Master Thesis

Master's Program in Electronics Designs, 60 credits

2.45 GHz Antenna Designs with Impedance Matching Network

NIBE AB, Markaryd, Sweden

Electronics Design, 15 credits

Halmstad, 2018-08-21
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HALMSTAD UNIVERSITY

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2018

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Master thesis report
School of Information Technology
Halmstad University

Preface

We would like to express our sincere gratitude to Halmstad University and NIBE AB, Markaryd for giving us the opportunity to do this master thesis project.

We would like to thank our technical advisor Mr. Per-Olof Klarsson for the guidance and helping us to design the antenna prototypes. We would also very thankful to Mr. Per Fager to provide us all the technical details we needed during our project from NIBE AB. Without their knowledge and guidance this thesis project would not be possible.

We would also want to thank PhD student Mohammad Karimi to give us the proper guidance in thesis writing.

We are grateful that Dr. Pererik Andreasson gave us the opportunity to do this master thesis project and provided us the simulation software which helped us a lot.

Finally, we are thankful to our family and friends who supported us and encouraged us throughout the last year.

Abstract

This master thesis is a part of digitization project at NIBE AB, Markaryd, Sweden. Nowadays, the demand for digitization is increasing. One of the main goals of digitization is to build smart houses and industries to offer better lifestyles.

NIBE is a company which produces heat pumps, water heaters, district water heaters, digital stoves and etc. NIBE AB is planning to launch their new products with a communication module which helps users to control NIBE AB's products remotely through their personal devices such as mobile phones, remote control devices and etc.

The main objective of this thesis project is to improve these communication modules by improving their antenna with better design or replacing them with other kinds of antennas for efficient communication and also accordingly design impedance matching networks for the system.

This work presents the integrated results of an antenna for NIBE AB, tuned to cover 2.45 GHz ISM band which will implemented on a communication module. We designed and simulated four types of different Printed Circuit Board (PCB) antennas and we got the better simulation results of Gain, Reflection Coefficient, VSWR and Band Width from these designs.

Also, we used different types of substrates in the simulation to get good results and design the impedance matching networks accordingly. If we compare the results with the current monopole antenna and its parameters, we have good characteristic results in most of the aspects.

List of Abbreviation

ISM – Industrial, Scientific and Medical

PCB – Printed Circuit Board

IoT – Internet of Things

SMA – Sub Miniature Version A

ECH – Electronics Centre in Halmstad

VSWR – Voltage Standing Wave Ratio

S parameters – Scattering parameters

FNBW – First Null Beam Width

HPBW – Half Power Beam Width

2D – Two-Dimensional

3D- Three-Dimensional

IEEE – Institute of Electrical and Electronics Engineers

SWR – Standing Wave Ratio

SNR – Signal to Noise Ratio

CAD – Computer Aided Design

FEKO - FEIdberechnung fur Korper mit beliebiger Oberflache

MoM – Method of Moments

ADS – Advance Design System

MLA – Meander Line Antenna

PIFA – Planer Inverted-F Antenna

FR-4 – Flame Retardant 4

RLC Circuit – Resistive, Inductive and Capacitive Circuit

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1 Introduction

In this chapter some of the basic types of conventional antennas and corresponding advantages are described. Many types of different antennas are available for different applications. The summary of the different antennas is given in following categories.

- **Wire antennas:** Monopole antenna [1], dipole antenna [1] , loop antenna [2], half wave dipole antennas [3], Yagi-Uda antenna [4].
    - This type of antenna has low gains and the application range is in lower frequency. The merit of this design is light weight, low cost, and simple structure [5].
- **Aperture antennas:** Rectangular or circular horn antenna [4], Reflector antenna [2], Lens antenna [4], Open waveguide and reflect array antenna [3].
    - These types of antennas are used in microwave frequencies and they have higher gain [4].
- **Printed antennas:** Printed dipole antenna [1], Printed slot antenna [4], Micro-strip patch antennas [1]
    - These antennas can be fabricated on printed circuit board. The advantages are high gain, low cost and easily arrayed. These antennas are mostly used in microwave frequency range and millimeter wave frequencies [6], [7].
- **Array antennas**: It has a regular arrangement of antenna elements with a feeding network. By this arrangement beam pointing angle and side lobe levels can be controlled by adjusting the amplitude and phase excitation of the array elements [1], [4].

1.1 Background

Internet of things (IoT) is one of the main topics of today's current technology. IoT is the network which plays a very important role in everyone's life as most of the daily activity associated with internet and sharing of the data. The main objective of the IoT is to develop the devices which can communicate with each other for better efficiency. Major advantage of the IoT is communication. IoT improves the machine to machine communication which leads to better efficiency and quality. IoT provides the comfort to every day's life as people do not have time to worry about small things. With the help of IoT, machines communicate with each other and not only save time but also save money and resources. The communication plays very important role in IoT. To provide a good communication, IoT devices need to use better antennas [8].

An antenna is a device that converts a guided electromagnetic wave on a transmission line to a plane wave propagating in free space (transmission), or vice-versa (receive) [4]. Antenna design mainly contains two parts: Electrical circuit and waveguide propagation in free space. To understand the antenna operation, one can understand from the Maxwell's equations and also need to consider the boundary conditions of an antenna [4].

Design of an antenna is being a very important topic since the innovation of communication devices. Especially, since the World War II, the research and development to build a better antenna has always been a very demanding subject.

There are more than thousands of antennas designs available for different applications. From the advancement of the technology, the trend is developed smaller electronics devices with better efficiency which can communicate with other via innovating new designs that merges components and make devices denser.

1.2 About NIBE AB, Markaryd, Sweden

NIBE AB is the Swedish company which was founded in 1952 by Nils Bernerup. The company is in heating industry. They produce and sell the heating equipment such as heat pumps, water heaters, district water heaters and electric stoves. The head office is in Markaryd, Swedish.

Currently the company is focusing on three core businesses: NIBE climate solutions, NIBE element, NIBE stoves. The aim is to design and develop products which can be controlled digitally, which makes it easier to control heat, ventilation and cold. The products are both energy efficient and eco-friendly [9].

1.3 Problem Statement

NIBE Industry AB intends to launch their new products with the I/O microwave communication module. They have developed such a microwave communication module which can communicate with other devices such as mobile phones, remote control devices and etc. With the help of these devices, one can control NIBE AB's products remotely. As for the starter, NIBE AB designed a module which uses a stubby quarter-wavelength monopole antenna which is connected with the I/O circuit device via SMA connector. But NIBE want to improve their current design because the SMA connector is costly and there are always some connection losses while using SMA connector. Also, the antenna is being attached separately.

NIBE industry AB wants to design and develop a new communication module with a new antenna design which eliminates or reduces these problems while keeping the performance and efficiency high.

1.4 Contributions

The major contributions of this thesis work are:

- New antenna designs which will be used in I/O module.
- Design of an impedance matching network for each antenna.
- Study the characteristics about the different antennas by the simulation software

- Acquiring knowledge about the characteristics such as Gain, Reflection Coefficient, VSWR, Return loss, Bandwidth and far-field radiation pattern.
- Also learning about the physical parameters such as size of an antenna, effects of different materials and external effects.
- Compare the results and select the best antenna design parameters which can replace the stubby monopole antenna.

1.5 Thesis Layout

The first part of this thesis is to learn about the different antenna designs and select few designs which can fit best for the application. The next chapter is about the designing several antennas in software and compare the different characteristics. Finally, the thesis ends with the chapter about the conclusions and the future proposals.

2 Antenna Theory, Impedance Matching Network, Software Introduction

Antenna is used to transmit and receive electromagnetic waves in a specific direction. Some of the antennas are used to transmit and receive signals from all directions. A good antenna should be efficient for power transmitting and receiving. Also, the resonance frequency range of an antenna should be desirable. In order to be able to design an antenna with high functionality, one should know the basic fundamental properties of the antenna which are given below.

2.1 Antennas reciprocity

Antenna reciprocity is electrical and magnetic properties of the antenna. These properties include radiation pattern, gain, beam width, bandwidth, antenna efficiency, s parameters, input impedance and voltage standing wave ratio (VSWR).

2.1.1 Radiation Pattern

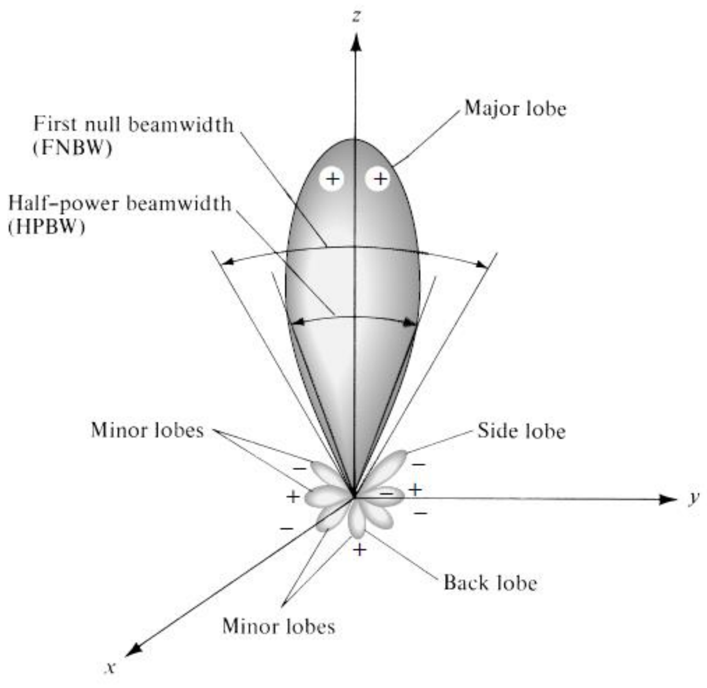

Figure 1 - Radiation Lobes and Beam widths of the radiation pattern [1]

An antenna radiation pattern is defined as ``*a mathematical function or graphical representation properties of the antenna as a function of space coordinates. The radiation pattern is determined in the far-field region and is represented as a function of the directional* *coordinates* [1].´´ Radiation pattern is a 2-D or 3-D energy distribution which is plotted in polar graph. Usually, this radiation pattern is being normalized and also plotted in decibel (dB) unit.

Figure 1 shows the three-dimensional pattern of the radiation field. Major lobe, also known as main beam, is where the maximum radiation occurs. In some antennas, there are more than two major lobes. Other lobes are called minor lobes which can be further divided into two parts: side lobes and back lobes. Side lobes are usually adjacent to the major lobe. Back lobe is opposite to the major lobe and make an angle of 180 degree (θ = 180º). The main goal for a good antenna is to reduce the side lobes and increase the major lobe for better radiation.

2.1.2 Beamwidth

The beamwidth is defined as the angular separation between two identical points on opposite side of the pattern maximum [1]. Mainly two types of beamwidths are used: 1) Half Power Beam Width (HPBW), 2) First Null Beam Width (FNBW).

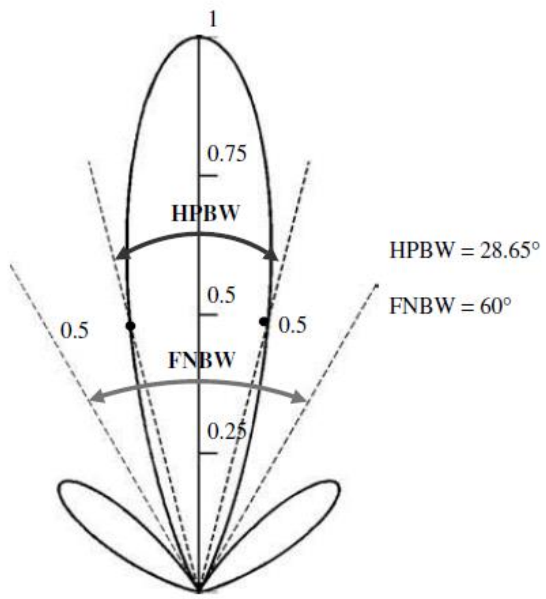

Figure 2 - Two-dimensional power pattern [1]

Half Power Beam Width (HPBW) is defined by IEEE as: ``*in a plane containing the direction of the maximum of a beam, the angle between the two directions in which the radiation intensity is one-half value of the beam*´´ [1].

