multilayer structure antenna. While a gain improvement is a very difficult criterion for a microstrip antenna with a conventional structure, it is possible to increase the gain with multilayer structure, without increasing the size [4], [5].

Design of antennas for industrial remote controllers is still of great interest. One of the challenges is to keep the dimensions of the antenna as small as possible. However, antennas with sizes less than the operational wavelength brings about significant constraints [6], for example, lower efficiency and bandwidth as discussed in [6], [7] and [8]. This trade of, involving size, efficiency and bandwidth was revealed by Wheeler [7] and Chu [8] theoretically, and it has been validated by experiments. Then, design of electrically small antennas or antenna miniaturization is still a challenging issue for many different applications. In the literature, most of the miniaturization studies have been conducted for frequencies of upper GHz bands or multi band operations [9-14]. Various techniques have already been proposed such as use of high-dielectric substrate, multilayer structures [15], [16], introducing slots and notches [17], fractal shaped patches [9], [18], various shape strips and loop structures [10], [19-22], and employing metamaterial loading techniques [12], [23]. Using high-dielectric substrate material, so called superstrate, increases the quality factor but it also causes an increase in electric field concentration [24]. In the selection of high-dielectric material, the targeted band of operation should be considered firstly. On the other hand, for the sub-GHz bands, FR4 is mostly preferred [10], [20] due to its cost and availability. Increasing the thickness and length of the feeding line may reduce the antenna area; therefore, multilayer structure may exceed the limits for the thickness of the substrate and the dimension restrictions for the feeding line [25].However, all these methods effectively increase the electrical length of the current only in small areas, which means that the applicability is still limited [17], [18]. Furthermore, despite the availability of these miniaturization techniques, most of the papers report that planar structures are mostly preferred [10], [19], [20], [22] for license free sub-GHz bands. Because these structures are designed for uses the radiated patch area in very small sizes effectively. In some applications, relatively bigger ground is used in order to miniaturize antenna size while increasing the electrical dimension of the antenna at sub-GHz bands. Even though antenna patch size seems to be small, it is impossible to achieve miniaturization greatly without metallic ground plane. In this type of antennas, patch may have slots or strips [26-28]. In the light of the literature review, the design and fabrication of novel, miniaturized, low profile, easy-to-manufacture antenna for sub-GHz applications is still a challenge.

The developmensts regarding the RF transmitters employed in re-configurable communication systems which support multpile communication standarts and services promote the research efforts towards multi-band microstrip patch antenna designs. There are multi band operations in many areas. In the In literature, antennas with multi-layered antenna structures and strip paths are the most common methods for multi band operation. [29], [30]. This studied antenna is also satisfy this requirement with resonate both 1.3GHz and 887MHz bands. It is appropriate for use in short distance remote control applications. Thus, it is performed two communication area in one system such as data transferring and location determining at the same time, as control system need.

Microstrip antennas have lacks in terms of some features which are being aesthetics, suited with around, durable to difficult conditions, etc. Therefore, they are usually not used alone, they are placed in a box or structure. To make it durable, it can be embedded or placed into box. Plastic box which is mostly used in remote control applications to place circuits, therefore antenna sizes are restricted due to box dimensions. On the other hand microstrip antennas are preferred due to reaching small sizes and to fit antenna into box. Thus, with using microstrip antenna both box dimension restriction and microstrip antenna poor durability are eliminated. Furthermore, while the interaction of the antenna with around is minimized, it is protected from external factors and impacts. In the direction of this information, it is required to consider the effect of the radome housing on the scattering and radiation patterns of antennas [31], the produced antenna was placed into a radome made of plastic. Although polystyrene is widely used in the production of radomes [32], other materials can also be investigated in terms of their relative permittivity and other features. In the current study, polyamide was chosen as the material for the box of the antenna to minimize its possible effects on the results. The return loss and radiation pattern of the antenna are examined and same measurements are also made after antenna was placed into the box and these results are compared.

When the literature is examined, it is clearly demonstrated that there is a need for researches at miniaturization at sub-GHz bands and antenna studies in remote control systems. There is no study including simple, miniature microstrip antenna at sub-GHz bands for remote control system and housing box effect is available on the literature. Small antenna studies usually have been conducted for frequencies of upper GHz bands or multi band operations [4-9]. In some applications [16] and [21], miniaturized antennas have been performed at sub-GHz bands but their gains are lower than 0 dB. In [21], [22] and [23], relatively bigger ground is used in order to obtain small antenna size. Even though antenna performances such as patch size, return loss, gain are similar to the proposed antenna, it is impossible to achieve miniaturization without metallic ground plane and to use in remote control systems. it is compared the designed antenna with another study [33] on antenna size, antenna design requirements and fabrication challenge. In this study, the miniaturize antenna has been realized as an array antenna with loops to achieve antenna design specific at sub-GHz bands and the antenna size was reported 90 x 90 mm. Therefore, it is more complicated to fabricate due to its complex shape, and its size is big when we compare to our proposed one.

All the techniques and literature researching is considered and theory is realized before simulation and measurement examination. Although patches are determined with optimization and simulations of strips' weight, length, they are implemented with FEM (finite element method) and FIT (finite integration technique) based design tools and these design tools work according to the theory [31]. Therefore, also theory of microstrip antenna should be known. After patch shapes is determined, miniaturization techniques are considered and antenna is redesigned according to the best performing conditions in terms of substrate thickness, material and feeding line length, weight. So many design, researching and implementation is made on this.

Secondly, the effects of the housing box on the antenna parameters are studied experimentally and it is produced after finding appropriate material. For this purpose, material properties of commercial industrial housing boxes are studied extensively, and electromagnetic (EM) model is developed in order to investigate its effects on the antenna parameters. The rest of the thesis is organized as follows: the next section describes theory of microstrip antennas basically. Even there are so many methods are described at the literature. In theoretical background, transmission-line model is mentioned for rectangular and circular patches due to they have been mostly used. It is important to comprehend the theory in terms of interpreting the results of designs which is made by using FEM based design tools. Section 3 presents design methodology. Patches are designed with defined models, results are compared, miniaturization techniques are examined and measurements are demonstrated. Furthermore, this section contains the experimental results of the antenna parameters with and without plastic box housing. Finally conclusions are provided.

CHAPTER 2

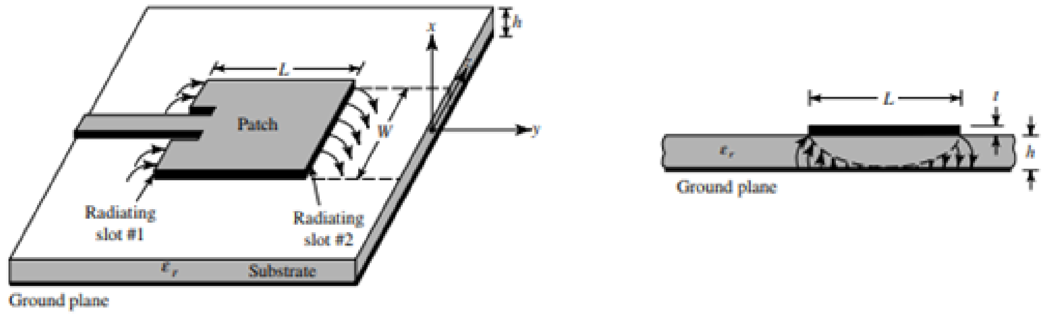
Microstrip Antenna Theory

In the direction of design and production processes of antennas, microstrip antenna structure is selected due to its convenience for miniaturization applications. Without understanding the microstrip antenna theory, it is not possible to mention about the antennas which are designed and produced. Although the design of antennas cannot be precisely determined by any theoretical calculation due to antenna patch shapes, the consistency of theory and production results can be compared by making approaches.

2.1 Basic Operational Principles of Microstrip Antenna

Microstrip antennas have drawn attention since 1970s due to its lightweight, inexpensive, low-profile and easy to integrate. A microstip antenna mainly consists three part which area conducting patch at the top, dielectric layer at the middle and ground patch at the bottom as it is seen in figure 2.1.

Microstrip antennas, stand out by having a very thin metallic strip (patch) which is defined by $t << \lambda_0$ and the length L of the patch element is usually defined as $\lambda_0/3 < L < \lambda_0/2$. Patch is followed by thin dielectric substrate below with $h << \lambda_0$ usually, $0.003\lambda_0 \leq h \leq 0.05\lambda_0$ above a ground plane. There are various substrates can be selected for design of microstrip antennas in the direction of their usage area, and substarate's dielectric contants are usually changed between $2.2 \leq \epsilon_r \leq 12$. The selection of ϵ_r is made according to frequency that will be operate. However, it can be mentioned for generalization, to obtain good antenna performance, thick substrates are desired, also dielectric constant is selected in the lower case because it provides



(a) Front View (b) Side View

Figure 2.1: Basic Geometry of Microstrip Antenna [34]

better efficiency, larger bandwidth and also provides loosly bound fields for radiation into space but this condition is valid for the larger size of the antenna. Thin substrates with higher dielectric constants are desirable for circuits which require tightly bound fields to minimize undesired radiation and coupling such as microwave circuitry and that condition is valid for antennas which have smaller element sizes. Even tightly bound field restrict undesired radiation, on the other hand, it occurs to much losses so performance efficiency and bandwidth become smaller. For miniaturization process of the antenna, this information about dielectric part should be considered also [34].

2.2 Microstrip Antenna Patches

Radiating element of antenna is called as patch which is placed above the dielectric layer and consist of conducting material. General shape of patch at the top defined with its length and weight in rectangular form according to its operating frequency. However, lower frequencies shape of the antenna become larger and other shapes are required to design desired size in the direction of application area. Radiating patch may be square, rectangular, thin strip (dipole), circular, elliptical, triangular, or any other configuration as it is seen in figure 2.2.

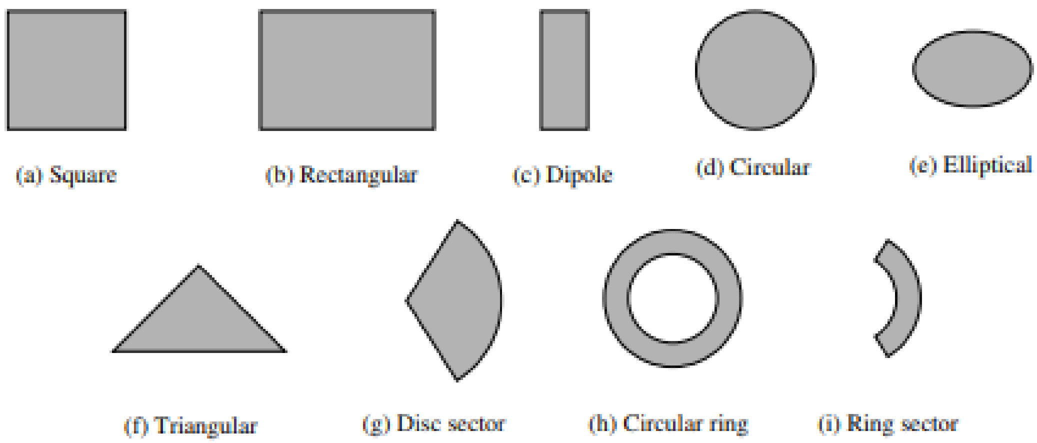


Figure 2.2: Various of Microstrip Antenna Radiating Patch elements [34]

Square, rectangular, dipole (strip), and circular are the most selected patches due to theirs easily fabrication, and their attractive radiation characteristics. Also miniaturization processes, conducting patch shape has an importance as well as dielectric substrate. When shape of the patch which is determined operating frequency should be considered first. As it is mentioned in the introduction part, miniaturized microstrip antennas which are operating in sub GHz bands' shapes determination base on extend the electrical length of the conducting patch. For that reason, winding shapes are mostly used for miniaturized antennas [34].

2.3 Microstrip Antenna Application Field and Reasons

The reason of preference of microstrip antennas by industry can be easily explained with lightweight, inexpensive, low-profile and easy to integrate features. However, there are advantages and disadvantages of microstip antenna according to its usage field.

Microstrip antennas has advantages in terms of being light weight, low profile, inexpensive. It has small sizes, ease of production, ease of parametric studies and forming array. It can be designed to work in multiple bands. It is conformable to integrated circuits and can be mounted devices easily. Adjustable in terms of polarization, frequency, impedance and pattern with true optimization.

It has a disadvantage in terms of having low gain, low efficiency and performance. It has narrow bandwidth, high Q and low polarization purity. There can be seen, undesired radiation due to feeding.

2.4 Feeding Techniques of Microstrip Antenna

For feeding of microstip antennas, many configurations can be mentioned, however, there are four main methods which are the microstrip line, coaxial probe, aperture coupling, and proximity coupling techniques as described below;

2.4.1 Microstrip Line Feeding

In accordance with microstrip line feeding technique, a strip line is used as feeding line which is united with radiated patch. It has simple model and is easy to fabricate and match by controlling inset position. However, when the substrate thickness increases, it is easy to encounter with undesired radiation.

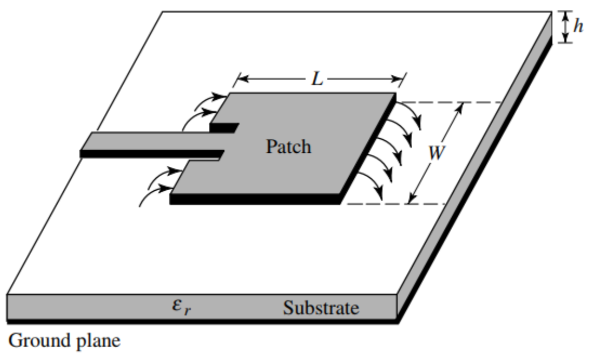


Figure 2.3: Basic Geometry of Microstrip Line Feeding [34]

2.4.2 Coaxial Probe Feeding

In coaxial feeding method the inner conductor of coax is connected with radiated patch and outer conductor is adherent to ground plane as seen in figure 2.4. It is widely used for feeding antenna due to its easily fabrication and the well matching, it can restrict undesired radiation arise from feeding easily. However, it has narrow bandwidth and, it is hard to model for thick substrates.

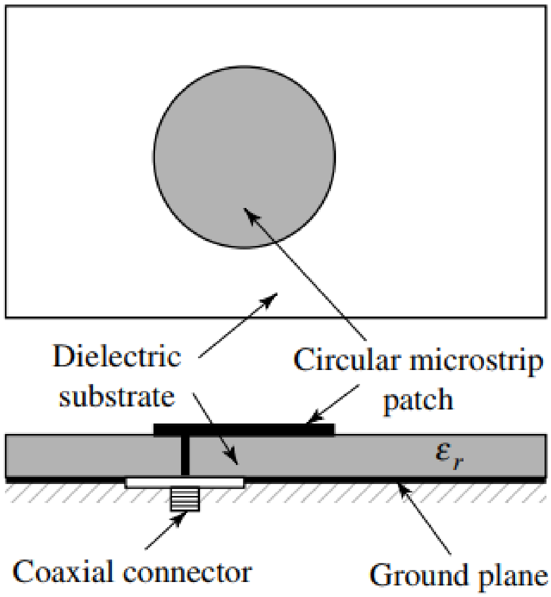


Figure 2.4: Basic Geometry of Prope Feeding [34]

2.4.3 Aperture Coupling

In aperture coupling technique, it is easy to model and undesired radiation level may acceptable. In this technique, two different substrates and a ground plane in the middle of them are used. On the second substrate's bottom side, there is a microstrip feed line and ground plane between two substrates has slot as seen in figure 2.5. According to working principle, there is energy coupling between feed line and patch which pass through ground slot. Undesired radiation is isolated when energy passes through the slot of ground . Matching condition can be obtained by optimizing width and length of slot and feeding line. Furthermore, higher ϵ_r substrate is used at bottom and lower ϵ_r substrate is used at top in general.