First Null Beam Width (FNBW) is defined as the angular separation between the first null of the radiation pattern [1].

2.1.3 Directivity

Directivity of an antenna is defined as ``*the ration of the radiation intensity in a given direction from the antenna to the radiation intensity averaged over all directions. The average radiation intensity is equal to the total power radiated by the antenna divided by 4π. If the direction is not specified, the direction of maximum radiation intensity is implied*´´ [1].

In simple form, directivity can be represented in mathematical term as following.

$$D = \frac{U}{U_0} = \frac{4\pi U}{P_{rad}}$$

Where,

D = directivity
U = radiation intensity
U_0= radiation intensity of isotropic source
P_{rad}= total radiated power (W)

2.1.4 Gain and Antenna efficiency

Gain of an antenna is defined as ``*the ratio of the intensity, in a given direction, to the radiation intensity that would be obtained if the power accepted by the antenna were radiated isotopically. The radiation intensity corresponding to the isotopically radiated power is equal to the power accepted by the antenna divided by 4π*´´ [1].

$$Gain = 4\pi \frac{radiation\ intensity}{total\ input\ power} = 4\pi \frac{U(\theta, \varphi)}{P_{in}}$$

Antenna efficiency is defined as the ratio of radiated power over input power.

$$\eta = \frac{P_{rad}}{P_{in}}$$

2.1.5 S-parameters (Reflection Coefficient) and Bandwidth

The most commonly used parameter regarding antenna is S11. S11 shows how much power is reflected from the antenna and is known as reflection coefficient or return loss. If S11 = 0 dB, then all the power is reflected from the antenna and nothing is radiated. If S11 = -10 dB, this implies that if 3 dB of power is delivered to the antenna, -7 dB is the reflected power [1].

Another important parameter is bandwidth. Bandwidth describes the range of frequencies over which the antenna can properly radiate or receive energy. The bandwidth of an antenna is defined as" *the range of frequencies within which the performance of the antenna, with respect to some characteristics, conforms to a specified* *standard"* [1]. Bandwidth is also defined as the span of frequencies in which certain parameters of the antenna are inside operational range.

2.1.6 VSWR (Voltage Standing Wave Ratio)

VSWR which stands for Voltage Standing Wave Ratio and also known as Standing Wave Ratio (SWR). It is defined by the reflection coefficient as how much power reflected back from the antenna. It can be defined mathematically by the reflection coefficient (Γ) as below.

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

VSWR is ranging from 1 to ∞ ($1 \leq VSWR \leq \infty$). For the ideal antenna, VSWR is 1.0 which means no power is reflected back from antenna. Antenna with the VSWR between 1.0 and 2.0 is considered to be a high performance antenna.

Reflection coefficient also known as the S11 (scattering parameter) which represents how much power is reflected back from the antenna.

2.2 Impedance Matching

The topic of impedance matching is an important topic of a transmission line and in microwave communication link. Impedance matching network is taking placed between the load impedance (antenna) and a transmission line (feed point) which in our case is between the antenna and the feeding line. It should be lossless to avoid power loss in it. With the help of the matching network the reflection loss will be eliminated in the transmission line, but still sometimes there will be a multiple reflection are present and to avoid this multiple reflection, one needs to change the value of the matching networks, which is also known as tuning [10].

2.2.1 Importance of impedance matching or tuning

- Maximum power is transmitted when the load impedance is matched with the line impedance, and the power loss due to the refection in the feed line is minimized [10].
- Impedance matching network will improve the single-to-noise ratio (SNR) of the components like antenna and low-noise amplifier of the system [10].
- In such antenna arrays the impedance matching network will help to reduce the amplitude and phase errors [10].

2.2.2 Types of matching network

- E11 also known as L type matching network (lumped components)
- Lossless T network or PI(π) Lossless network (lumped components)
- Micro-strip Matching Network (PCB printed Trace)
    - Open Circuit stub
    - short Circuit stub [10]

2.3 Software Introduction

- **CAD FEKO: -** CAD FEKO is a comprehensive computational electromagnetics (CEM) software used in industries like automobile, aerospace, defense and more in telecommunications. This software is developed by the US company named Altair Hyperworks. The name FEKO is coming from the German acronym "FEIdberechnung fur Korper mit beliebiger Oberflache", which is in English "field calculations involving bodies of arbitrary shape". The main objectives are 3D electromagnetic simulator. FEKO gives the options to work on several frequency and time domain EM solver under a single license. The method of moments (MoM) or boundary element method is a numerical computational method of solving linear partial differential equation which is known as Maxwell's integral equation [11]. This software is used for antenna structure design and its simulation measurements to derive all electrical properties [12].
- **Advance Design System (ADS): - ADS** is an electronic design automation software for RF, microwave, high speed digital, and power electronics applications. It is used by the companies in the wireless communication & networking, aerospace & defense, automotive, and energy industries. ADS provides full standard-based design and verification with wireless and other applications. It is owned by the EEsof, today known as Keysight EEsof EDA. This software is being used in this project for the matching impedance circuit for different antenna designs and for the strip designs [13].

3 Current Setup, PCB Antenna Designs and Simulation results with comparison

3.1 Current Setup

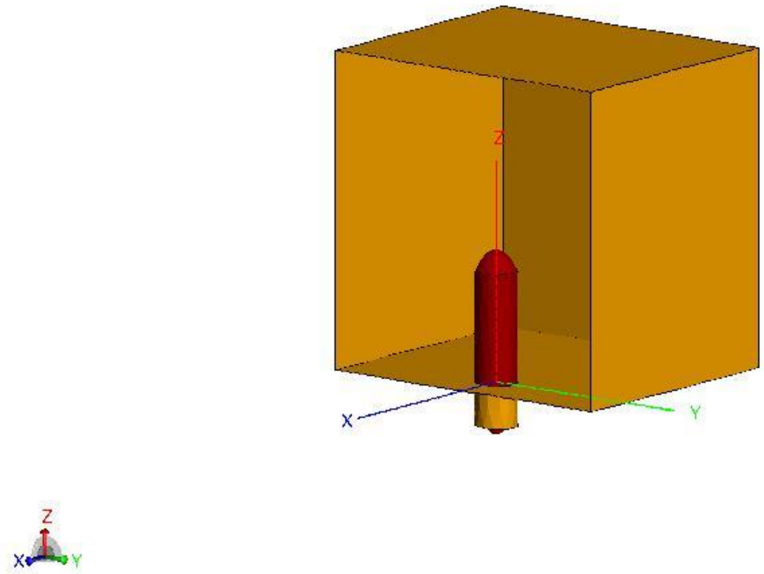

Figure 3 - Current Monopole Antenna Setup with metallic box

In the above figure 3 the current antenna set up is shown. Here stubby quarter-wavelength monopole antenna is used. It is connected to the Printed Circuit Board (PCB) via SMA connector. The antenna is made of copper with rubber cap outside. As shown in the figure 3, the antenna mounted inside the metallic box to reduce the back-side radiation. Also, this metallic box prevents the radiation disturbances from the heating system which is located behind the box. The bottom layer of the box performs as a ground for the antenna.

To design the geometrical model, CAD FEKO is useful because of many useful features. One can build the actual physical model in CAD FEKO with the design specification and can also add the properties of the material such as dielectric constant, conductivity, delta tangent etc. The current monopole antenna setup has one monopole antenna with the copper wire which has the conductivity of $5.8 \times 10^{7} S/m$. The metallic box is made from the teen-steel which has the conductivity of $1.1 \times 10^{6} S/m$. All the physical and metallic properties can be assigned in CAD FEKO.

It is very useful software to generate the far field data. It has many solver settings such as Multilevel Fast Multimode Method (MLFMM), Finite Element Method (FEM), Finite Distance Time-Domain (FDTD) method, Method of Moments

(MoM), Boundary Element Method (BEM). For the frequency of 2.45 GHz, MoM solver is good because of fast and accurate results.

Some of the simulated results such as reflection coefficient, VSWR, bandwidth and gain of the antenna are given below using CAD FEKO far field solver.

Figure 4 shows the reflection coefficient of this monopole antenna setup. The reflection coefficient is -16.57 dB at 2.45 GHz. The bandwidth is 400 MHz. The bandwidth can be defined from the reflection coefficient graph by taking the frequency range at -10 dB.

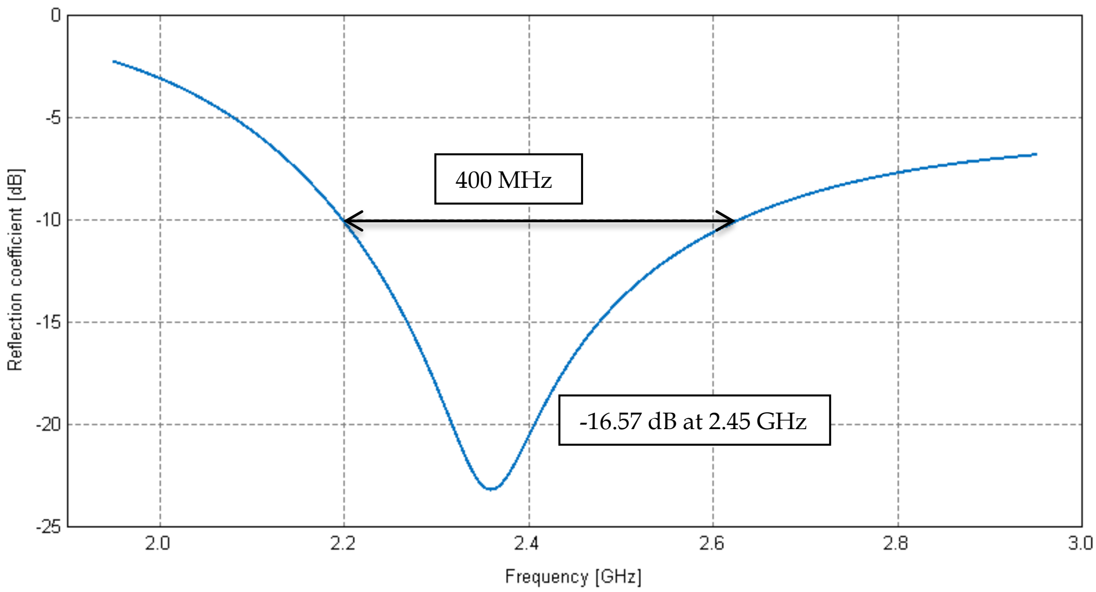

Figure 4 - Reflection Coefficient of Monopole Antenna

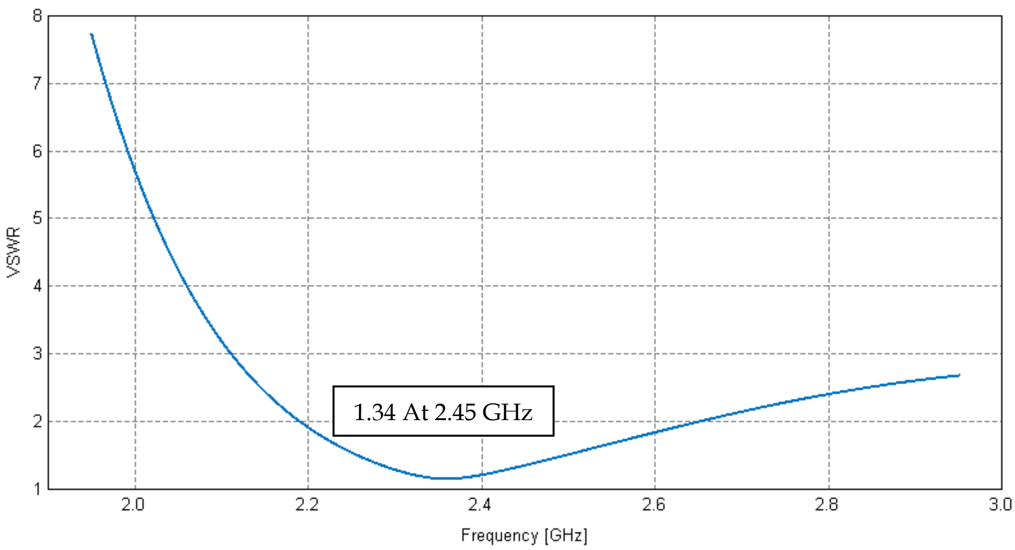

Figure 5 - VSWR for Monopole Antenna

Figure 5 shows the voltage standing wave ratio of this monopole antenna at 2.4 GHz and it is around 1.3. For a good antenna design VSWR below 2 is necessary. If the VSWR is above 2 which means the reflection coefficient is higher than -10 dB. If it is higher than -10 dB than the most of the power is reflected back to antenna rather than transmitting.

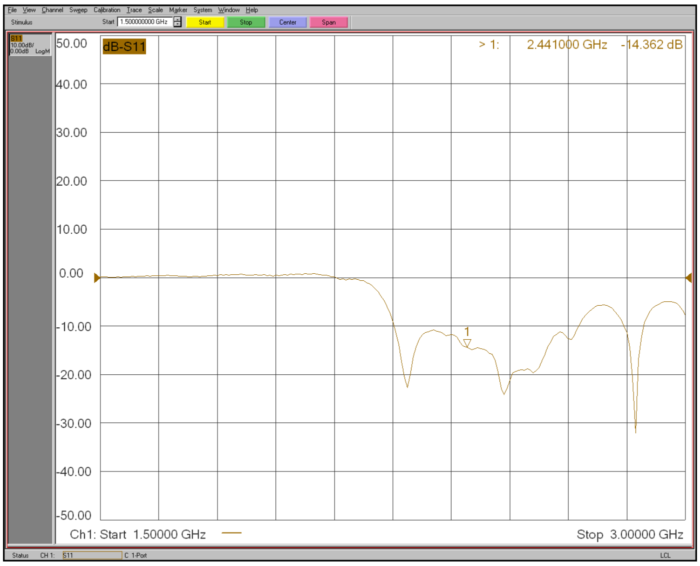

Figure – 6 Reflection Coefficient of monopole antenna (measured in ECH facility) [14]

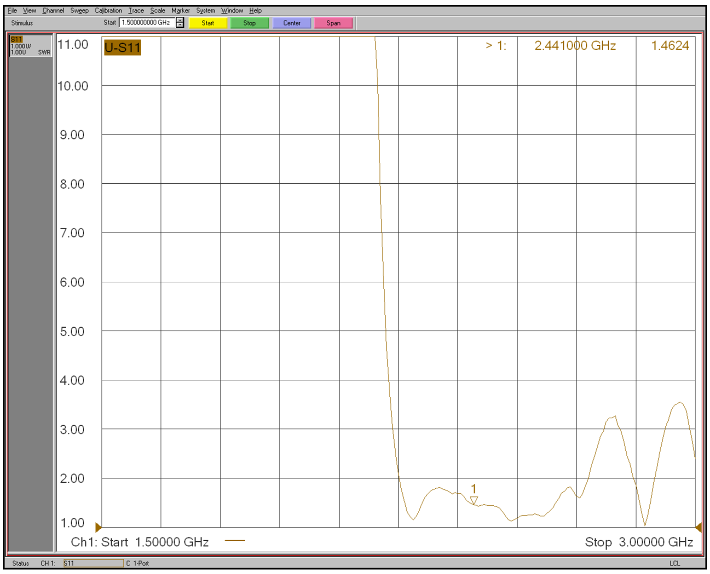

Figure – 7 VSWR of monopole antenna (measured in ECH facility) [14]

Figure 6 and figure 7 shows the reflection coefficient and VSWR of the actual monopole antenna measured in the ECH facility by VNA (Vector Network Analyzer). The simulation results and the actual results are very similar.

From the CAD-FEKO simulation, the 2-D polar graph is taken. It shows the radiation pattern on 2-D plot. The gain of the monopole antenna is 3.19 dB at 90 degree which is reasonable gain for this type of commercial antenna.

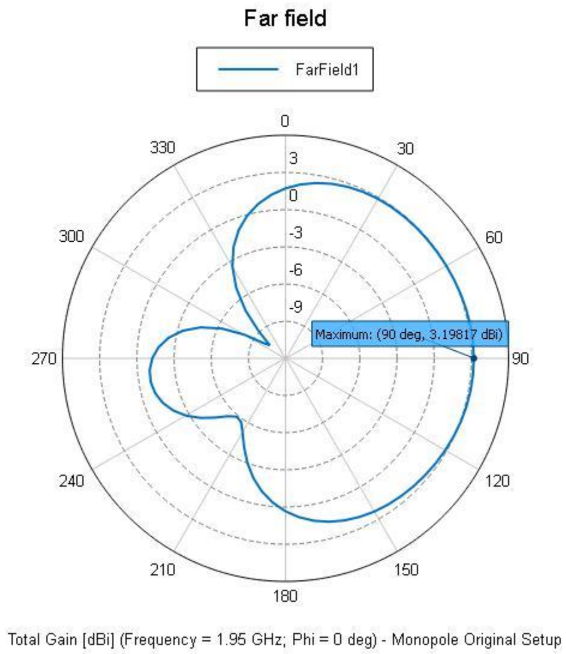

Figure 8 - Two-Dimensional Radiation Pattern with Gain of the monopole Antenna

In this thesis project, the main task is to replace this monopole antenna by PCB antenna with same or better performance in the all parameters. The design parameters of this monopole antenna are taken from the data sheet provided by the company. The main problems associated with the present antenna in the module are connection loss because of SMA connector, high price of the antenna and SMA connectors [15].

3.2 Introduction of PCB Antenna

The first micro-strip antenna appeared in 1974, but it was suggested first time in 1953 by Descamps [16]. A simple design of a printed circuit board (PCB) consists of a radiating patch on one side of the dielectric substrate and a ground plane on the other side. The top radiating patch can be designed in the shapes of rectangular, circle, square, triangular, semi-circular, sectoral, rings or in the form of meander. In PCB antenna the radiation is generated due to the fringing E-fields between the patch and the ground plane.

There are several advantages of PCB antenna which are given below [16]:

- Low weight
- Small volume
- Ease of fabrication by using printed-circuit technology
- Several configurations according to applications
- Low cost
- Easy to accommodate in the circuit
- The possibility of having numbers of different types of feeding techniques

For this thesis project the appropriate designs were chosen according to the requirement. The goal is to find a PCB antenna designs with better physical parameters in compare to the present antenna in the module. For the I/O module, PCB antennas are the best suitable choices to communicate with each other. There are lots of PCB designs available in the market and in the internet. In order to obtain better gain and bandwidth, planar inverted-F antenna (PIFA) and meander line antenna (MLA) designs are good choices because they are easy to design and calibrate. Several kinds of antenna designs are suggested in this chapter.

3.3 Meander Line Antenna (MLA)

Making an antenna compact enough to be able to fit into the small PCB layout is one of the biggest challenges, especially, when the antenna is working on a low frequency such as 2.45 GHz or less. In general, the length of a small antenna is around $\lambda/2$ or $\lambda/4$ for. Sometimes the size of the printed antenna is also problem to accommodate in small place with the other electronic components. MLA antenna is one of the best choices to overcome this problem. It is a combination of the line and patch antenna.

There are several techniques being used to reduce the size of the micro-strip antennas such as: use of high permittivity material, shorting pins, and meander line. Meander line concept is convenient among those techniques. Meander line is the bunch of micro-strips placed in a zig-zag pattern as shown in figure 7 which forms the turns. Efficiency of the antenna depends on the number of turns. The resonant frequency inversely proportional to the spacing distance between the meander lines. So, if the spacing distance between meander line increases than the resonance frequency decreases. Radiation efficiency is good compare to the radiation efficiency of typical line antenna because meander line antenna is designed in such a way so that it can work as patch antenna rather than micro-strip line antenna [17]. Few type of meander line antennas is suggested below with the results.

3.3.1 Meander Line Antenna (MLA) Design 1

In this setup, antenna is made on the FR-4 substrate with dielectric constant, $\varepsilon_r = 4.7$ and loss tangent, $\tan\delta = 0.0019$. The proposed antenna as shown in figure is comparatively smaller than micro strip antenna with the same radiation pattern and efficiency. There are three turns of meander line with micro strip feeding point. Thickness of the substrate is 1.6 mm with the copper trace thickness of 0.039 mm. The ground plane in this design performed as the impedance matching [18].

3.3.1.1 Design specifications of the meander line antenna 1

Specification of the MLA design 1 is given in the table 1. Different configurations were tested by changing the number of turns and by changing the width of the feeder in order to find optimum design parameters. The best results were obtained for the specifications which are given in the table 1. These specifications were tested in the reference paper [18] and the best results were taken for the simulation in CAD FEKO in our design specification.

Table 3 Dimensions of MLA 1

Type of length	**Dimension (mm)**
Width of feeder (W1)	1
Width of ground &substrate (W2)	13
Vertical length of turns (L2)	3
Vertical length of ground (L3)	27
Vertical length of substrate (L4)	37.75

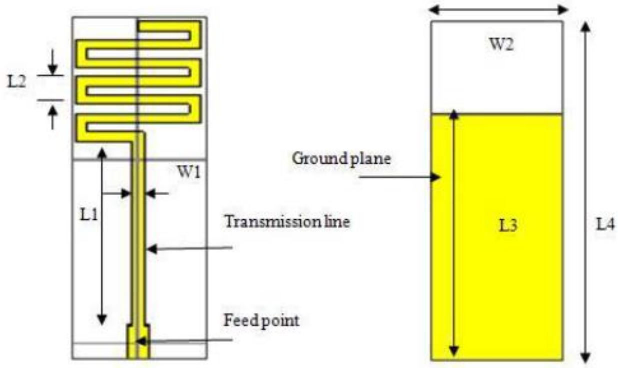

Figure 9 - MLA 1 layout according to reference paper [18]

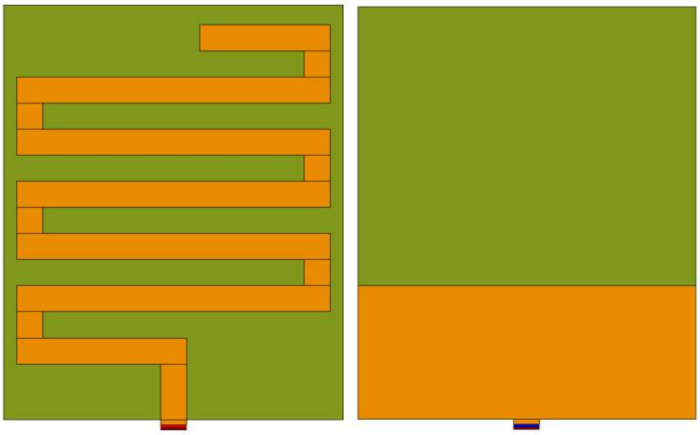

Figure 10 - Proposed MLA 1 layout

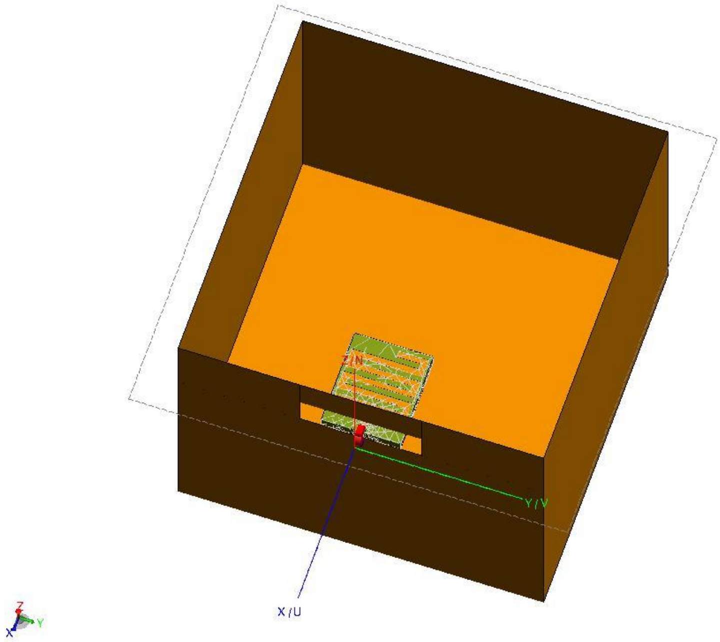

Figure 11 - Proposed MLA 1 layout with metal box

In this proposed antenna setup, vertical length of the ground (L3) is 5.125 mm and vertical length of the substrate (L4) is 15.875 mm.