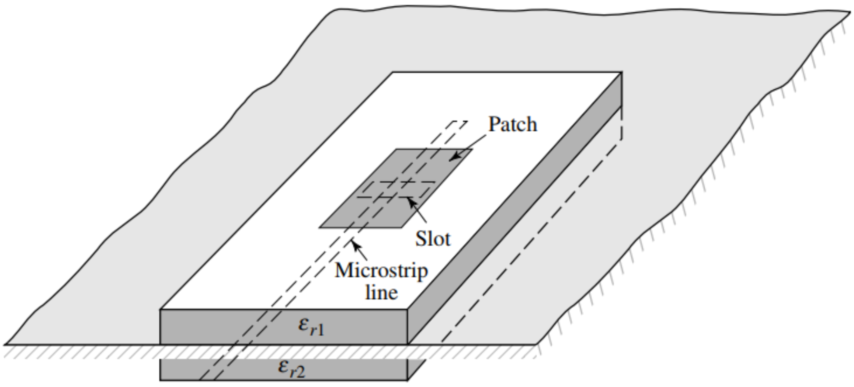


Figure 2.5: Basic Geometry of Aperture Coupling [34]

2.4.4 Proximity Coupling

In proximity coupling, two dielectric substrates are used like the aperture coupling but in this method, feeding stub is placed between two substrates and there is a patch at the top. It has the largest bandwidth when it is compared with other methods. Also, while it is easy to model, it is hard to produce .

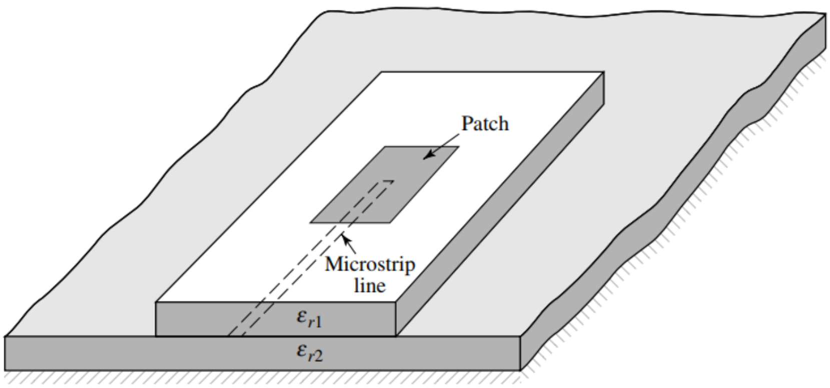


Figure 2.6: Basic Geometry of Proximity Coupling [34]

2.5 Methods of Analysis

There are three basic methods defined for analysis of microstrip antennas. These are mentioned as transmission line, cavity and full wave. Although transmission line is the easiest one due to its physical insight, its accuracy is low. Even cavity method is more accurate when it is compared with transmission line, it has low accuracy. Even physical insight of cavity is good, modeling of coupling is complex. The full-wave models accuracy is high. Even, it has complex model and less physical insight, it is very sophisticated, and it can also treat single elements, finite and infinite arrays, stacked elements, arbitrary shaped elements, and coupling. In the theoretical background transmission-line model is mentioned for rectangular and circular patches.

2.5.1 Rectangular Patch

The most used model in microstrip antennas because it is easy to analyze using both transmission line and cavity model that are accurate for thin substrates. Furthermore, it has advantages in terms of modeling and fabricating. Even the designed antenna has so many strip and it is not completely rectangular, there can be made an assumption from rectangular patch calculations due to small rectangles.

2.5.1.1 Transmission Line Model for Rectangular Patch

Transmission line model is the easiest way to model an antenna and it gives good physical insights as well. Basically, the transmission-line model idicates two slots and a low-impedance Z_c transmission line which is length called as L, width is called as W and substrate thickness is h.

2.5.1.2 Fringing Effects and Effective Dielectric Constant

Fringing effect can be explain with the fields at the edges of patch which has finite physical dimensions as lenght and width pass on fringing. This effect is occured for along both length and width, between two conducting surface. Fringing function is depend on dimensions of the patch and the height of the substrate. fringing function for E-plane (xy-plane) can be defined by the ratio between the length of the patch L and the height h of the substrate (L/h) and also the dielectric constant ϵ_r of the substrate. When the ratio $L/h >> 1$, fringing decrease but, it should be also considered that this ratio can effect the resonant frequency. Basic electric field propagation on microstrip antenna is shown in figure 2.7, which demostrates that electric fields exist between two medium of substrate and air.

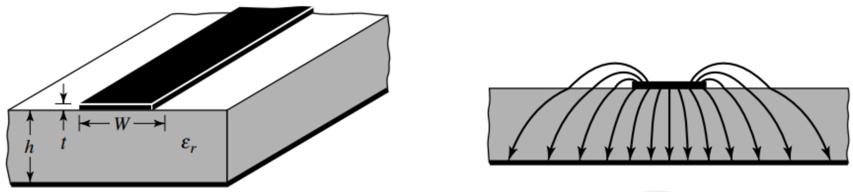


Figure 2.7: Electric Field Propagation on Microstrip Structure [34]

As seen clearly, most of the electric field lines exist on the substrate and some lines exist on air. When two conditions exist which are $W/h >> 1$ and $\epsilon_r >> 1$, the electric field lines concentrate mostly on the substrate. This condition presents that microstrip line seems electrically bigger than line physical dimensions provide. Due to some of waves travel through air and most of travel through dielectric, ϵ_{eff} is defined to find exact fringing and wave propagation.

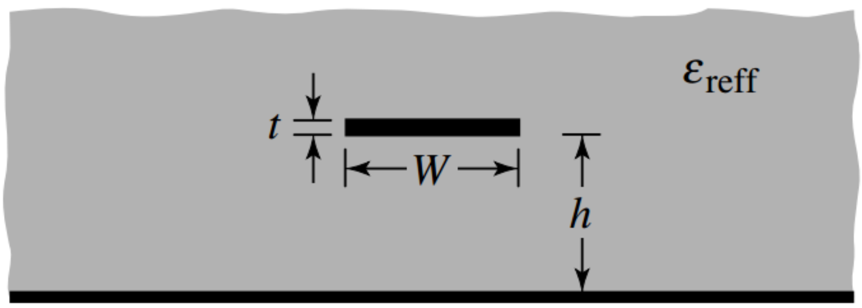


Figure 2.8: Effective Dielectric Constant Structure [34]

Effective dielectric structure is shown in figure 2.8. A conductor is embedded into dielectric center with its original dimensions above the ground plane. ϵ_{eff} is defined as the dielectric constant of the uniform dielectric material . The effective dielectric constant has values in the range of $1 << \epsilon_{eff} << \epsilon_r$. For most applications, dielectric constant of the substrate is selected as much greater than unity. So the value of ϵ_{eff} become closer to the actual value of dielectric constant. However, it should be considered that dielectric constant value can change operating frequency. The effective dielectric constant defined as below with relation between width of patch, height and dielectric constant of the substrate.

$$\epsilon_{eff} = \frac{\epsilon_r + 1}{2} + \frac{\epsilon_r - 1}{2}[1 + 12\frac{h}{W}]^{-1/2} \tag{2.1}$$

Effective dielectric constant is defined as it is in the equation 2.1, when $w/h > 1$.

2.5.1.3 Resonant Frequency, Effective Length , and Effective Width

As it is mentioned before, due to the fringing effect, microstrip antenna looks wider electrically than its physical dimensions. For basic E-plane, it is demonstrated in figure 2.9. As it is seen, dimensions of patch are extended by ΔL from both sides.

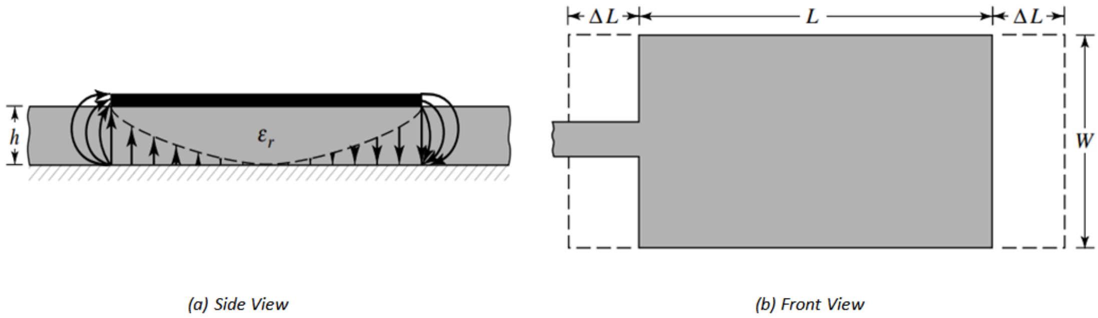


Figure 2.9: Physical and Effective Lengths of Microstrip Antenna [34]

ΔL is the function of effective dielectric constant and the ratio between weight and height. As defined in equation 2.2;

$$\frac{\Delta L}{h} = 0.412\frac{(\epsilon_{eff} + 0.3)(\frac{W}{h} + 0.264)}{(\epsilon_{eff} - 0.258)(\frac{W}{h} + 0.8)} \tag{2.2}$$

Due to the patch length is extended at the both side by ΔL, new effective length of patch is defined as mentioned in equation 2.3;

$$L_{eff} = L + 2\Delta L \quad (2.3)$$

After determinin effective length, resonant frequency of microstrip antenna is defined as below;

$$f = \frac{c}{2 * L * \sqrt{\epsilon_r}} \quad (2.4)$$

The relation of frequecy and width can be demonstrated as shown below;

$$W = \frac{c}{2 * f} * \sqrt{\frac{2}{\epsilon_r + 1}} \quad (2.5)$$

2.5.1.4 Directivity and Gain

Antenna directivity can be explained by 4π times the ratio of radiation intensity and radiated power over all directions, as demonstrated below;

$$D = \frac{4\pi * U_{max}}{P_{rad}} \quad (2.6)$$

Where U is;

$$U_{max} = \frac{|V_0|^2}{2\eta_0\pi}(\frac{\pi W}{\lambda_0})^2 \quad (2.7)$$

And where P_{rad} is defined according to one slot ;

$$P_{rad} = \frac{|V_0|^2}{2\eta_0\pi}\int_0^{\pi}[\frac{sin(\frac{k_0W}{2}cos\theta)}{\cos\theta}]^2 sin^3\theta d\theta \quad (2.8)$$

Gain defines the antenna performance which is related with directivity. Antenna gain is defined with ratio between radiation intensity and total input power. In gain measurement, ratio intensity is selected as the certain direction. Isotropic omnidirectional antenna gain is defined as below;

$$Gain = 4\pi \frac{U(\theta, \phi)}{P_{in}} \tag{2.9}$$

2.5.1.5 Quality Factor, Bandwidth and Efficiency

Quality factor, bandwidth and efficiency are determined the quality of antenna. They have relationship between them. If optimization process are made, one of these features should be selected instead of optimizing all.

Quality factor is defined as the losses which are radiation, conduction (ohmic), dielectric and surface wave losses. Quality factor can be defined as below;

$$\frac{1}{Q_t} = \frac{1}{Q_{rad}} + \frac{1}{Q_c} + \frac{1}{Q_d} + \frac{1}{Q_{sw}} \tag{2.10}$$

Where Q_c;

$$Q_c = h\sqrt{\pi * f * \mu\sigma} \tag{2.11}$$

Where Q_d;

$$Q_c = \frac{1}{tan\delta} \tag{2.12}$$

Where Q_{rad};

$$Q_c = \frac{2\omega\epsilon_r}{hG_t/l} K \tag{2.13}$$

$tan\delta$ is the loss of tangent of substrate material, σ is the conductivity of conductors which are patch and ground. G_t/l is the total conductance per unit of radiating aperture length.

Bandwidth defines the working frequency range of the antenna. When resonant frequecy is selected as center, the ratio between lowest and highest frequecy define the bandwidth.

$$BW_{broadband} = \frac{f_H}{F_L} \tag{2.14}$$

2.5.1.6 Voltage Standing Wave Ratio And Return Loss

Voltage standing wave ratio is the ratio between minimum voltage to maximum voltage. VSWR is depend on reflection coefficient which is the ratio between incident wave voltage amplitude (V_i) and reflected wave voltage amplitude (V_r). Reflection coefficient is defined as below;

$$\Gamma = \frac{Z_{input} - Z_0}{Z_{input} + Z_0} \tag{2.15}$$

Z_0 is defined as characteristic impedance. The relation between reflection coefficient and VSWR is defined as follow;

$$|\Gamma| = \frac{VSWR - 1}{VSWR + 1} \tag{2.16}$$

or it can be written as;

$$VSWR = \frac{|\Gamma| + 1}{\Gamma - 1} \tag{2.17}$$

2.5.1.7 Radiation Pattern

Pattern of antenna can be defined with demonstration of radiated antenna function at space coordinates. For defining the pattern, function of directional coordinates, far field must be considered . Radiation pattern can be defined with flux density, field strength, directivity, radiation intensity, phase and polarization. Radiated energy along the path or surface defined as a function and this energy distribution is demonstrated at the two or three dimensional space. Demonstration of radiation pattern is shown in figure 2.10.

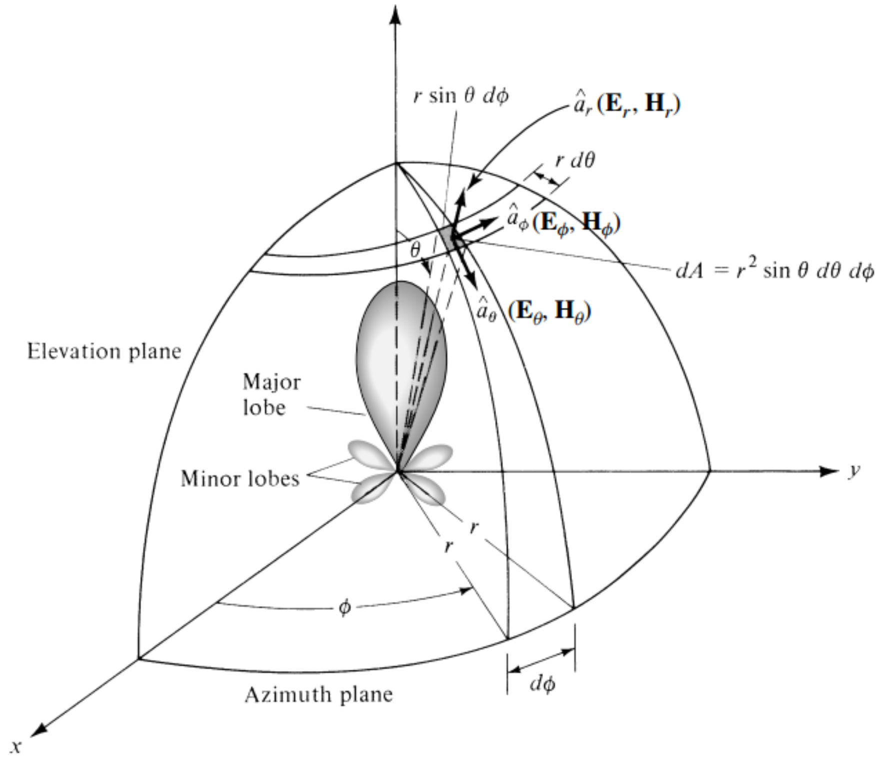


Figure 2.10: Coordinate System for Antenna Analysis [34]

2.5.1.8 Polarization

Polarization of antenna is defined by " the polarization of wave transmitted (radiated) by antenna". If the direction is not considered, polarization is taken as the direction of gain maximum. Direction of polarization varies with radiated energy from antenna center. For that reason, radiation pattern can varies with the direction of polarization of the antenna.

"that property of an electromagnetic wave describing the time-varying direction and relative magnitude of the electric-field vector; specifically, the figure traced as a function of time by the extremity of the vector at a fixed location in space, and the sense in which it is traced, as observed along the direction of propagation."[34] Thus, polarization is defined with the curve traced by instantaneous electric field arrow.