It is quite convenient to design the PCB antenna model in CAD FEKO. The dielectric material with the physical properties can be determined in CAD FEKO. Also, one can assign the ground plane and also the micro-strip line to power supply. There are also options to design the multilayer PCB as well of different dielectric layers.

One major flaw in CAD FEKO is that it is very difficult to calibrate the design to get the best results. There is no tuning option in CAD FEKO. Also, you cannot add the electrical components such as resistors, capacitors and inductors into the model. One important aspect one needs to take into account is the impedance matching between the module and antenna. Advance Design Systems (ADS) is very useful to design the impedance matching network.

In ADS, there are different options to design the impedance matching network such as RLC-network, stub circuit, filter network. The combination of these different networks can also be possible. In these Antenna design, stub elements are being used to design the impedance matching network because there is not major impedance different between the model and the antenna. Also, the operating frequency is 2.45 GHz. So the sizes of the stub elements are small and to build the actual physical model, stub elements are cheaper than the RLC components.

In ADS, there are built in function to design the matching networks called Impedance Matching Utilities, in which Standard Stub Matching (SSMtch) can be designed. This tool determines the length and width of the stub elements based on the impedance of the two ports, dielectric constant of the material and the operating frequency. In MLA 1 design, the same method is being used to design the impedance matching network for the PCB antenna.

In the following antenna design the same design methods are being used in both CAD FEKO and in ADS.

3.3.1.2 MLA 1 Simulation Results

Simulations results are given below with the specification of the company. The results are the radiation pattern, gain, reflection coefficient and VSWR for the antenna simulated by CAD FEKO.

The impedance matching circuit and its layout are obtained using ADS. The CAD FEKO provides the antenna design layout.

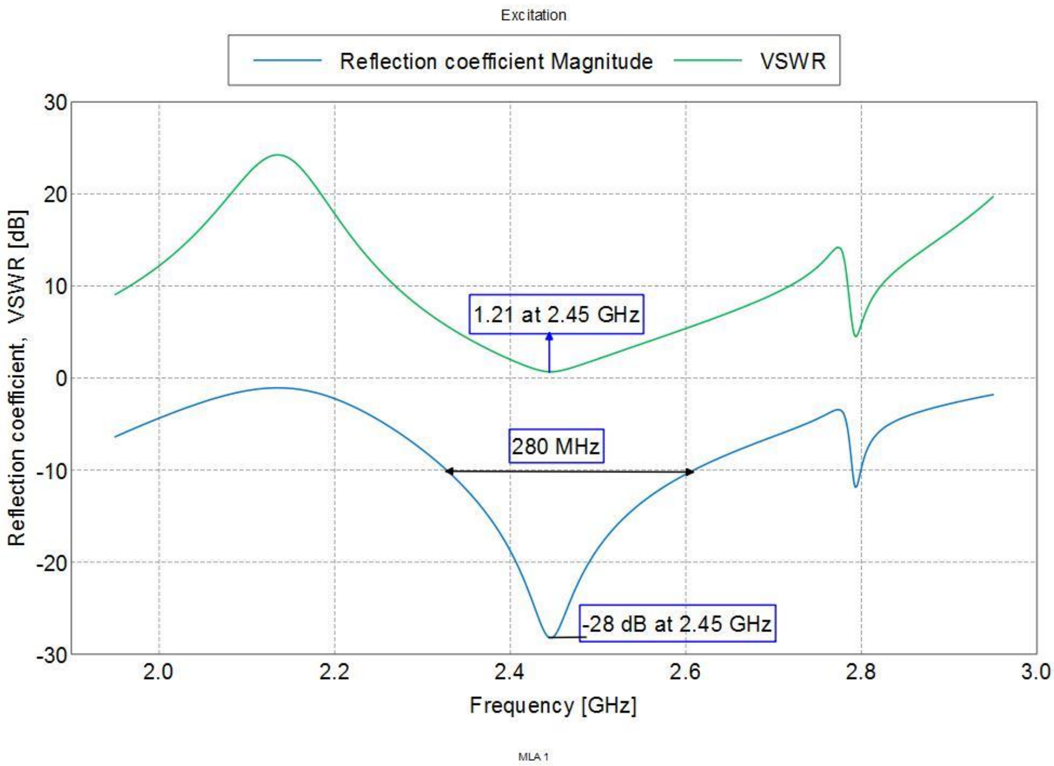

Figure 12 - Reflection Coefficient and VSWR of MLA 1

The reflection coefficient of the MLA 1 is -29.15 dB with the bandwidth of 330 MHz. Also, the Voltage Standing Wave Ratio (VSWR) is 1.21 which shows that most of the power is transmitted through the antenna with the efficiency of 60%.

Figure 12 shows the VSWR of the MLA 1 antenna. The value is 1.21 at 2.45 GHz. This VSWR shows that most of the power is transmitted. VSWR can also determine by the reflection coefficient.

One of the important parameter of the antenna is gain. The gain of the MLA 1 antenna design is shown in Figure 13. From the simulation results, the gain of the MLA 1 is 5.36 dB at 2.45 GHz.

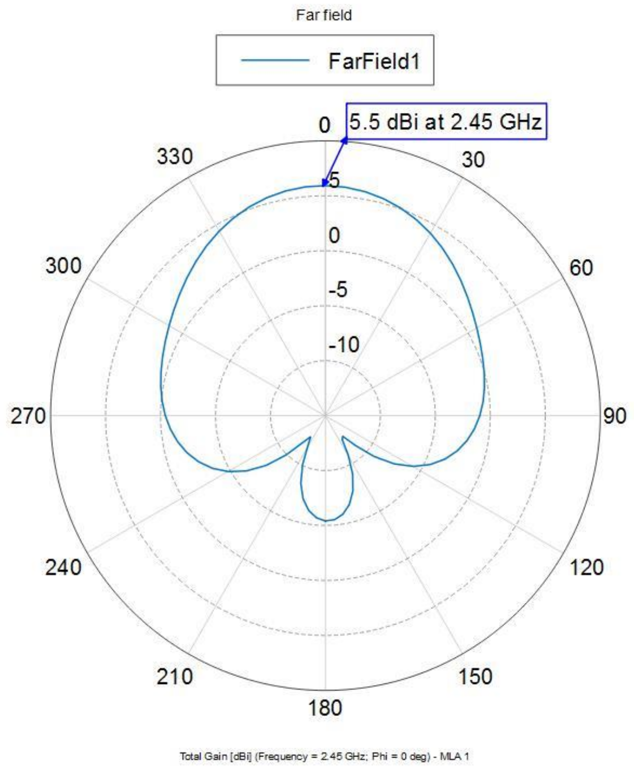

Figure 13 - Gain of MLA 1

Similar results were achieved for reflection coefficient from the ADS after making an impedance matching network as following.

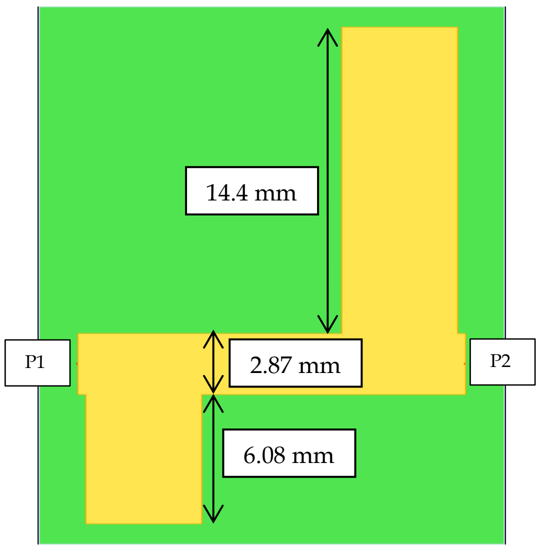

Figure 14 - Proposed Matching Network for MLA 1

In figure 14, the impedance matching network is shown with all the important parameters. The matching network is being optimized to get the result for the setup. Figure 13 shows the proposed matching network with stub elements. The port P1 is the I/O module port and P2 is the port of the antenna.

3.3.2 Meander Line Antenna (MLA) Design 2

Another MLA antenna design is the dual-band antenna which works at 2.45 GHz and 5.0 GHz. This antenna contains two meander lines, conducting strip [19], [20] and micro-strip matching network. The length of the second mender line section and conducting line helps to adjust the resonant frequency [21].

3.3.2.1 Design specifications of the MLA 2

Similar to the previous antenna design, this antenna does not have a ground plane behind the meander line structure. The reason for not putting the antenna behind the trace is that the ground plane works as a receiving antenna in near field and absorbs some radiation. It will radiate some of the energy but most of the energy will dissipate as heat. It will absorb most of the antenna power and greatly change the antenna characteristics.

The design specification of the meander line antenna 2 is given in the table 2.

Table 2 Design specification of MLA 2 [21]

Substrate	Width(mm)	20
	Length(mm)	57
	Thickness(mm)	0.813
Strip	Width 'a' (mm)	1.95
	Length(mm)	2.5
1st Meander-line section	Width(mm)	1.3
	Length(mm)	9
	Space(mm)	2.5
2nd Meander-line section	Width(mm)	1.3
	Length(mm)	9
	Space(mm)	2.5
	b (mm)	1.3
	c (mm)	6.5

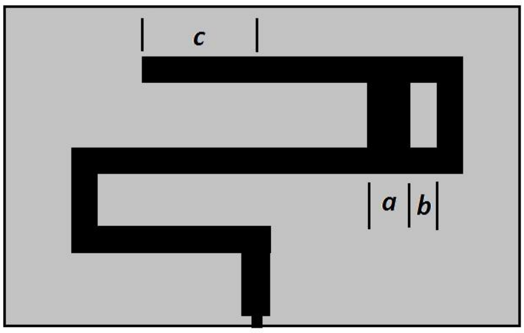

Figure 15 - Close view of meander line antenna [21]

As shown in figure 15, by tuning the length *c* and width *a*, one can tune the S11 parameters (reflection coefficient) of the antenna. This antenna operates as a dual-band antenna with resonance frequencies of 2.45 GHz and 5.0 GHz.