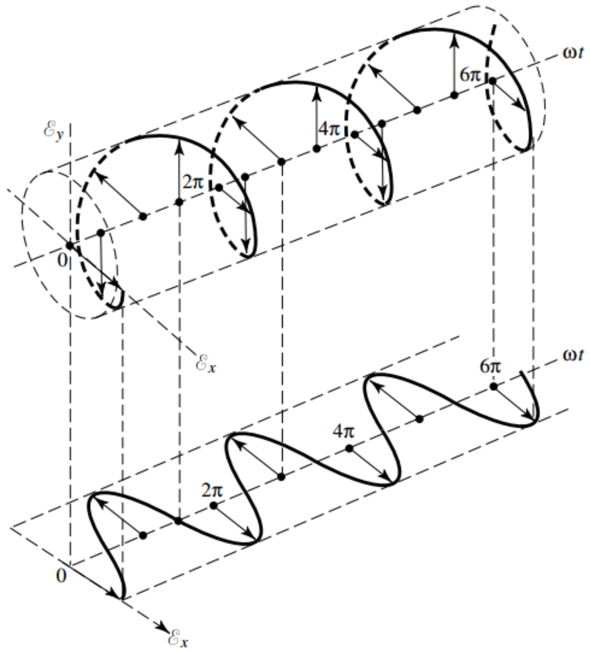


Figure 2.11: Rotation of Wave [34]

2.5.1.9 Circular Patch

Other most popular configuration is the circular patch or disk, as demonstrated in figure 2.12. Circular patch can be used as single patch or array configurations.

Circular patch antenna theory can be determined with modes of antenna as it is in the cavity model. However, instead of using theoretical models for design novel antenna patch, optimization and illustrations is performed with 3D solvers according to the literature. So getting knowledge about theory of patch models are enough to understand infrastructure of 3D design tools. Design parameters of circular patch radius are

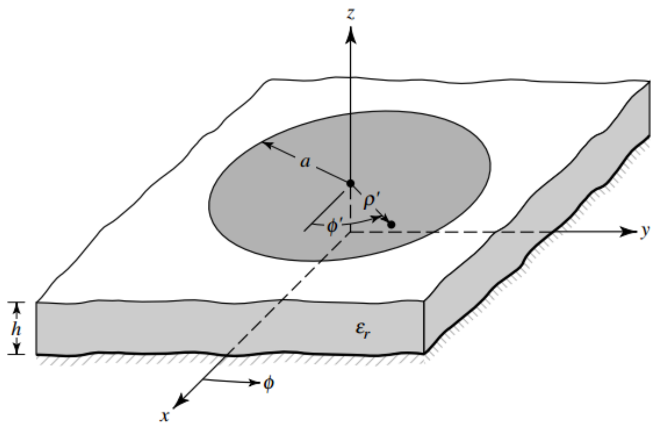


Figure 2.12: Circular Microstrip Patch [34]

concluded after so many theoretical calculations as below;

$$a = \frac{F}{[1 + \frac{2h}{\pi \epsilon_r F}[ln(\frac{\pi F}{2h}) + 1.7726]]^{1/2}} \tag{2.18}$$

Where F ;

$$F = \frac{8.791x10^9}{f_r \sqrt{\epsilon_r}} \tag{2.19}$$

Radius of circular patch is defined as "a" and it is given in equation 2.18. To find the radius, it is required to know the desired frequency, dielectric constant and thickness.

CHAPTER 3

DESIGN AND SIMULATION OF MINIATURE ANTENNA

3.1 Design Procedure

Antennas are still development which is used for remote control applications. For that type of applications the most important feature is to consider the sizes of antenna. However, it is hard to keep antennas at small sizes at Sub-GHz bands due to, when frequency become smaller, size of antenna become larger theoretically. For that reason at low frequencies, it is not possible to design microstrip miniaturized antenna with conventional methods. In the literature miniaturization techniques are mentioned which are using of high dielectric substrate, designing multilayer antenna, using of strip and slot patches, moreover using fractal shapes. The main idea behind using of fractal shape and using of microstip antenna is that increasing the conducting way current flow, keep small sizes and increase the area radiated in small dimensions. It can be contribute to design small size antenna at sub-GHz band.

3.1.1 Antenna Patch Design

Antenna Patch Design started with designing the patch of the antenna. Firstly it is started with simulation of miniature antenna in the literature [20] as it is shown in figure 3.1.

At the beginning the aim is to design a new miniature antenna patch from simulation of the antenna in the literature and then adding new strips to increase the electrical length. In figure 3.1, Model 1 has dimensions as 78 x 45 x 0.6 mm. FR4 is used as substrate (ϵ_r= 4.4). The initial shape is included a conventional L-shaped strip antenna with 60 x 60 mm (0.18λ x 0.18λ) square patch.

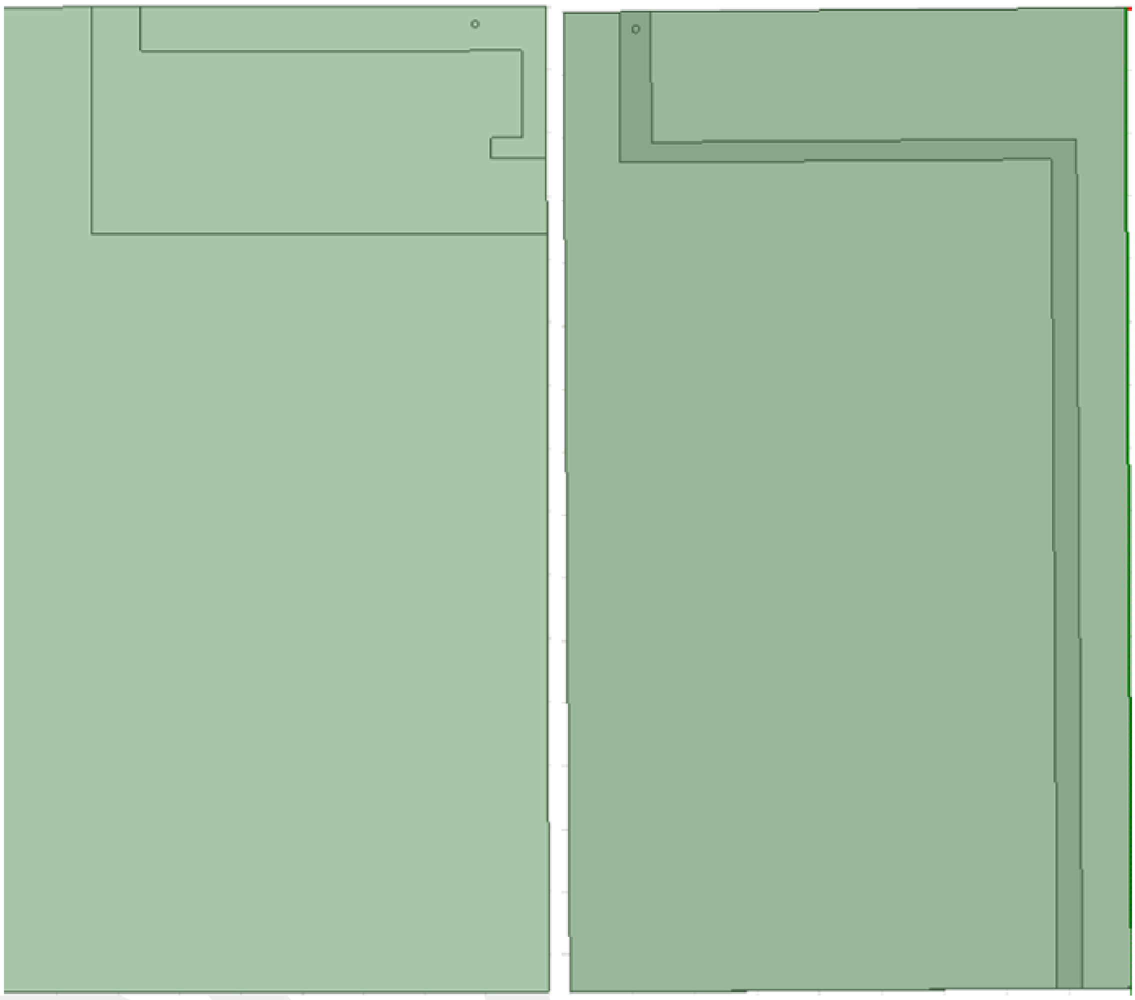


Figure 3.1: Front and back side of Model 1 (simulated)

Return loss of Model 1 is obtained as -24 dB at 941MHz. Even return loss of the antenna gives good performance, the operating interval of bandwidth is too wide. And also operating frequency can be reduced.

The gain of antenna is obtained as -5dB. The performance of the antenna does not reach to desirable values. Due to the miniature sizes, it is not possible to increase gain without optimizing strips' weight and length.

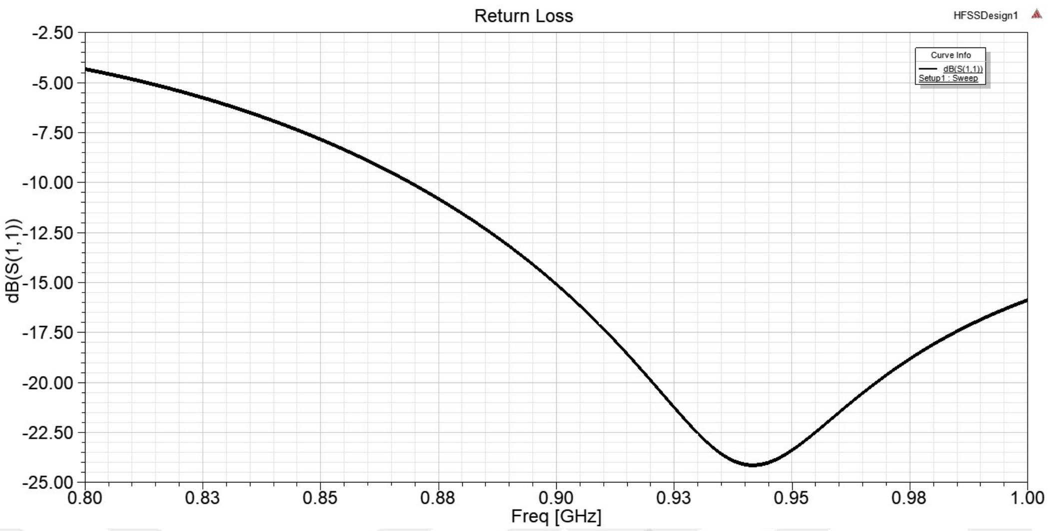


Figure 3.2: Return Loss of Model 1 (simulated)

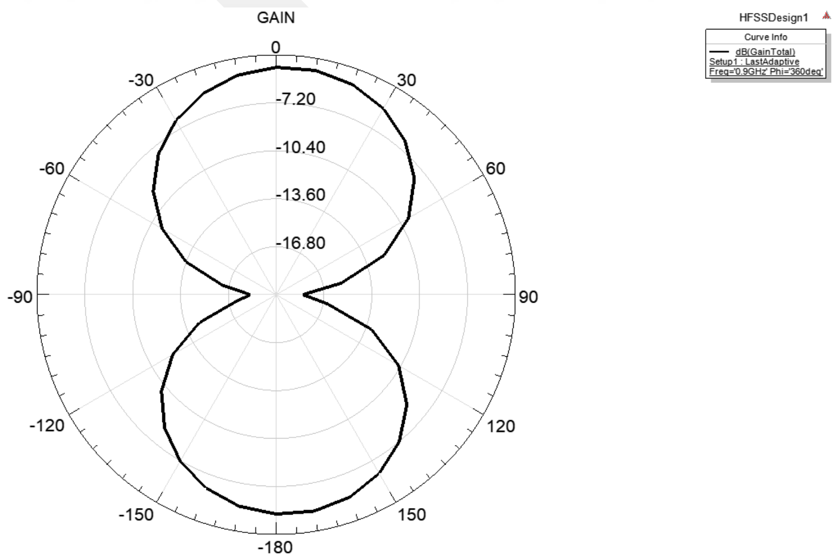


Figure 3.3: Gain of Model 1 at x-z plane (simulated)

Model 2 has dimensions as 95 x 42 x 1.6 mm. New S-shape and L-shape stubs are used together to increase electrical length via increasing current path length as shown in Figure 3.4. FR4 is used as substrate.

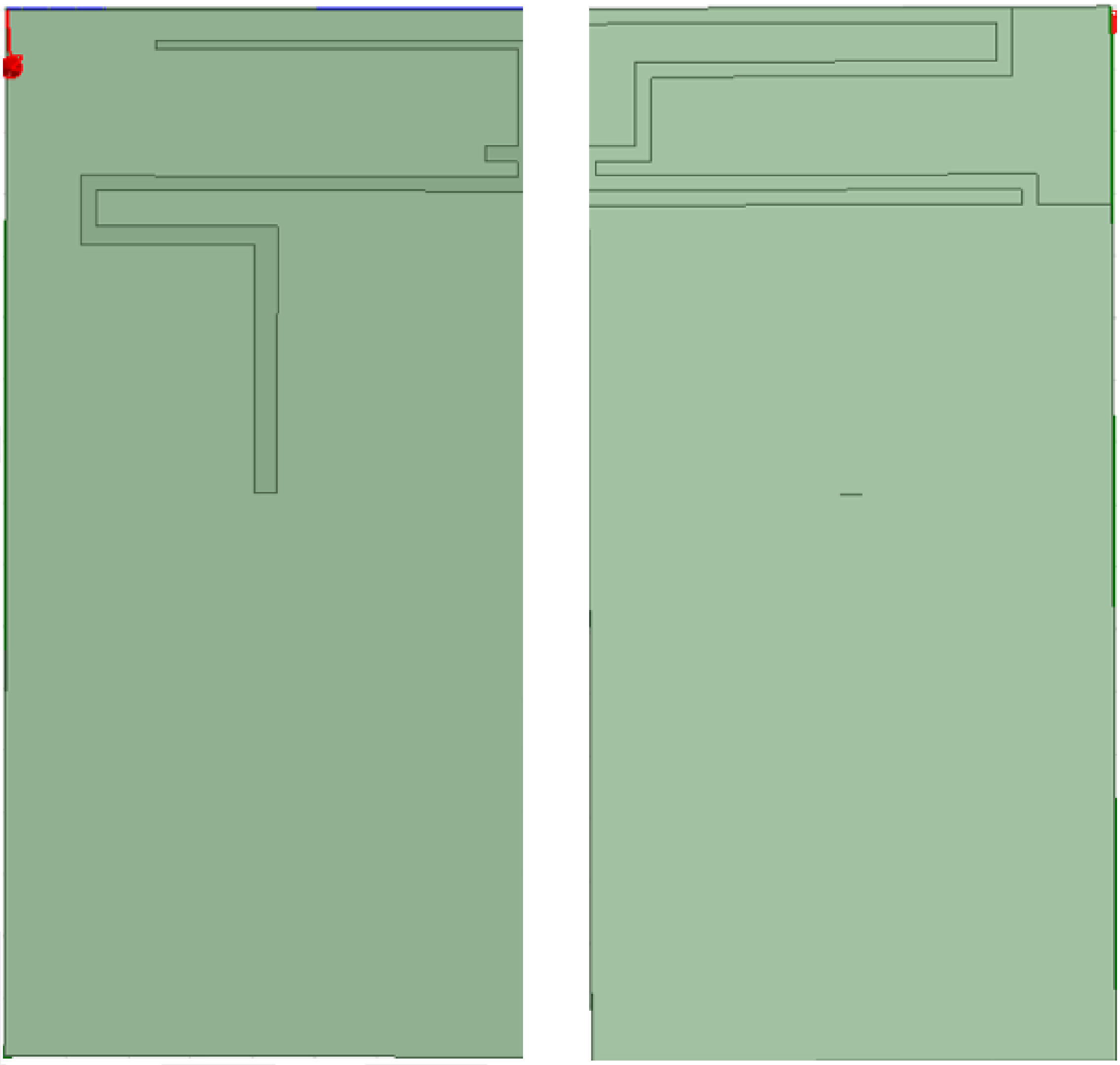


Figure 3.4: Front and back side of Model 2 (simulated)

Feeding line length did not include to increase electrical length of antenna. Therefore, antenna strips length become inadequate to reduce frequency. As it is seen in figure 3.5, frequency is shifted to the GHz bands.

Gain increases near to 0 dB, due to feeding point match condition the dimensions of antenna increases while the polarization does not change.