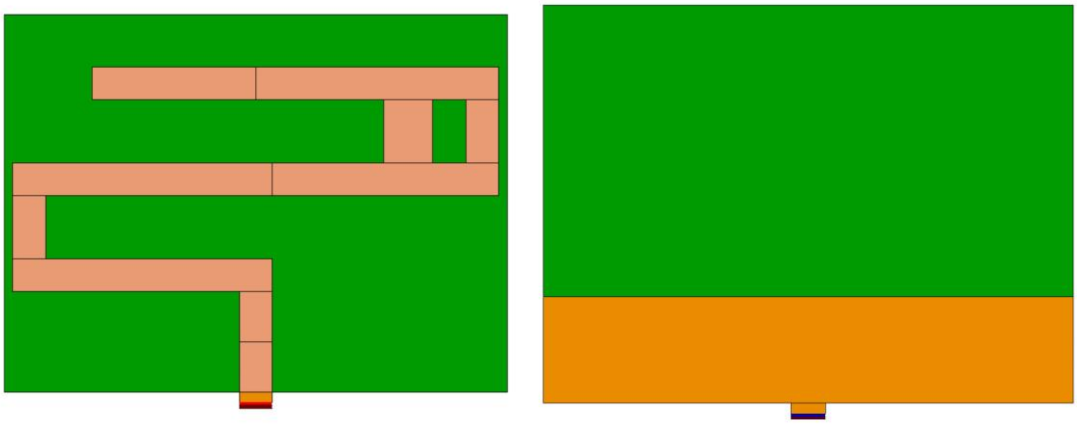

Figure 16 - Close view of the meander line antenna section of the proposed antenna with back view

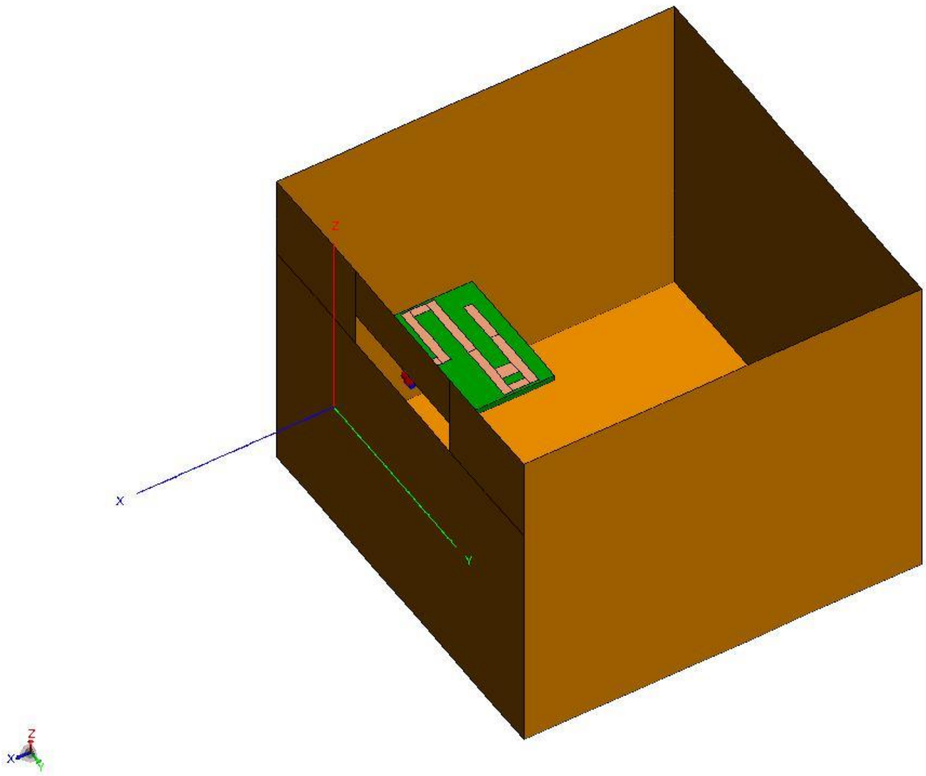

Figure 17 – MLA 2 with metal box

3.3.2.2 MLA 2 Simulation Results

The simulation results for the MLA design 2 from CAD FEKO are given below such as reflection coefficient, gain and VSWR.

The reflection coefficient of the meander line antenna design is -22 dB with the bandwidth of 156 MHz as shown in the Figure 18.

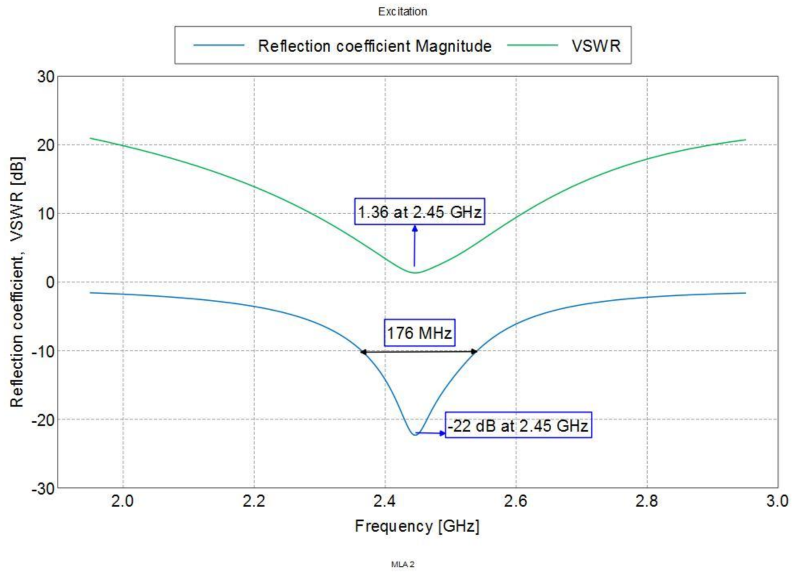

Figure 18 - Reflection Coefficient and VSWR of MLA 2

The VSWR is 1.36 for the meander line antenna design 2.

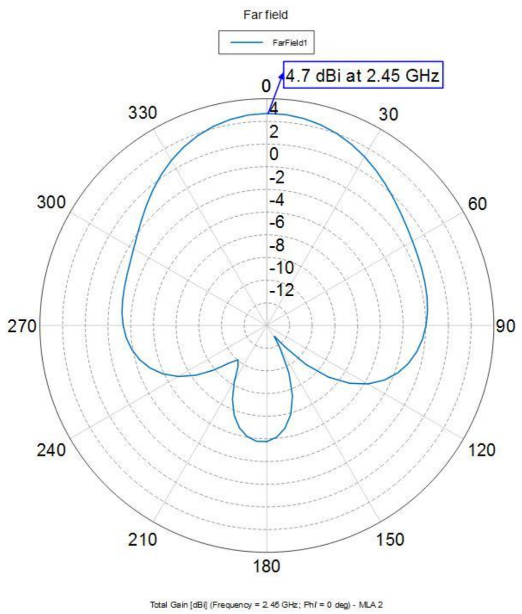

Figure 19 - Gain of MLA 2

Gain and HPBW are similar as the MLA design 1 because both the antennas have similar parameters and in the same metal box structure.

There is an impedance matching problem with the antenna impedance of (31 + j*56) Ω. The proposed impedance matching network with design specification is given below in Figure 20.

The design layout for this stub impedance matching network is given below in figure 20.

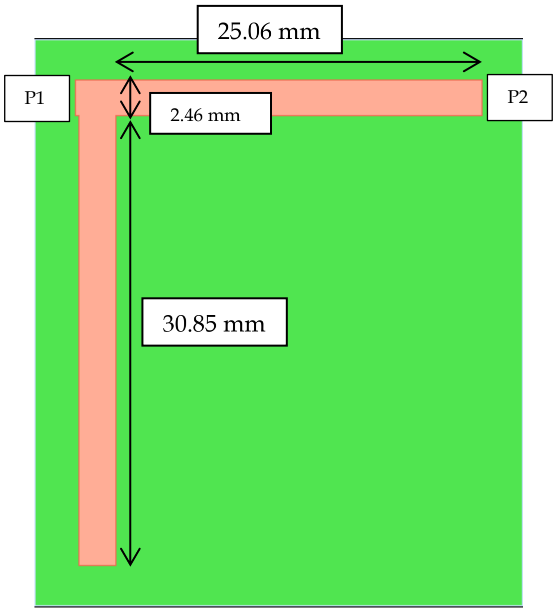

Figure 20 - Impedance matching network layout for MLA 2

There are many different layouts that can be built for the impedance matching network. One can also build the matching network with RLC-components as well. Here, the matching network with the open circuit stub element is suggested. The goal is to cancel out the reactive component of the load to be matched, so that it will work on a specific frequency [22].

3.4 Planar Inverted-F Antenna (PIFA) Design

The PIFAs have the advantageous of low dimension. The gain and bandwidth of the PIFAs are decent. There is always some trade-off between the gain and the bandwidth of the antenna. For the PIFA structure, the antenna is printed on the printed circuit board and the connection is given by strip line. There are lots of different kinds of antennas available for different frequency bands. Some PIFAs are also working on dual band. Two types of PIFA designs are mentioned in this chapter.

3.4.1 Planar Inverted-F Antenna (PIFA) Design 1

This antenna design is similar as the dipole antenna printed on the PCB. The design of the antenna is very simple as shown in the figure 21. It is similar to the dipole antenna with the difference that one side of the antenna is bent. This antenna is mounted on the RT/Duroid 5880 substrate with the dielectric constant of $\varepsilon_r = 2.2$ and the thickness of$t = 1.6\ mm$. The substrate RT/Duroid is cheaper than the FR-4 substrate.

3.4.1.1 Design Specification of Planar Inverted-F Antenna (PIFA) 1

The design of the antenna is shown in the figure 21. The optimized parameters of the antenna are given in the table 3. The resonance frequency can be tuned by the length,h_1. By tuning the length,h_1 the overall length of the antenna changed. This changes the resonance frequency.

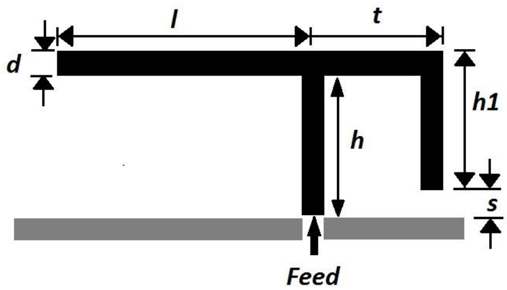

Figure 21 - Inverted-F Antenna [23]

The feed line is the micro-strip line which works as the impedance matching network. Width of the antenna feed line is one of the main factors for the impedance matching.