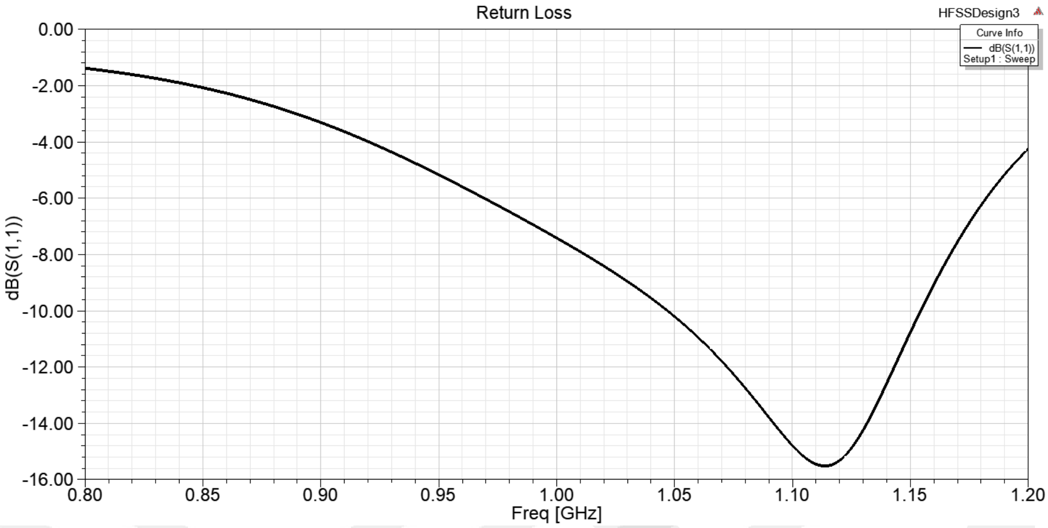


Figure 3.5: Return Loss of Model 2 (simulated)

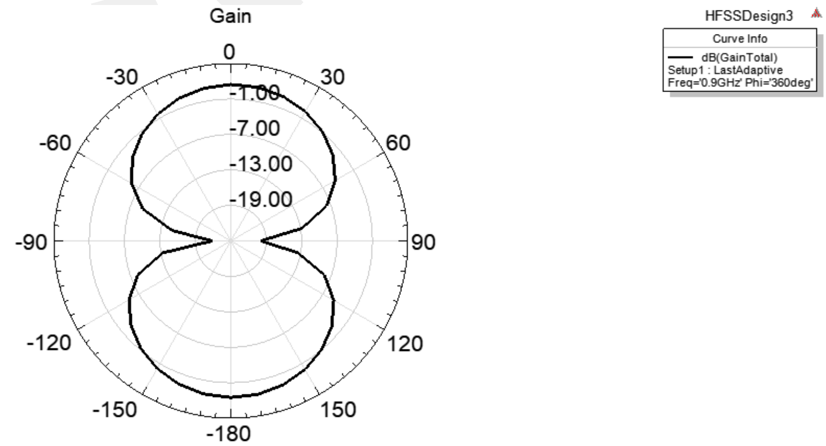


Figure 3.6: Gain of Model 2 at x-z plane (simulated)

In model 3 with dimensions 114 x 42 x 0.5 mm, it is necessary that increasing number of strips and increasing electrical length of patch more.

Therefore, new paths and U shape stub are attached to the left side as given in the [10], [19], [22] and small piece of strip at the right side is removed, as shown in Figure 3.7. In order to find the best matching point, length and width of strips and length of the feed line are optimized. And substrate is selected as FR4.

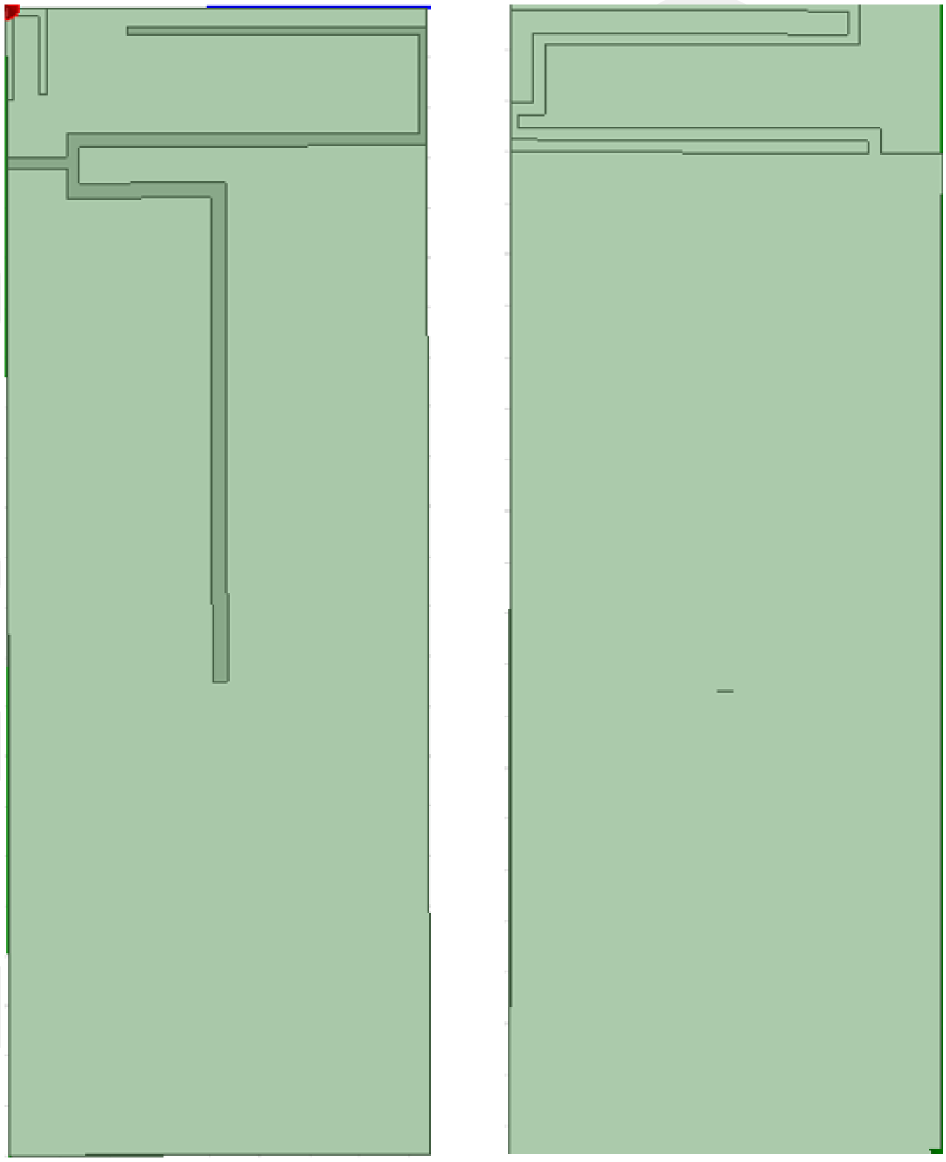


Figure 3.7: Front and back side of Model 3 (simulated)

Model 3 operates at 808 MHz and return loss is obtained as -15 dB. It is a proof that as the length of strip increases, the frequency shift to MHz bands. As mentioned in theory, the addition of a new strip and a 9mm increase in the length of the overall antenna had a direct effect on the antenna frequency.

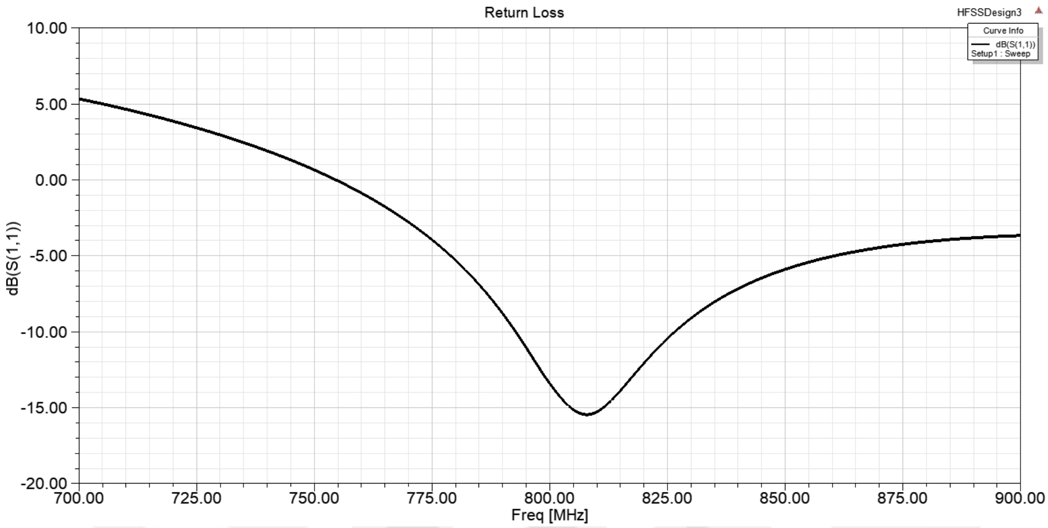


Figure 3.8: Return Loss of Model 3 (simulated)

Gain of Model 3 is obtained as -1 dB and polarization at x-z plane does not change. Gain of antenna can be developed with optimization of dimension with strips and feeding line width, length.

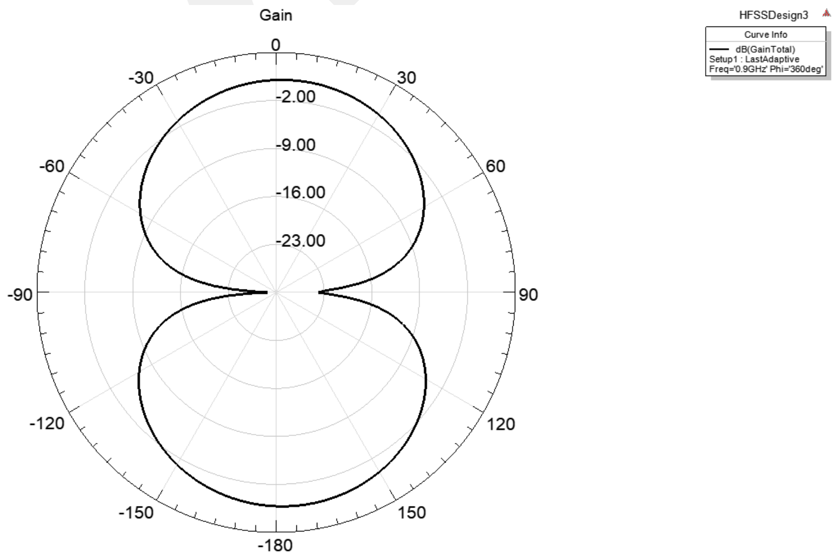


Figure 3.9: Gain of Model 3 at x-z plane (simulated)

Although antenna theory has been proven with Model 3, electrically extending cannot be considered as a single criterion for miniaturization. The match point of the feeding line, the substrate, the proximity and shape of the strips are of great importance as it is examined at Model 4.

3.1.2 Renewed Model 4 Design and Production

At Model 4, new strip is added to the left side of the patch which is inspired from [22]. After adding the loop structure, length and weight of strips are optimized. Initially, the antenna structure is designed as follows;

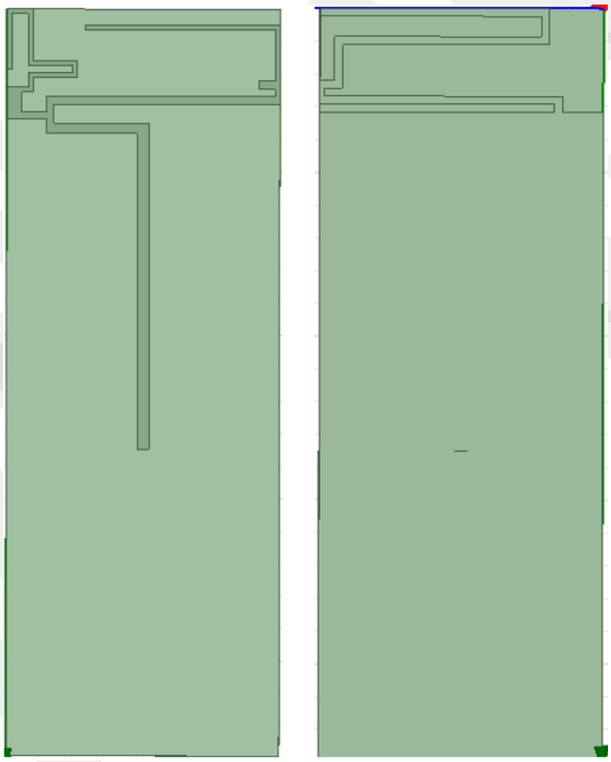


Figure 3.10: Front and back side of Model 4 (simulated)

Antenna at figure 3.10, dimensions with 114.6 x 42 x 0.5 mm and substrate is selected as RT Duroid 5880 (ϵ_r= 2.2). The frequency is expected to be decreased by increasing the length of the radiating patch, but as the substrate is changed and the added new strips interact with each other due to their sharp corners, the result is not consistent in terms of the frequency. These sharp and close strips also led to quite inconsistent results during optimization process. As the number of strips increased and closer to eachother, it was difficult to obtain consistent results in terms of frequency and return loss in miniaturization improvements. Even the dimensions of the antenna are larger than desired, it can be acceptable. The antenna return loss obtained as in figure 3.11,

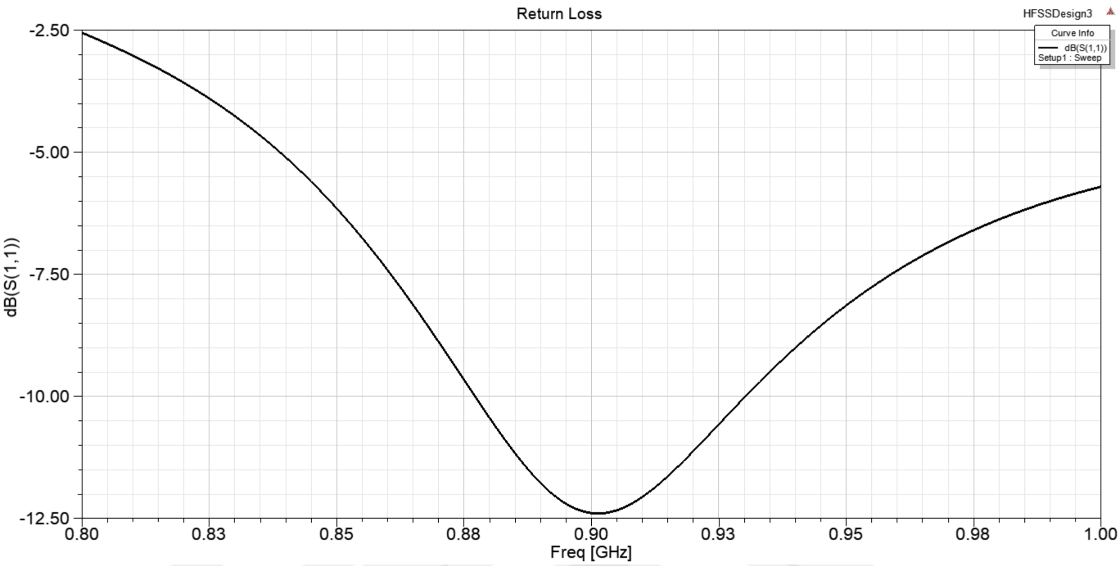


Figure 3.11: Return Loss of Model 4 (simulated)

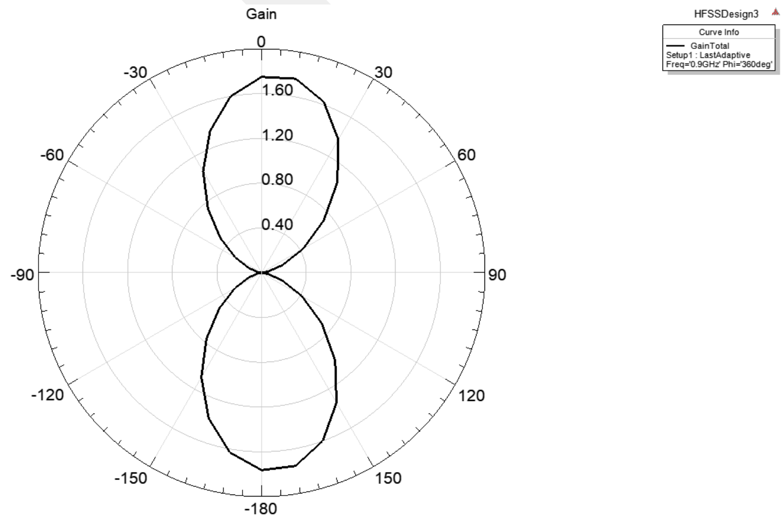


Figure 3.12: Gain of Model 4 at x-z plane (simulated)

Due to the reasons are mentioned above, although the sizes of antenna are not reduced according to model 3, the gain is obtained as 1.7 dB, because both dimensions and length of strips are increased. The polarization structure in the x-z plane gets narrower, but the general structure has not changed.