Table 3 Design parameters of the PIFA 1 [23]

Antenna Parameters	Values(mm)
l	28
t	6
h	16
h_1	12
d	2
s	6

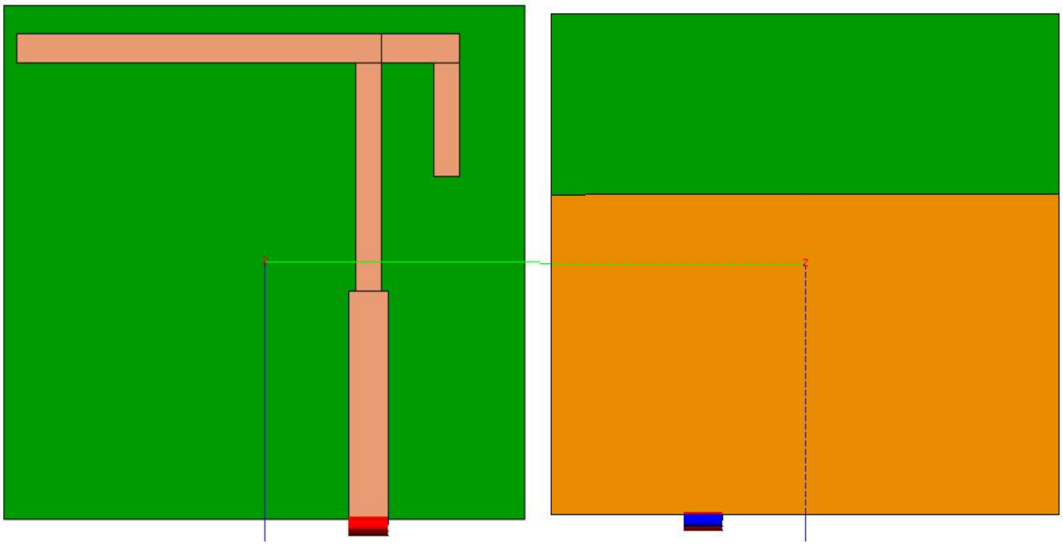

Figure 22 - Proposed PIFA 1 design

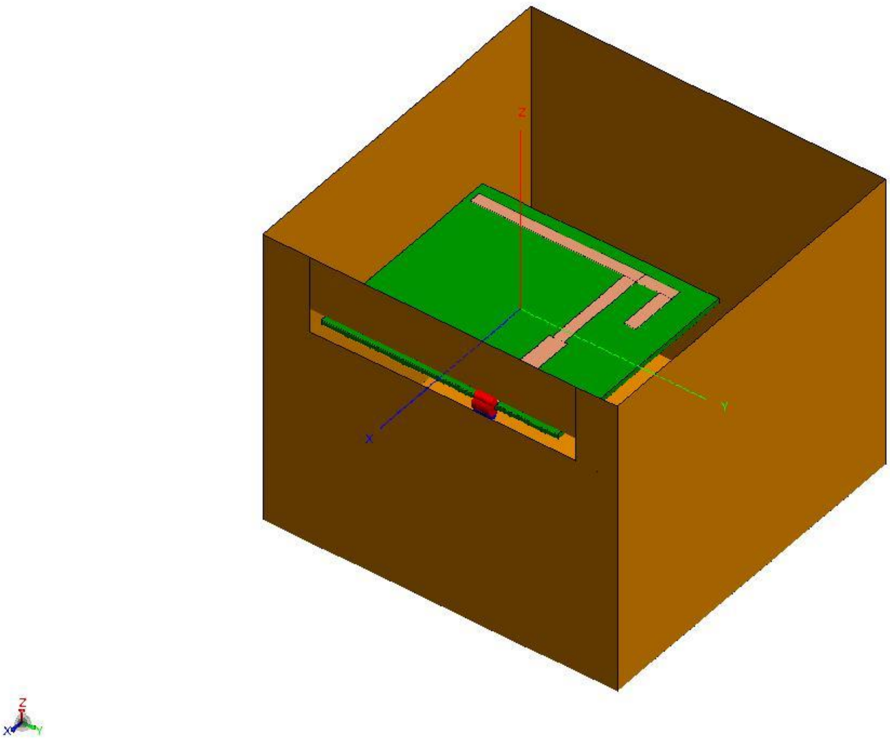

Figure 23 – PIFA 1 layout with metal box

For the tuning purpose the length ‘h1’ in the Figure 21 is changed to 10 mm instead of 12 mm as suggested in the paper.

3.4.1.2 Simulation results for PIFA 1 design

The PIFA 1 has the return loss (reflection coefficient) of -28.14 dB at 2.45 GHz. The antenna is a wideband antenna with the frequency range of 280 MHz. Bandpass filter can be used to make the bandwidth narrower. Figure 24 shows the VSWR of the PIFA 1. In the Figure 25, the gain of the PIFA 1 is shown with the half power beam width.

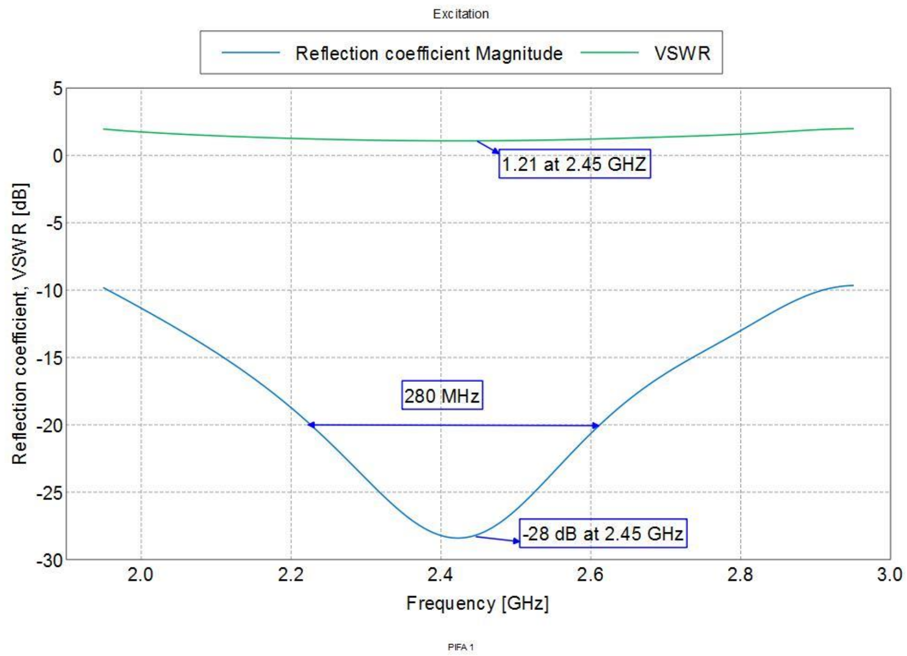

Figure 24 - Reflection Coefficient and VSWR of PIFA 1 design

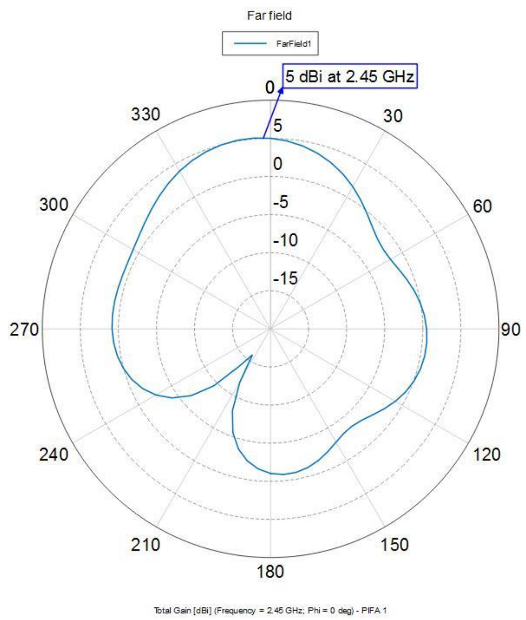

Figure 25 - Gain of PIFA 1

The impedance of the antenna is 13 Ω. To match the circuit with 50 Ω impedance I/O module, a 37 Ω resistance can be attached in series with the antenna. For the PCB design purpose, a stub elements matching network is proposed as shown in the Figure 26.

The impedance matching network is optimized in ADS to get the best results. As shown in figure, the micro-strip transmission line `TL5´ works as the waveguide and it has the length of λ/4. The PCB layout structure is given in Figure 26.

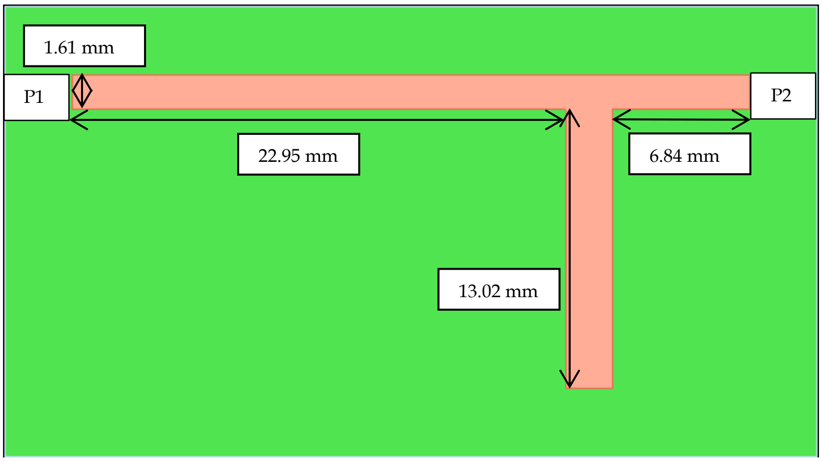

Figure 26 - Impedance Matching Network on PCB for PIFA 1

The impedance matching structure is built on the same dielectric substrate as the antenna. The dielectric material is RT/Duroid 500 which is cheaper. There is a problem with the fabrication with the I/O module because of the different dielectric material. The I/O module is made on the FR-4(ε_r = 4.7) substrate and the antenna with the matching network has the substrate which has the dielectric constant of 2.2 (ε_r = 2.2). There are some fabrication methods which can be used to fabricate different dielectric materials.

3.4.2 Planer Inverted-F Antenna (PIFA) Design 2

The design structure of PIFA 2 is more complicated from the previous design. The PIFA 2 works as the monopole antenna with the feed line close to the center. The C section on the left side as shown in figure 28 works as the inductor and the center part where two patches separated by the height 'H5' works as the capacitor. When the impedance of the capacitor and inductor matches then antenna radiates the signals.

3.4.2.1 Design Specification of Planer Inverted-F Antenna (PIFA) 2

The structure and dimensions of the antenna are given in Figure 28 and Table 4 simultaneously.

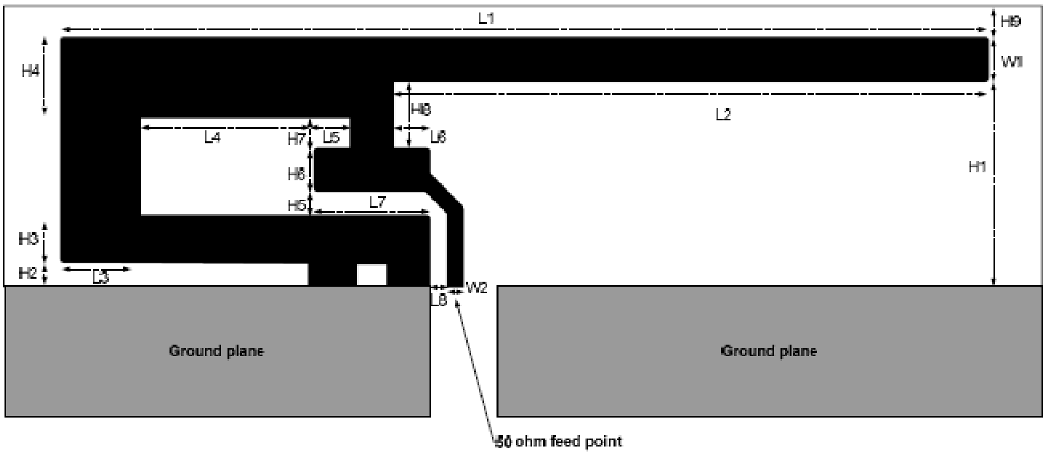

Figure 27 - Printed Inverted-F Antenna [24]

The design of this planer inverted-F antenna is more complicated than the previous design, but the advantage is that this design does not require any impedance matching.