The model 4 can be produced after optimizing dimensions, return loss and operating frequency. It was started with substrate RT Duroid 5880 and than replaced by FR4, as it is readily available and supports operating at sub-GHz bands. Also optimizations are made on strips and optimal values are determined as it is shown below;

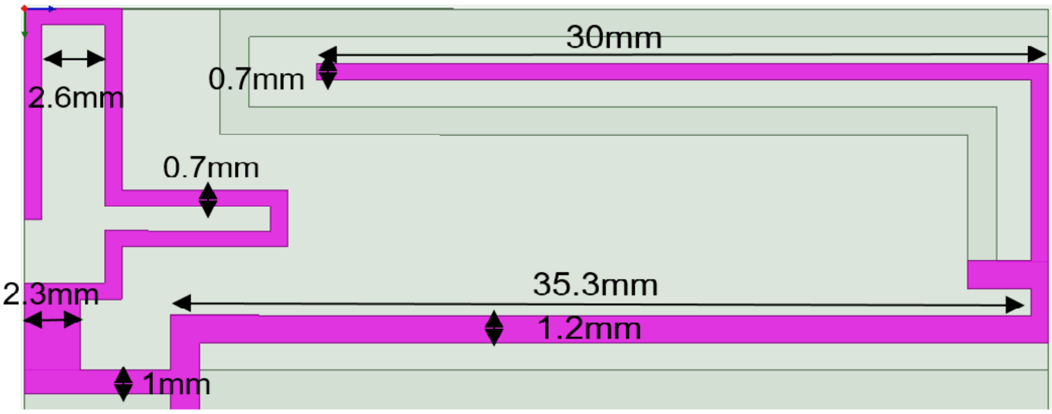


Figure 3.13: Optimal value of optimized strip dimensions

After optimizing the strip, the antenna sizes were reduced to 89.6 x 42 x 1.6 mm with changing of substrates to FR4. And return loss of renewed antenna is obtained as below;

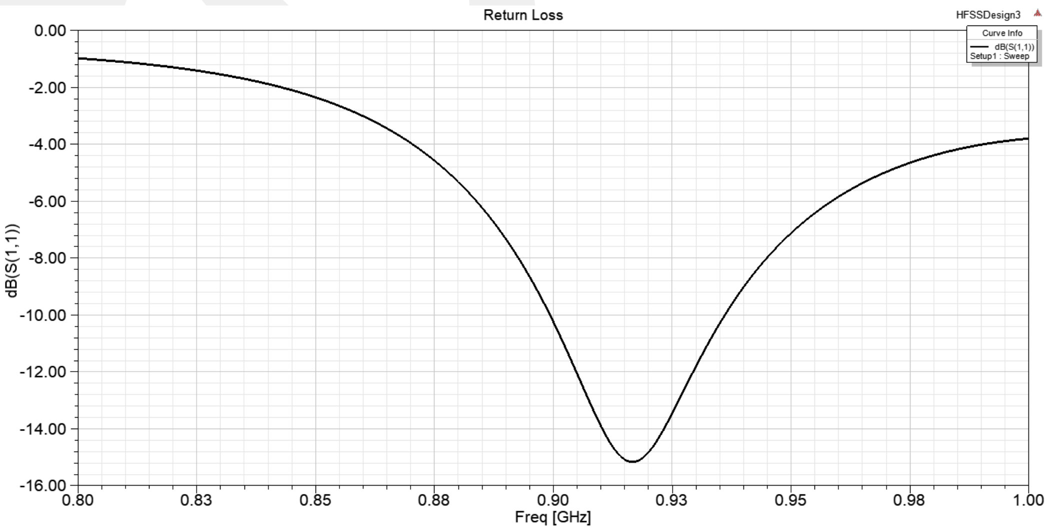


Figure 3.14: Return loss of renewed Model 4 (simulated)

Return loss is obtained as -15 dB at 917 MHz, frequency does not change so much as it is expected and dimension of antenna is reduced at the mean time with the optimization of strips. Gain of antenna is obtained as 1.4 dB with the optimization of feeding line.

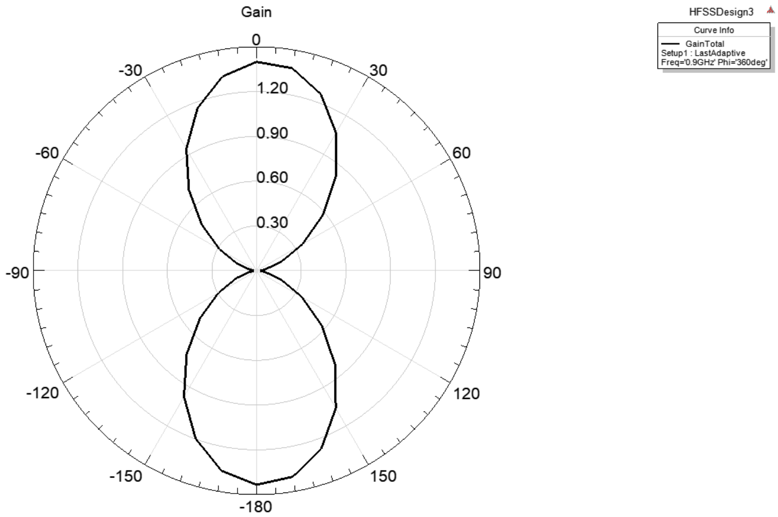


Figure 3.15: Gain of renewed Model 4 at x-z plane (simulated)

A renewed antenna supply miniaturized antenna requirements. The production was performed to compare the results of the antenna design and the results of measurements in the laboratory. Produced antenna is shown in 3.16;

Antenna return loss measurement is made at the laboratory and -9 dB is obtained at 962 MHz. Result of measurement and simulated values are not close to each other as shown below;

The measured antenna return loss in the vicinity of -10 dB and the antenna strips are occurred by rectangular strips that electrically influence each other. For that reason fluctuations are occurred at the antenna frequency and return loss values. it is obvious that the antenna shape should be developed to eliminate fluctuations and to increase performance.

Figure 3.16: Produced antenna of renewed Model 4

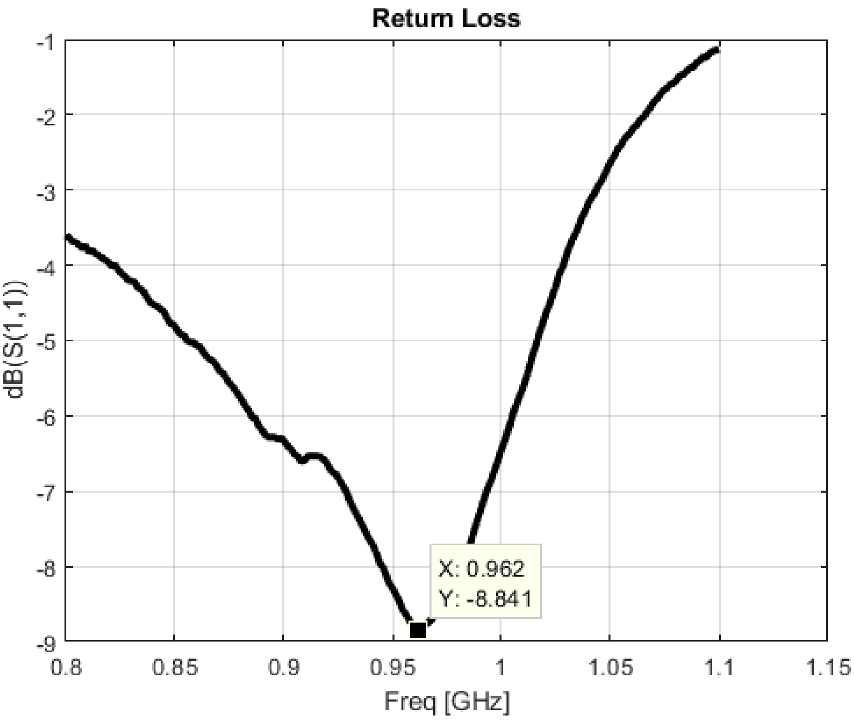


Figure 3.17: Return loss of renewed Model 4 (measured)

3.1.3 Proposed Antenna Design and Production

After considering the miniaturization techniques and designed patches in the literature, the proposed antenna is developed. For this purpose, the proposed design includes a s-strip and f-strip patch with a polygonal geometry. Since we have the accuracy of finite element method (FEM) and finite integration technique (FIT) in this small size antenna comparison results, we decided to use FEM based 3D solver for all design, simulation and optimization processes of the antenna [31].

Miniaturization process was undertaken to obtain the smallest easy to manufacture antenna while achieving relatively high gain compared with equivalent designs. For this purpose, length of feeding line, substrate material and thickness were considered initially to achieve this. Most of the reference antennas [10], [19-22] have many corners with nested loops to increase the electrical length. After examining the antennas described in the literature, the final shape of the patch was determined through the optimization of strip dimensions and adding of circular patch.

3.1.3.1 Effect of Circular Patch

As previously mentioned, adding only strips could create contrasts in increasing electrical extension. The fact that the corners are close and sharp make the optimization more difficult and cause fluctuations in frequency.

This problem was overcome with the addition of circular patch. The rectangular strips need to be optimized in both length and weigth, whereas the circular patch requires only radius optimization as theory mentioned. Since it has no corners, it is thought to reduce the interactions between strips and eliminate the contradictions. The results obtained also provide this idea. The effect of the added circular patch radius on the return loss is examined as 3.18,

Since the total length of the strips is designed to operate under the GHz band, the change in radius can be interpreted in these bands as consistent. When the radius is less than 5 mm and greater than 10 mm, it does not operate at these bands. However, when the radius is between 6 mm and 9 mm, the frequency has shifted upwards as the

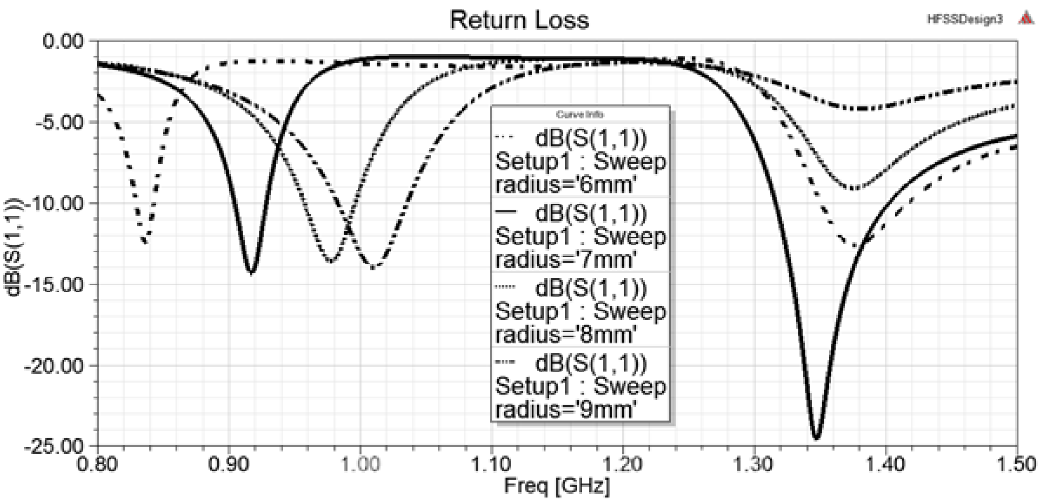


Figure 3.18: Effect of circular strip radius on return loss (simulated)

radius increases for sub-GHz bands. In the GHZ bands, return loss does not consistent due to this design do not support operating at GHz bands properly. Since the band closest to 900MHZ is provided in radii of 7 mm and 6 mm, the selection of these radii will be appropriate. Besides, 7 mm's retun loss is superior to 6 mm, though they are all close scale. Therefore, 7 mm radius is selected.

3.1.3.2 Effect of Feeding Line Length

After obtaining the general shape of patch, feeding line effect and substrate material is additionally examined since increasing the thickness and length of the feeding line, substrate material and thickness may reduce the antenna area. First the length of feeding line was optimized for miniaturization. Figure 3.19 demonstrates the effect of the changes in the feeding line length on return loss.

As shown by Figure 3.19, it was not possible to define a straight forward relationship between length and frequency change; e.g., when the frequency increases, the length also increases. The values did not follow a consistent pattern with the frequency resonance value does not only depending on the length of line but also changes in the direction of interaction of patch strips. Therefore, rather than considering that the best result can be obtained by increasing the length of feeding line, optimization processes should be undertaken to determine the value of length that would minimize the effect

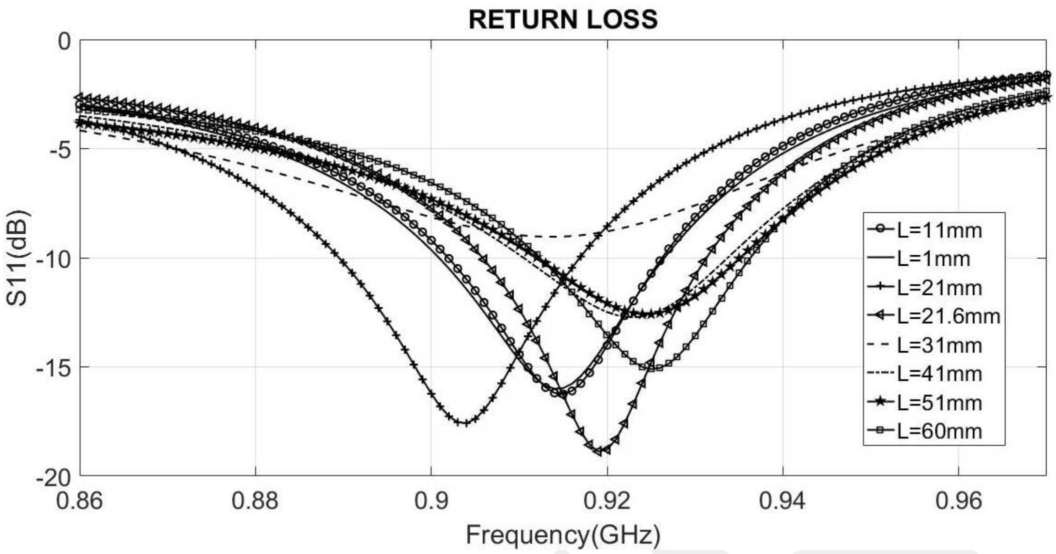


Figure 3.19: Optimization of feeding line length

of interaction between the strips. In this study, after the optimization process, the best result was obtained from the feeding line length of 21.6 mm, confirming the idea that an increase in the length of feeding line would not necessarily have a positive effect. This can also be interpreted as the length increases in the feeding line may not be included in the electrical length increment, since match conditions must also be considered. Although the main aim is to increase the electrical area, the interaction between the corners and loops (strips) should be considered to a greater extent in the type of antennas described here.

3.1.3.3 Effect of Substrate Thickness and Material

The substrate material and thickness is another design parameter in antenna optimization. The cost and availability of the substrate is a critical issue, and is mostly ignored by the designers. For the mass production of the antenna and easy-to-manufacture, the cost plays a critical role. On the other hand, in miniaturization techniques, generally substrates with high permittivity are preferred. Although FR4 (ϵ_r= 4.4) is used in the fabrication due to its availability, other materials such as RT duroid 5880 (ϵ_r= 2.2), Arlon AD600 (ϵ_r= 6.15), and Rogers RO3010 (ϵ_r= 10.2) can also be considered. However, unit costs of these material are not comparable with FR4.

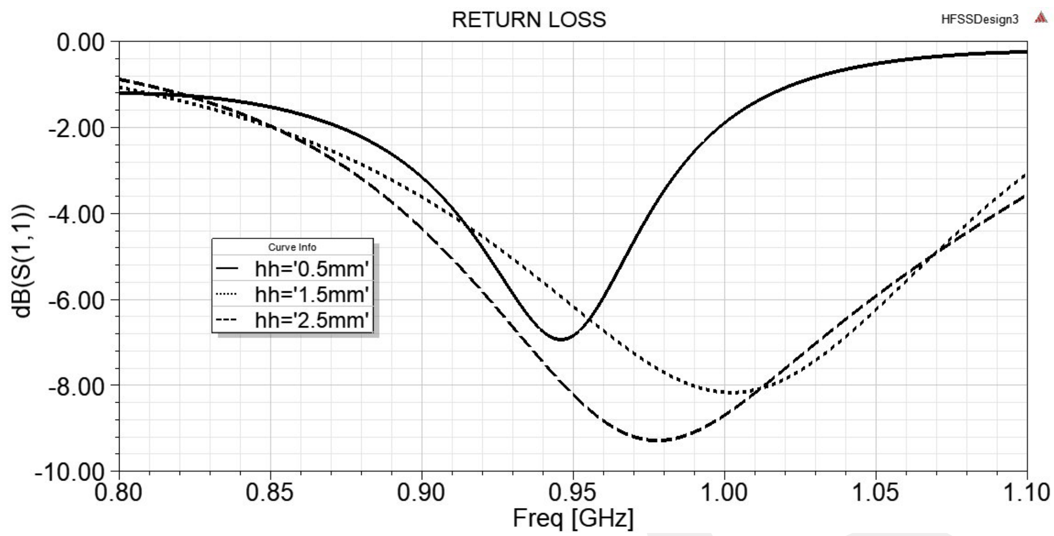


Figure 3.20: RT duroid 5880 thickness optimization process

Figure 3.20 presents the variation of the return loss for three optimal values of substrate thickness (h). It should be noted that RT Duroid 5880 with relative permittivity of 2.2 seems to be inappropriate for this type of antenna. No consistent pattern was observed with the variation of the thickness of the substrate. The thickness of RT Duroid 5880 may not be the main design parameter for such designs.

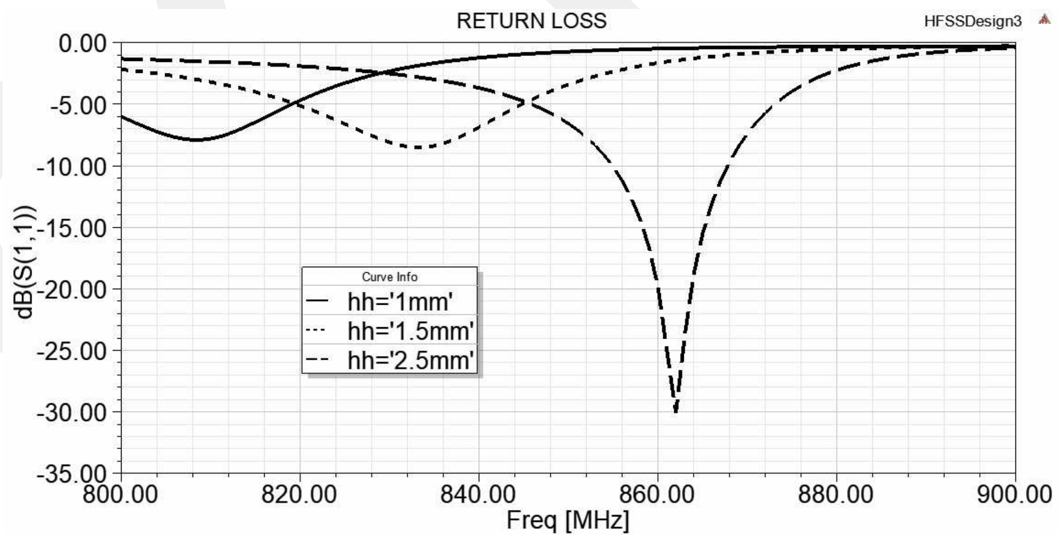


Figure 3.21: Arlon AD600 thickness optimization process

Figure 3.21 demonstrates that Arlon with relative permittivity of 6.15 produced consistent results in terms of the changes in the thickness values, and thus presented as a better option since at 2.5 mm thickness, the return loss reached -30 dB at 862 MHz.

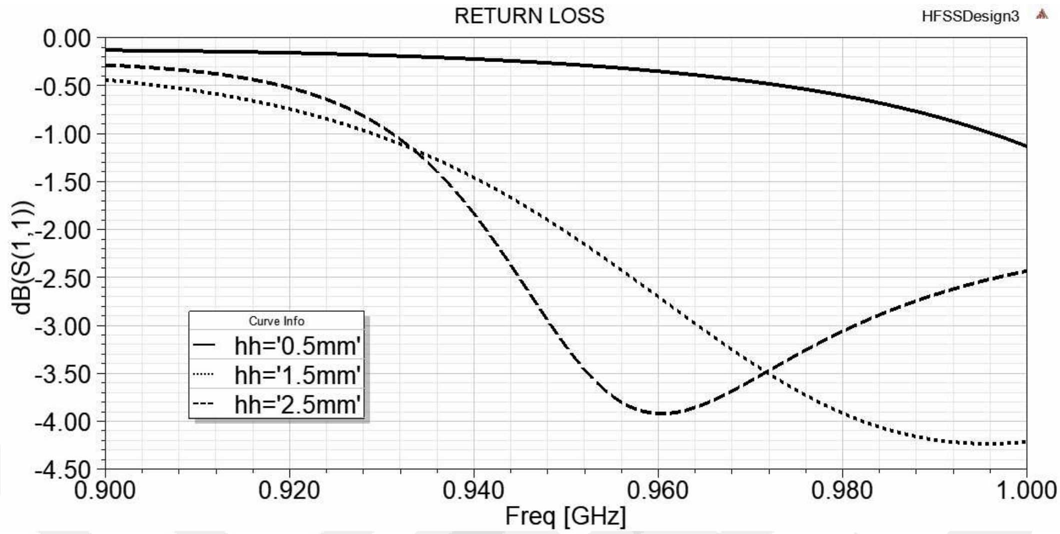


Figure 3.22: Rogers RO3010 thickness optimization process

In Figure 3.22, the optimization values of RO3010 with relative permittivity of 10.2 are shown. At lower thickness of the substrate, the frequency values shifted toward higher values, but they exceeded the sub-GHz band. For general miniaturization processes, high-permittivity substrates are usually recommended, but when the sub-GHz band is considered, it may be necessary to overlook this recommendation and focus on the material that is suitable for the sub-GHz band.

FR4 with relative permittivity of 4.4 is mostly used for sub-GHz bands, and it is very easily available and cheap. As shown in Figure 3.23, when the thickness of the substrate increased, the working frequency also increased. The return loss value generally seemed to remain in the same scale. However, in the industry, the thickness of the available FR4 is 1.6 mm; therefore, when examining the simulation, FR4 with this thickness was considered. As mentioned before, the parameters used in simulations should be adjusted depending on the availability of material. According to the results of analyses, the optimal substrate was selected as FR4 with relative permittivity of 4.4. Table 1 presents the optimal values for all miniaturization parameters, namely the feeding line length, location and dimension of strips.

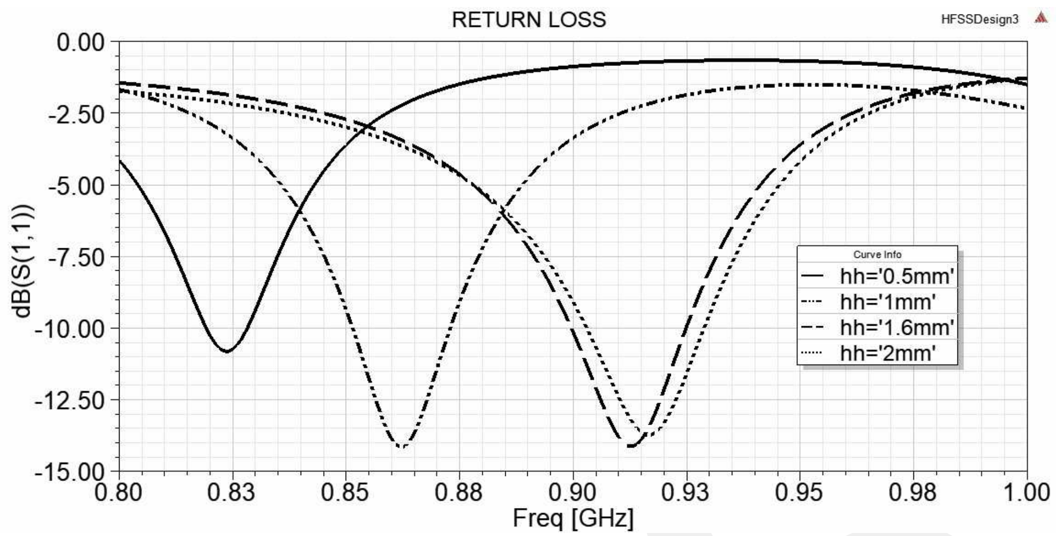


Figure 3.23: FR4 thickness optimization process

3.1.3.4 Fabrication and Measurements of Proposed Antenna

As the added circular patch is compatible with other patches, the miniaturization has been improved by increasing the electrical length. Optimizations were performed on strips, feeding line length, substrate material and thickness. Final dimension of the designed antenna was 0.25λ x 0.124λ x 0.0047λ (84.6 x 42 x 1.6 mm) with the free space wavelength at the resonant frequency, as Figure 3.24 shows the front and back of the designed antenna.

After completing the optimization process, the antenna was fabricated as shown in Figure 3.25 to verify the accuracy of simulations by comparing the results of simulations and measurements.

It should be noted that the return loss of the antenna was -19 dB at 920 MHz in the simulations while it is -18 dB at 887MHz in the measurements of the fabricated antenna (Figure 3.26). The radiation pattern and gain measurements were also undertaken in an anechoic chamber to compare with the simulations. As expected, some minor differences were observed between the simulation results and the measurement results as in many published works of the literature. Simulations represent the best possible parametric optimization.

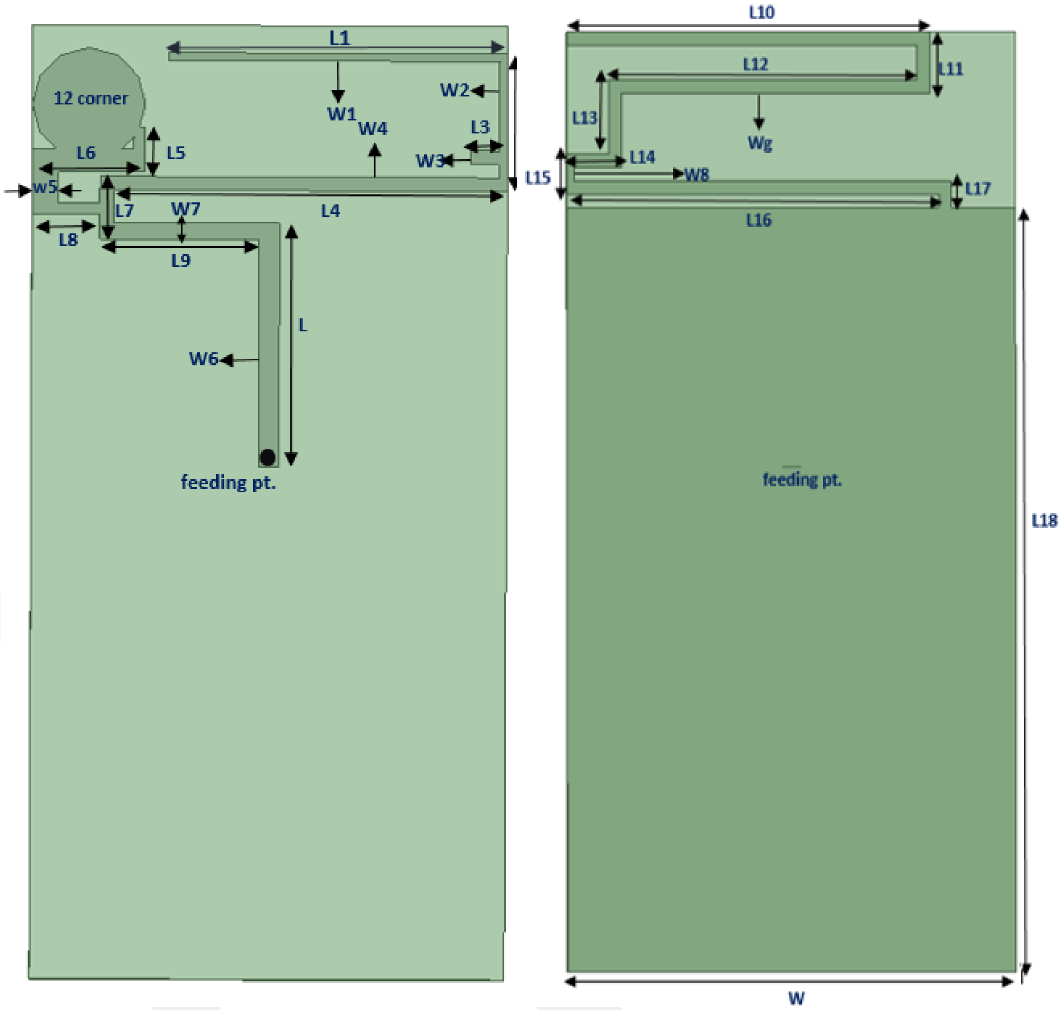


Figure 3.24: Top and bottom view of the proposed antenna (simulated)

Table 3.1: Optimal values of Proposed Antenna.