Table 4 Physical dimensions of the PIFA 2 [24]

H1	5.70	W2	0.46
H2	0.74	L1	25.58
H3	1.29	L2	16.40
H4	2.21	L3	2.18
H5	0.66	L4	4.80
H6	1.21	L5	1.00
H7	0.80	L6	1.00
H8	1.80	L7	3.20
H9	0.61	L8	0.45
W1	1.21		

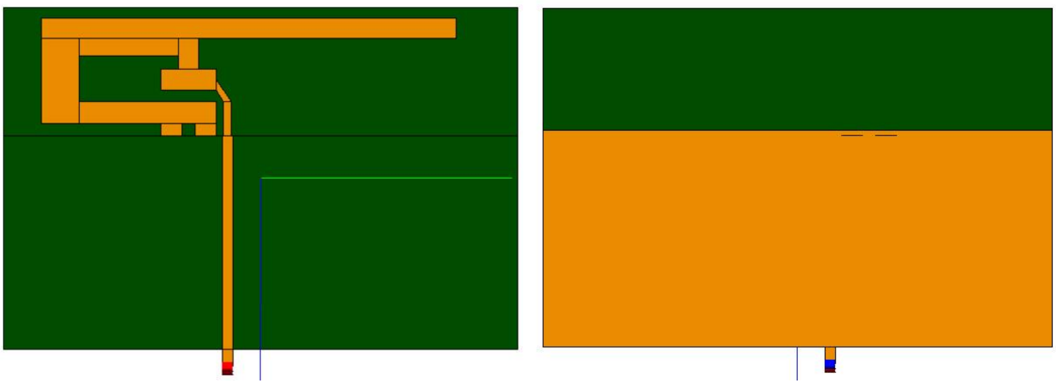

Figure 28 - Proposed PIFA 2 design

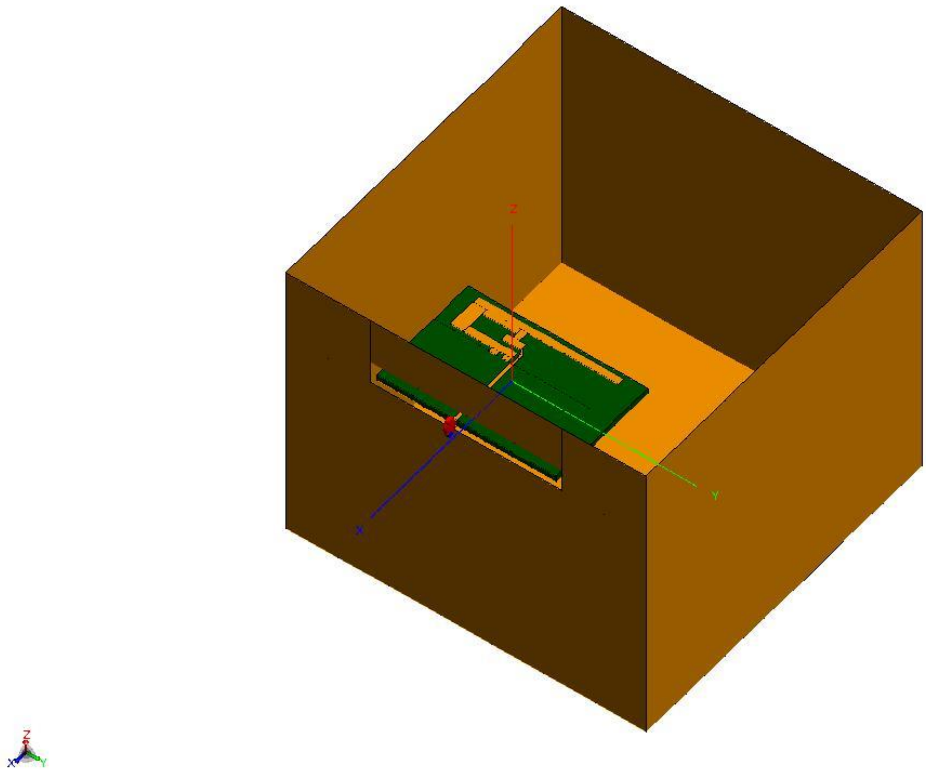

Figure – 29 PIFA 2 with metal box

The resonance frequency can be tuned by changing the length 'L1'. The length of the ground plane is set around λ/4 for better result. The ground plane is not kept under the antenna trace for better performance as the previous antenna designs. The long micro-strip line works as the impedance matching network in this design.

3.4.2.2 Simulation results for PIFA 2 design

The simulations results of PIFA 2 parameters are given below.

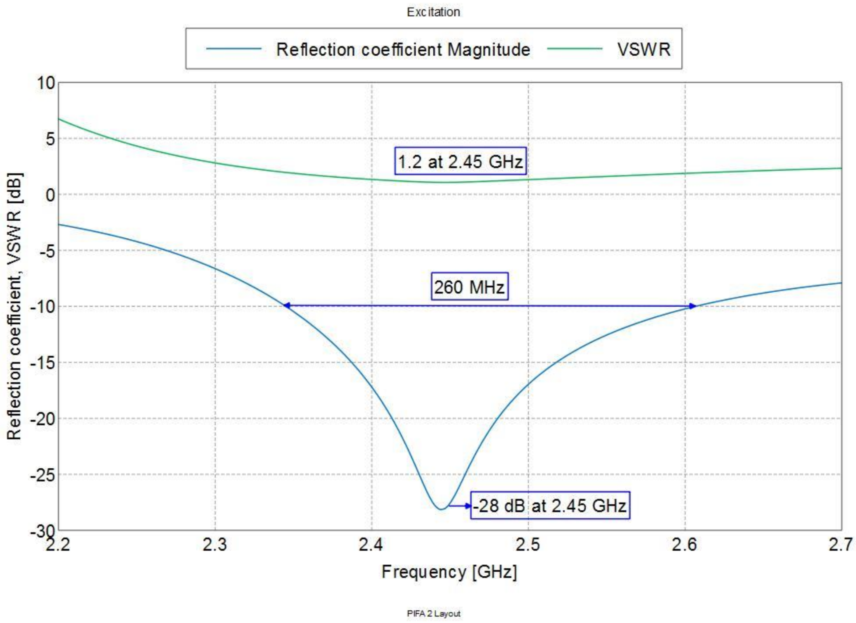

Figure 30 - Reflection Coefficient and VSWR of PIFA 2

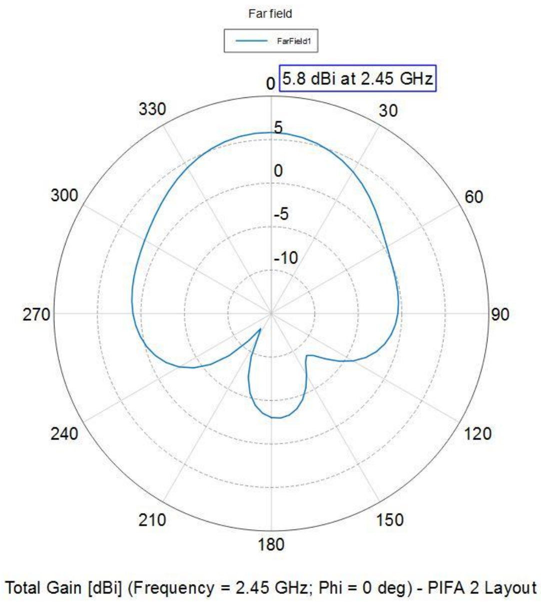

Figure 31 - Gain of PIFA 2

The return loss of the antenna is very low, -29 dB at 2.45 GHz. So, the antenna has a very good efficiency with 260 MHz of bandwidth. Figure 31 shows the gain and the half power beam width of the antenna. The gain of the antenna is 5.8 dBi. This type of antenna design is widely used now a day in many communication devices.

3.5 Simulation result comparison of different antenna designs

The comparison of the different parameters for the different antennas is given below. Not all the parameters are given but the important parameters such as radiation pattern, gain, reflection coefficient and VSWR are given below.

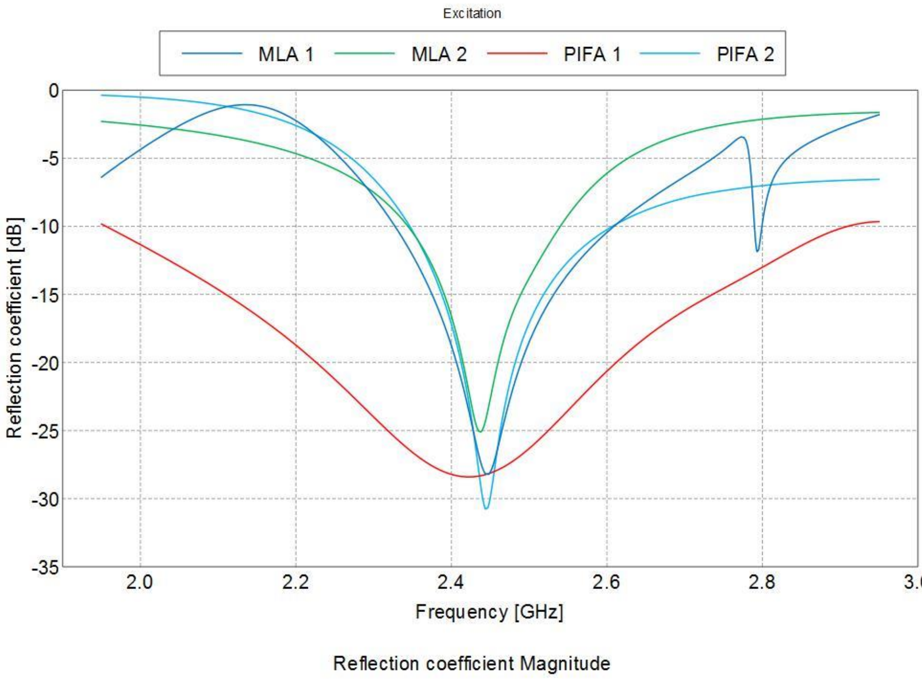

Figure 32 - Comparison of reflection coefficient of the antennas

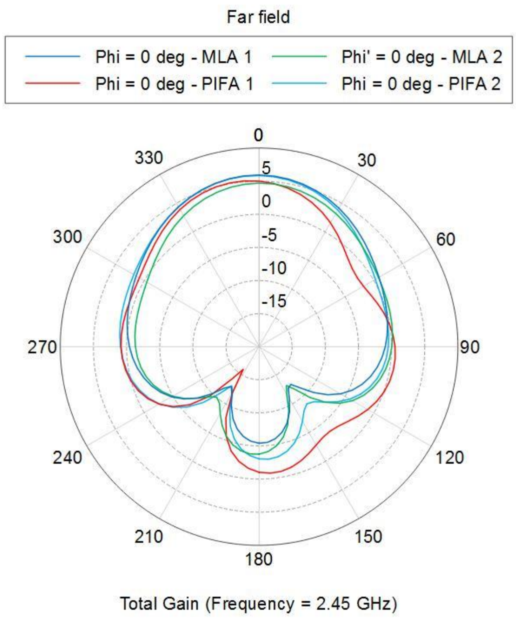

Figure 33 - Comparison of Gain of the antennas

3.6 Summary of results

In this section, comparisons of the different parameters of the antennas are given. The table includes the parameters such as type of substrate, resonant frequency, dielectric constant, thickness of the substrate, delta tangent, gain, reflection coefficient, VSWR and bandwidth.

Table 5 Summary of results

Antenna	Substrate	f_r (GHz)	ε_r	T (mm)	tan δ	Gain (dBi)	Γ (dB)	VSWR	BW (MHz)
MLA 1	FR-4	2.45	4.7	1.6	0.0019	5.36	-29.15	1.21	330
MLA 2	RT/Duroid	2.45	2.2	0.813	0.02	4.7	-23.15	1.34	156
PIFA 1	RT/Duroid	2.45	2.2	1.6	0.019	5.0	-28.14	1.21	280
PIFA 2	FR-4	2.45	4.4	0.8	0.0019	5.8	-29	1.2	260

Where,
f_r = Resonant Frequency
ε_r = Dielectric constant
T = Thickness of the substrate
tan δ = Loss tangent
Γ = Reflection Coefficient
VSWR = Voltage Standing Wave Ratio
BW = Bandwidth

According to the table 5, the meander line antennas are designed on two different substrates. MLA 1 has better gain; reflection coefficient and bandwidth compare to the MLA 2. So, it is better to select MLA 1 because the I/O module is also printed on the similar substrate as MLA 1, FR-4. The implementation of the antenna is quite easy because of the similar substrate.