Parameter	Length(mm)	Parameter	Length(mm)	Parameter	Length(mm)	Parameter	Length(mm)
L1	30	W4	1.2	L8	6	L14	5.1
W1	0.7	L5	4	W8	1	L15	4.8
L2	12.2	W5	2.3	L9	14.1	L16	34.8
W2	0.7	L6	10	L10	34	L17	2.4
L3	2.6	W6	1.8	L11	5.5	W	42
W3	1.2	L7	5.6	L12	30.1	L18	68.8
L4	36	W7	1.2	L13	7.9	Wg	1.2

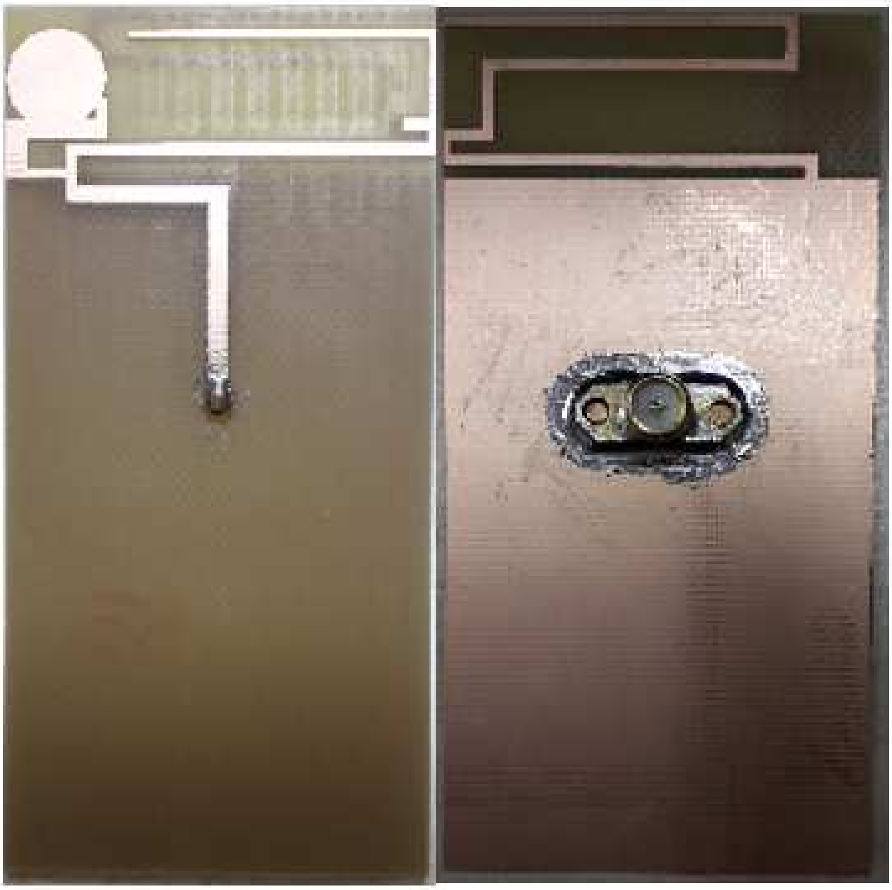


Figure 3.25: Top and bottom view of the produced antenna

Discrepancies between the simulations and the measurement results are described as follows;

1. It is reported that the measurements in the anechoic chamber have an error margin of within 1 dB (the measurement was sub-contracted to a well-known state center in RF measurements-BTK).
2. Fabrication tolerances of the PCB equipment and experience of the technician of the department was another very critical issue, especially, for such small antenna fabrication works (PCB equipment in the laboratory has about 0.2mm tolerances)
3. Soldering quality of feeding line and its EM modelare other important factors (very small conductive pieces, that could be modeled well, might affect the performance greatly)

4. Lastly, the authors have tried many such designs and their experience is that material thickness and properties of the substrate may not be homogeneous (however, this is rather minor issue in this size of antennas, in this specific design)

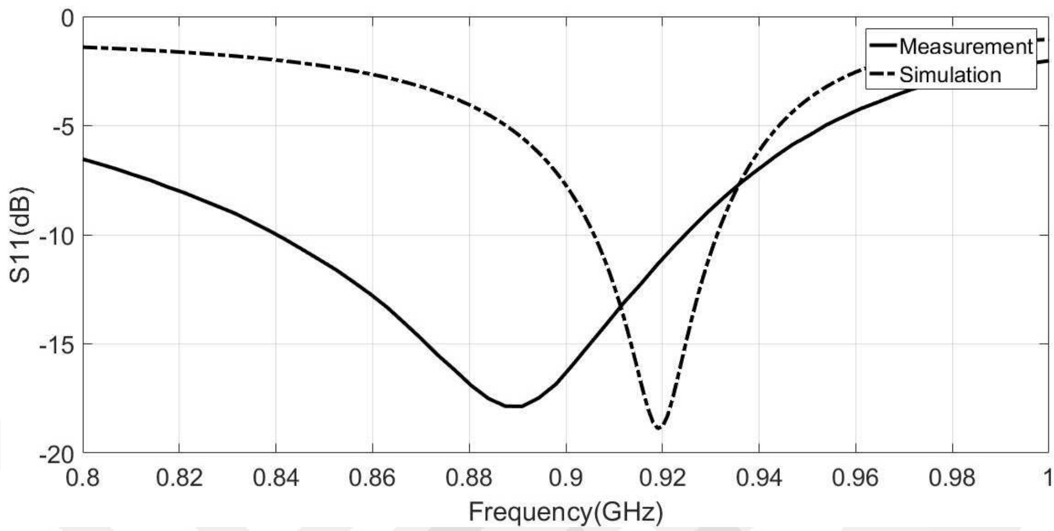


Figure 3.26: Return loss of the simulated and fabricated antenna

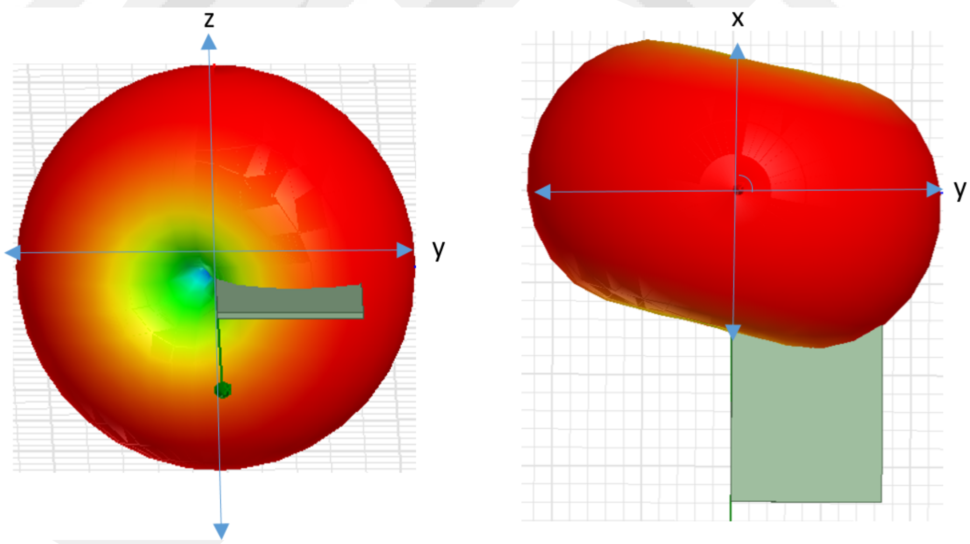


Figure 3.27: 3D polarization pattern of proposed simulated antenna

The measurement of the antenna was made for the (x-y plane) plane over -180 to 180 degree with the angle determined as the orthogonal projection of z-axis on the x-y plane. x-y plane defines the changing at ϕ angle. The polarization measurement of antenna made at y –z plane for all θ and ϕ = 70 degree which is determined according to the polarization of antenna as figure 3.27 shows

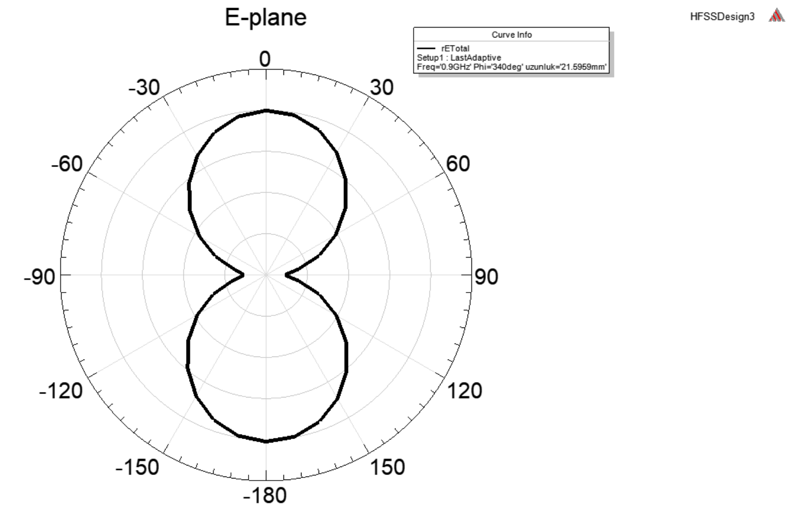


Figure 3.28: E-plane pattern of proposed simulated antenna

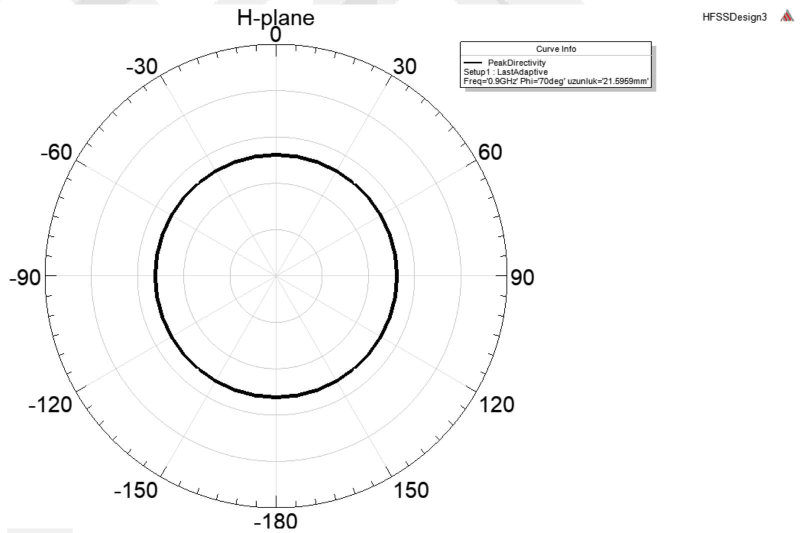


Figure 3.29: H-plane pattern of proposed simulated antenna

Polarization of simulated antenna at x-z plane and y-z plane is demonstrated. In that antenna E-plane (x-z plane) start from phi= 340 degree instead of phi=0 and H-plane(y-z plane) start from phi=70 degree instead of phi=90. E-plane and H-plane of antenna at phi=340 and theta all is obtained as above;

Figure 3.30 shows the measured gain at H-plane to be 1 dB within the measurement angle phi=70. Thus, as shown in Figure 3.30 the simulation result appears to be very close to the measurements. The discrepancies can still be attributed to the issues listed above.

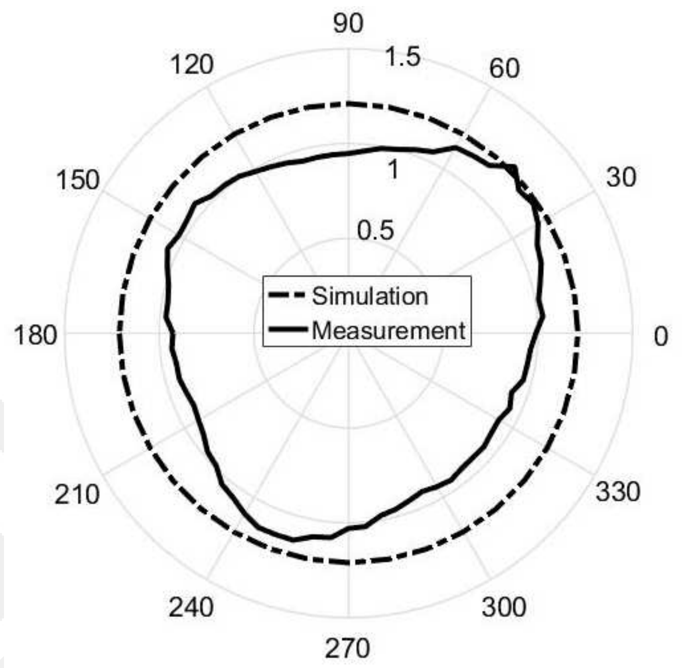


Figure 3.30: The radiation pattern of the simulated and fabricated antenna

3.1.4 Multi-band Operation

In remote control systems, multiband operations are an important factor due to requirements. Using of much antenna for different operating frequencies will result in cost. Proposed antenna can operate at multiband, using of it can reduces the cost and increases the usage area. The designed antenna provide this requirement of remote control systems with dual band operation capability. Return loss of simulated and fabricated antenna at GHz band is obtained as -18 dB at 1.34 GHz and -11 dB at 1.37 GHz.

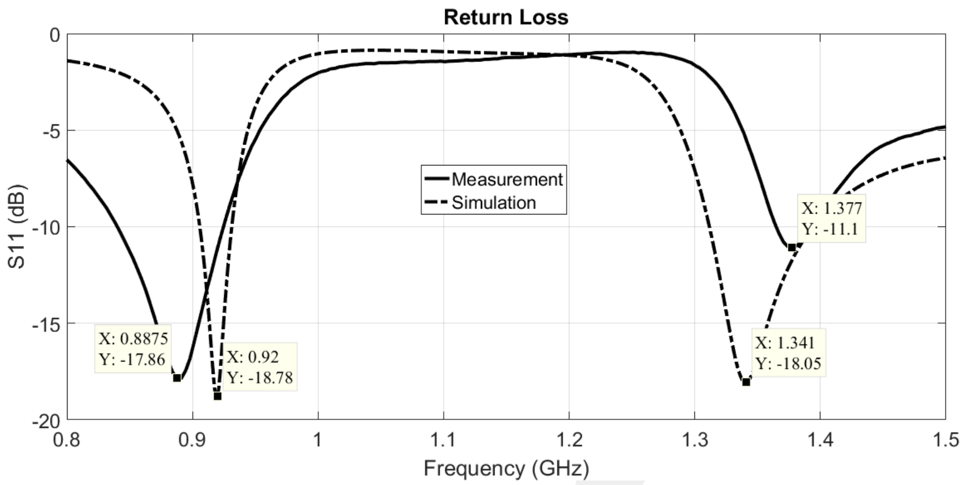


Figure 3.31: The return loss at multiband of the simulated and fabricated antenna

3.1.5 Multi-Layer Antenna Design

As mentioned in the introduction part, one of the miniature antenna design methods is to use of multi-layered antenna structure. The validity of this method is experienced by designing the multi-layered antenna. In the simulation of antenna design, [35] is taken inspiration as it is seen below;

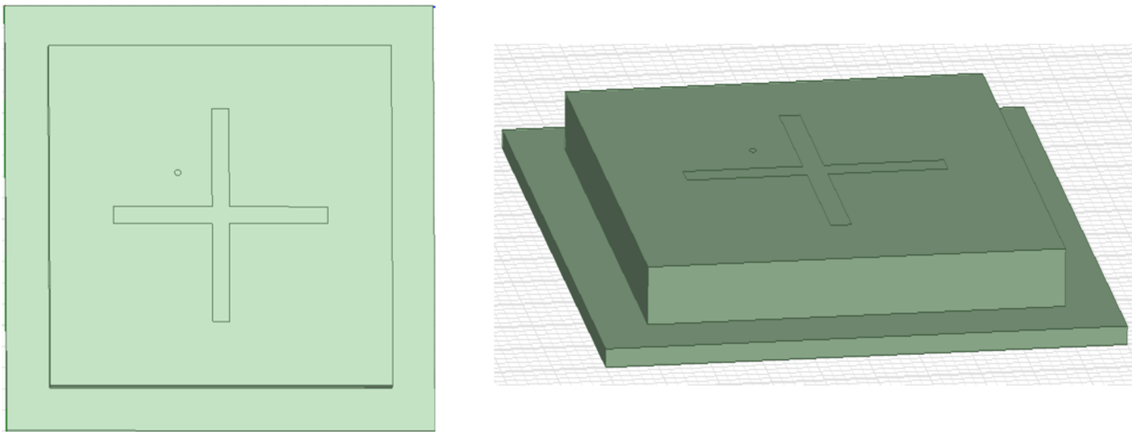


Figure 3.32: Front and Side view of multi-layered Antenna (simulated)

This antenna has dimensions as 100 x 100 x 6.6 mm with two layer, air layer at the top with 80 x 80 x 5 mm and FR4 layer at the bottom with 100 x 100 x 1.6 mm. Radiated patch was designed with slots and ground plane placed at the bottom. Feeding point placement and thickness of layer were optimized. As the result of simulations return loss was obtained as -43 dB at 876 MHz as shown below;

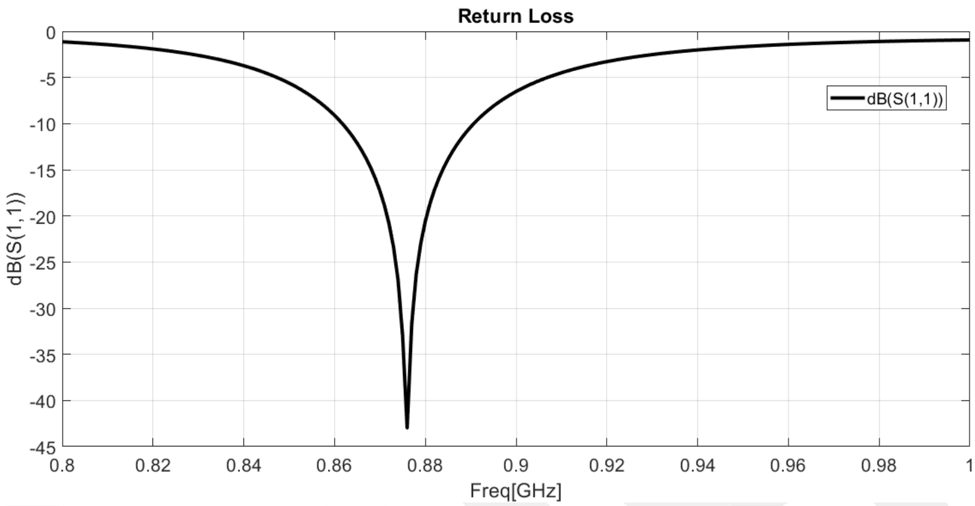


Figure 3.33: Retun Loss of multi-layered Antenna (simulated)

Gain of antenna was obtained as 1.8 dB. Gain has been obtained quite close with the previous proposed antenna. Also dimensions are slightly acceptable for miniaturization. Although it still needs to be minimized, it is obviously obtained that reduction can be performed with the multi-layered antenna structure.

Figure 3.34: Gain of multi-layered Antenna (simulated)

3.1.6 Effect of Plastic Box

In practice, command boxes are controlled with joysticks which are placed on the box in remote control systems. The box effect should be examined for this type of antenna. For the command box, plastic materials are mostly used in which the dielectric constant should be low. Materials such as polystyrene, polyethylene, and polyamide can be used as the box material due to their low dielectric constant.

The important consideration is the easy availability and low cost of the material to be selected. Therefore, in this study, polyamide material with the relative permittivity value of 4.3 was selected.

Figure 3.35: Sample command box used in the industry

The box was produced in a way that it could be used in the control sector. A sample command box used in remote control applications is presented in Figure 3.35.

In accordance with the current industrial use, the box dimensions were determined as 200 x 250 x 100 mm (0.59λ x 0.74λ x $0.3\ \lambda$). The antenna was placed into the fabricated box as shown in Figure 3.36.

The return loss and gain were measured again after the antenna was placed into the box, and the results of return loss were compared Figure 3.37

Figure 3.36: Top and side view of the box into which the antenna was placed

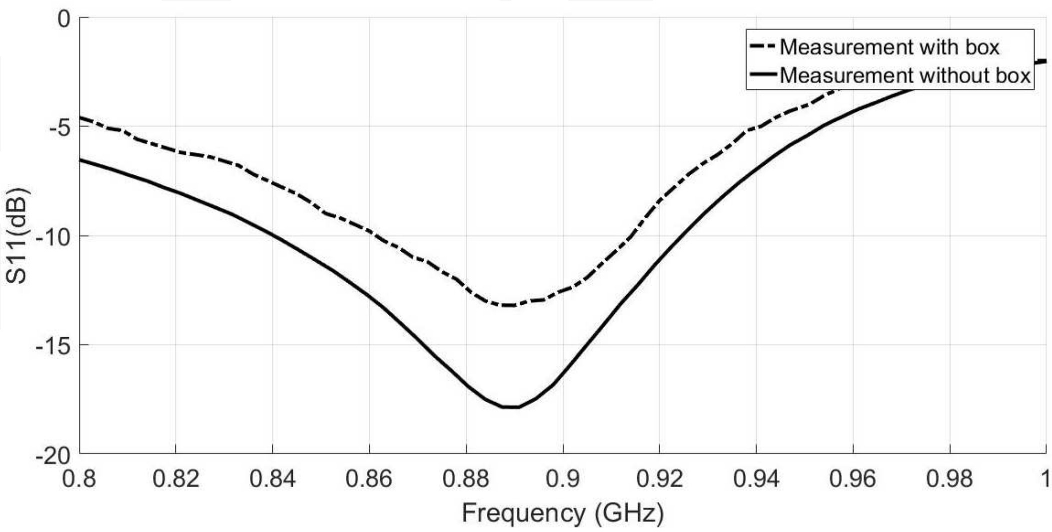


Figure 3.37: Return loss of antenna and the antenna in the box

As expected, placing the antenna in the fabricated box reduced the return loss to -13.2 dB, but this did not have an effect on the frequency value (Figure 3.37).

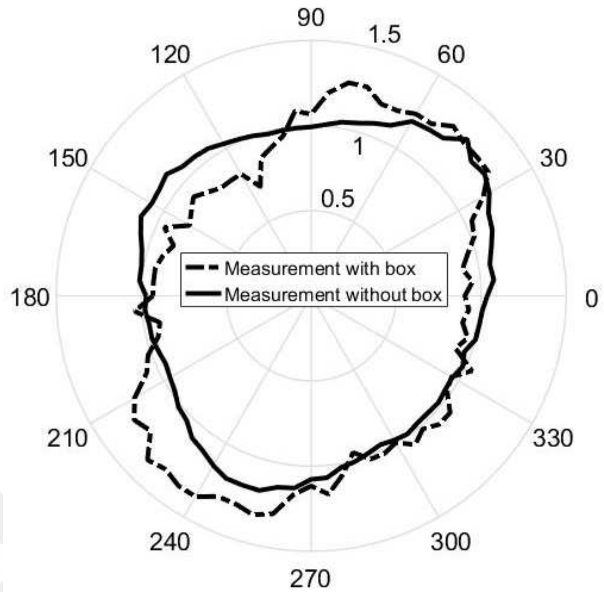


Figure 3.38: The radiation pattern of antenna and the antenna in the box

As it is seen in Figure 3.38, the radiation pattern of the initial measurement of the antenna and the measurement obtained when the antenna was placed into the box. Antenna performance with the housing box is found to be slightly perturbed. Although the wall of the box caused reflections and changes on the radiation pattern as expected, the result was not generally affected. Thus, it can be interpreted that the polyamide box did not shift the frequency values and the changes observed were not significant.

CHAPTER 4

CONCLUSION

Aim of this thesis is understanding of miniaturization techniques and examining the appropriation of these techniques for sub-GHz bands in the direction of remote control applications. Antenna theory was conceived and FEM based simulation tool was used for design process. Several iterations, designs and several analyses were made. With respect to these simulations, literature research was also considered and examined. Firstly, antenna patch which was composed with simulated models was designed. Optimizations and parametric studies were performed for designed patch. Results were interpreted related to theoretical background. After patch design completed, renewed Model 4 was produced and return loss was measured. Return loss of the first antenna produced with dimensions 86.9 x 42 x 1.6 mm was measured as -11 dB at 919 MHz. The consistency of design and measurement results was considered. Renewed Model 4 was developed and new antenna was designed after first antenna production. The new antenna had been designed with adhere to the principle of electrical length extension and smaller antenna had been obtained. The validity of this technique has been conceived. Miniaturization techniques stated at the literature was applied on this model and the techniques were used to reduce antenna dimensions as well as to experience their validity. Therefore, length of feeding line, thickness and material of substrate were examined. Results were interpreted and reasons are defined. Optimal values of strips' weight, length, material and thickness of substrate, dimensions were defined. This model was approved for production and measurements were performed. Return loss center frequency was obtained at 887 MHz and the dimensions were 0.25λ x 0.124λ x 0.0047λ (84.6 x 42 x 1.6 mm). The results of the simulations and measurements of the fabricated antennas were presented.

Another miniaturization method, multi-layer antenna structure was designed to examine the technique. This antenna has 100 x 100 x 6.6 mm with two layer, air layer at the top with 80 x 80 x 5 mm and FR4 layer at the bottom with 100 x 100 x 1.6 mm. Although the antenna performance satisfies the requirements, it is required that reduce the size of the antenna. It is also considered that designing of multi-layered antenna structure can reduce the antenna sizes.

Furthermore, the effect of a typical industrial box on the miniaturization process was investigated, and the material was approved as polyamide, after other materials were also experimented, additionally this material was stated as easy accessible and affordable. Dimensions of produced box were selected as in the industry. After box was produced, the antenna was placed into the produced box and measurements were undertaken. The results of all analyses confirmed that the produced miniaturized antenna inside a plastic housing box was suitable for using in remote control applications.

Finally, literature was considered for miniaturization techniques and remote control applications. Theory of microstrip antenna was conceived to interpret FEM based design tools. Antennas were designed after optimization processes and appropriate antennas were produced and measured. Miniaturization techniques were applied and several design were performed.

REFERENCES

[1] M. N. G. Murthi,K. S. K. Naveen, B. P. Bhavya, ”Performance Analysis of Microstrip Patch Antenna Using Coaxial Probe Feed Technique.” *International Journal of Technical Research and Applications*, vol.3, no. 3, pp. 365-367, June, 2015.

[2] J. Kaur, and K. Rajesh, ”Co-axial fed rectangular microstrip patch antenna for 5.2 GHz WLAN application.” *Universal Journal of Electrical and Electronic Engineering*, vol. 1, no. 3, pp. 94-98, 2013.

[3] H. D. Chen, J. Y. Wu, and T. W. Chiu, ”Broadband high-gain microstrip array antennas for WiMAX base station.” *IEEE transactions on antennas and propagation* vol. 60, no. 8, pp. 3977-3980, August. 2012.

[4] S. Shaik and R. P. Dwivedi, ”High gain stacked patch antenna with circular polarization for wireless applications,” in *Nextgen Electronic Technologies: Silicon to Software (ICNETS2), 2017 International Conference on IEEE*, 2017, pp. 322-326.

[5] E. Nishiyama, M. Aikawa, and S. Egashira. ”Stacked microstrip antenna for wideband and high gain.” *IEE Proceedings-Microwaves, Antennas and Propagation*, vol. 151, no. 2, pp. 143-148, 2004.

[6] Sievenpiper, Daniel F., et al. ”Experimental validation of performance limits and design guidelines for small antennas.” *IEEE Transactions on Antennas and Propagation*, vol. 60. no. 1, pp. 8-19, Jan. 2012.

[7] A. H. Wheeler, ”Fundamental limitations of small antennas.” *Proceedings of the IRE*, vol. 35, no. 12, pp. 1479-1484, 1947.

[8] L. J. Chu, ”Physical limitations of omni-directional antennas.” *Journal of applied physics*, vol. 19, no. 12, pp. 1163-1175, 1948.

[9] J.P. Gianvittorio, and R. S. Yahya, ”Fractal antennas: A novel antenna miniaturization technique, and applications.” *IEEE Antennas and Propagation magazine*, vol. 44 no. 1, pp. 20-36, 2002.

[10] Y. Hong, et al. ”Design of a multiband antenna for LTE/GSM/UMTS band operation,” *International Journal of Antennas and Propagation*, 2014 , Article ID 548160.

[11] D. Wen, et al. ”A Compact and Low-Profile MIMO Antenna Using a Miniature Circular High-Impedance Surface for Wearable Applications.” *IEEE Transactions on Antennas and Propagation*, vol. 66, no. 1, pp. 96-104, 2018.

[12] E.Y Ahmed, E. S. Abdenacer, ”Miniaturization of a printed dipole antenna using metamaterials for RFID UHF technology,” *Advanced Communication Technologies and Networking (CommNet), 2018 International Conference on IEEE*, 2018, pp. 1-5.

[13] Z. J. Yang, L. Zhu, and S. Q. Xiao, ”An Implantable Circularly Polarized Patch Antenna for Pacemaker Monitoring System,” *2018 International Conference on Microwave and Millimeter Wave Technology (ICMMT). IEEE*, 2018, pp. 1-3.

[14] Y. Mao, S. Guo, and M. Chen. ”Compact dual-band monopole antenna with defected ground plane for Internet of things.” *IET Microwaves, Antennas & Propagation*, vol. 12, no. 8, pp. 1332-1338, 2018.

[15] D. Upadhyay, and R. P. Dwivedi, ”Antenna miniaturization techniques for wireless applications,” *Wireless and Optical Communications Networks (WOCN), 2014 Eleventh International Conference on. IEEE*, 2014, pp. 1-4.

[16] S. R. Ryu, et al., ”Miniaturization of Microstrip Antenna,” *2017 Progress In Electromagnetics Research Symposium*, Singapore, 2017.

[17] J.P. Gianvittorio, Y. Rahmat-Samii, ”Fractal Antennas: A Novel Antenna Miniaturization Technique and Applications.” *IEEE Antenna’s and Propagation Magazine*, vol. 44, no. 1, pp. 20-36, 2002.

[18] D. Kalra, ”Antenna Miniaturization Using Fractals.” Master thesis, Thapar Insttitute of Engineering and Technology, India, 2007.

[19] D. B. Lin, J. H. Chou, S. O. Fu and H. J. Li, ”A Compact Dual-Band Printed Antenna Design for LTE Operation in Handheld Device Applications.” *International Journal of Antennas and Propagation*, 2014, Article ID 897328.

[20] K.C. Lin, C. H. Lin, Y. C. Lin, ”Simple Printed Multiband Antenna With Novel Parasitic-Element Design for Multistandard Mobile Phone Applications.” *IEEE Transaction on Antennas and Propagations*, vol. 61, no. 1, pp. 488-491, 2013.

[21] W. Huang, A. A. Kishk, ”Embedded Spiral Microstrip Implantable Antenna.” *International Journal of Antennas and Propagation*, 2011, Article ID 919821.

[22] T. Zhang, et al., ”A Novel Multiband Planar Antenna for GSM/UMTS/LTE/Zigbee/RFID Mobile Devices.” *International Journal of Antennas and Propagation*, vol. 59, no. 11, pp. 4209-4214, 2011.

[23] M. A. Antoniades, S.A. Rezaeieh, A. M. Abbosh, ”Bandwidth and Directivity Enhancement of Metamaterial-Loaded Loop Antennas for Microwave Imaging Applications,” *2017 International Workshop on Antenna Technology: Small Antennas, Innovative Structures, and Applications (iWAT)*, March 2017, pp. 249-252.

[24] S. Chatterjee, et al., ”Gunn-Mounted Active Microstrip Rectangular Patch Antenna – Revisited.” *International Journal of Microwave and Wireless Technologies*, vol. 5, no. 5, pp. 579-587, 2013.

[25] S. D. Gupta, M. C. Srivastava, ”Multilayer Microstrip Antenna Quality Factor Optimization for Bandwidth Enhancement.” *Journal of Engineering Science and Technology*, vol. 7, no. 6, pp. 756-773, 2012.

[26] Y. H. Lee, et al.,”Compact Folded C-Shaped Antenna for Metal-Mountable UHF RFID Applications.”*IEEE Transactions on Antennas and Propagation*, vol. 67, no. 2, pp. 765 – 773, 2019.

[27] Y. H. Lee, et al., ”Miniature Slotted-Folded-Patch Antenna for On-Metal UHF Tag.” *2018 IEEE Asia-Pacific Conference on Antennas and Propagation (AP-CAP)*, 2018, pp.492-493.

[28] W. H. Ng, et al., ”E-Shaped Folded-Patch Antenna with Multiple Tuning Parameters for On-Metal UHF RFID Tag.” *IEEE Transactions on Antennas and Propagation*, vol. 67, no. 1, pp. 56 – 64, 2019.

[29] D.K. Raheja, B. K. Kanaujia, and S. Kumar. ”A Dual Polarized Triple Band Stacked Elliptical Microstrip Patch Antenna for WLAN Applications.” *Wireless Personal Communications*, vol. 100, no. 4, pp. 1585-1599, 2018.

[30] Y. L. Kuo and K. L. Wong, ”Printed double-T monopole antenna for 2.4/5.2 GHz dual-band WLAN operations.” *IEEE transactions on antennas and propagation*, vol. 51, no. 9, pp. 2187-2192, Sept. 2003.

[31] G. Bilgin, et al.,”Comparative Assessment of Electromagnetic Simulationtools for Use in Microstrip Antenna Design: Experimental Demonstrations.” *Microwave and Optical Technology Letters*, vol. 61, no. 2, pp. 349-356, 2019.

[32] V. Shivangi, et al., ”Designs of Novel Planar Microstrip Patch Antennas and Applications:A Study.” *IJEEE*, vol. 4, no. 3, pp. 1694-2426, June 2017.

[33] S. Genovesi, et al., ”Wearable inkjet-printed wideband antenna by using miniaturized AMC for sub-GHz applications.” *IEEE Antennas and Wireless Propagation Letters* vol. 15, pp. 1927-1930, 2016.

[34] C. A. Balanis, *Antenna Theory*, John Wiley & Sons, 2016.

[35] K. L. Wong, *Compact and Broadband Microstrip Antennas*, John Wiley & Sons, 2004.