Also, in PIFA, both the antennas are made on a different substrate but PIFA 2 has the better characteristics than PIFA 1. So, it is better to choose PIFA 2.

4 Selection of the PCB antenna for manufacturing and testing

Previous chapter suggests different kinds of PCB antennas which can be used in the I/O module. It is not appropriate to design and manufacture all the PCB antennas because it is very time consuming and also cost inefficient. For the further testing the best appropriate antennas need to be chosen. Among the previous antenna designs, the Planer Inverted-F Antenna 2 (PIFA 2) is the best possible option.

4.1 Design constraints and PIFA 2 design advantages

According to the NIBE's requirements, the proposed antenna design must be on the FR-4 substrate with the dielectric constant of 3.97. Also, the thickness of the PCB must be 1.6 mm. In addition, the antenna needs to be inside the metal box. Also, the I/O module is on the other side of the PCB and antenna needs to be on the other side. These are the design constrains need to be taken into account. By considering all these parameters, PIFA 2 is the best possible option.

The biggest advantage of the PIFA 2 is that it does not require the impedance matching network between the module and the antenna as the simulation results suggests. As shown in the figure – 26, the design has the built in LC – network. It also can be tuned to adjust the resonant frequency by changing the size of the patch.

4.2 Simulation of PIFA 2

The PIFA 2 design in the CAD FEKO is shown below. Every parameters which suggested by the NIBE had taken into account while designing this PCB antenna.

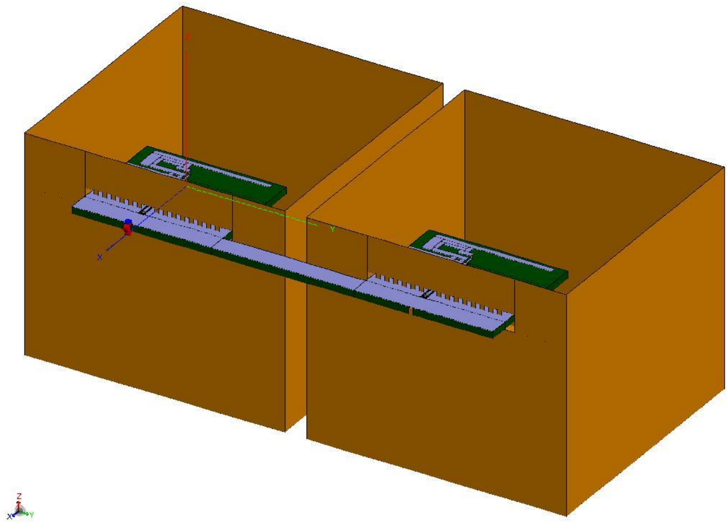

Figure – 34 final PIFA 2 design layout for printing

As from the figure above, there are two antennas being used because there are two I/O modules. Both antennas are on the single PCB and both are sharing the common ground plane. As the PCB ground plane, the coplanar ground planes are being used to design the antenna because the coplanar ground planes are useful to reduce the size of the micro-strip line and also it helps to reduce the radiation from the strip line. Also, the metal box is also connected with the PCB, so that it can work as the part of the antenna and helps to prevent the backside radiation and leakage.

One more design constraint is, the I/O module and the antenna are on opposite side of the PCB. So to connect them, one copper cylindrical pin is being used as shown in the figure.

The simulation software CAD FEKO gives the results of the different antenna parameters such as reflection coefficient, bandwidth, gain and VSWR. One important parameter need to be taken into account when two antennas are this close distance which is S21 (scattering parameter). S21 represents the power received at antenna 2 relative to the input power of antenna 1. Ideally, it should be less than -80 dB but it is very difficult to get.

4.3 Simulation results of the PIFA 2

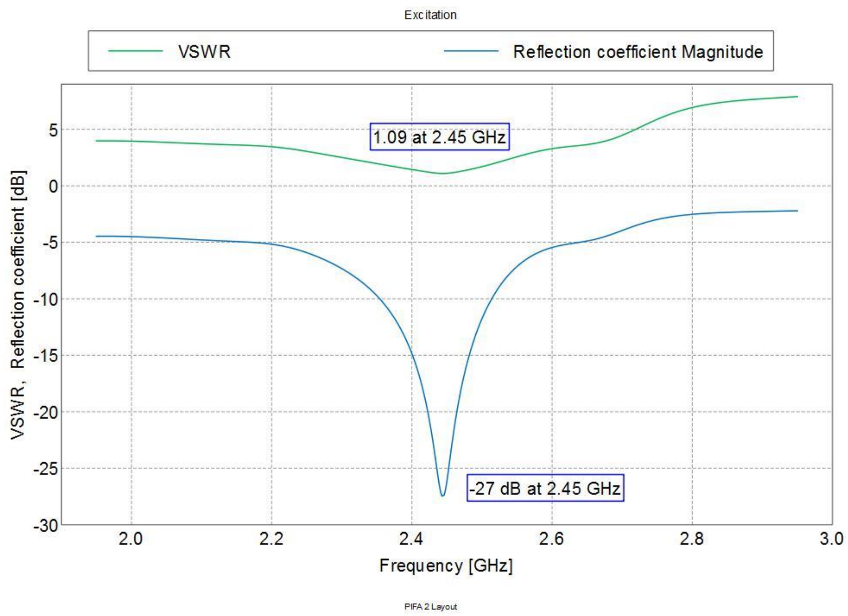

Figure – 35 VSWR and Reflection coefficient of PIFA 2

Figure – 35 shows the Voltage Standing Wave Ratio (VSWR) and the reflection coefficient of the antenna. The resonance frequency is 2.45 GHz. The reflection coefficient is -27 dB which meant if the antenna is working at 1 watt of power only 0.002 watt (0.2 %) power is reflected back.

Figure – 36 shows the scattering parameters of the antennas. The two antennas in the module work as the two port network. Two scattering parameters are shown below – S11 and S21. S11 is also known as the reflection coefficient and

S21 means the power receives by antenna 2 from the transmission power of antenna 1. For an example, if the antenna 1 transmit 1 watt power, antenna 2 will receive 0.063 watt of power only.

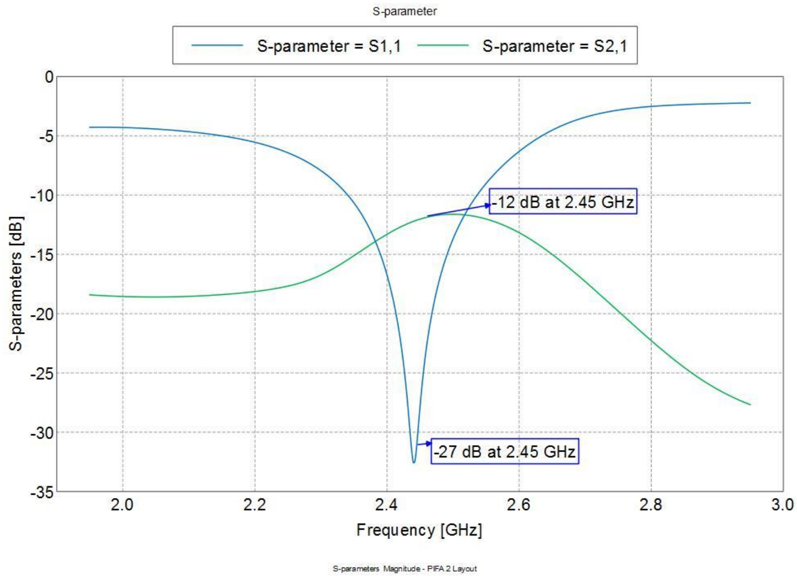

Figure – 36 scattering parameters of PIFA 2

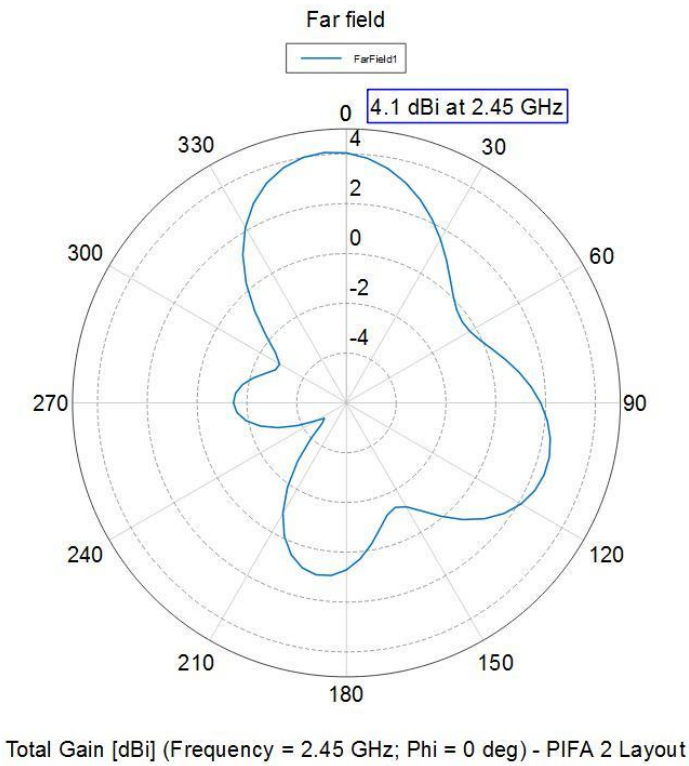

Figure – 37 Gain of the PIFA 2

Above figure - 37 shows the gain of the antenna at 2.45 GHz which is 4.1 dBi.

4.4 PIFA 2 prototype

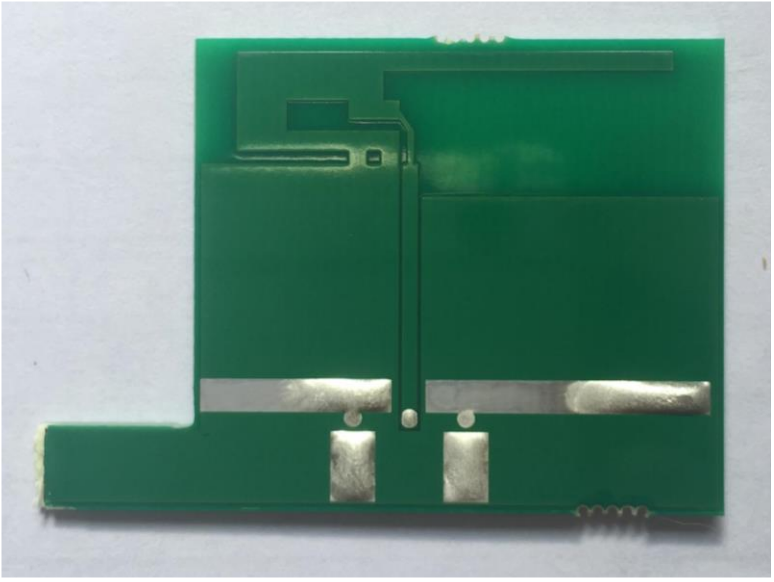

Figure – 38 PIFA 2 prototype

The above figure is the actual PIFA 2 antenna prototype. This PIFA 2 antenna will be connected with metal box via connector. As per the requirement from the NIBE, the dielectric material is FR-4 with the dielectric constant of 3.97 and the thickness of the PCB is 1.6 mm.

The next step is going to be the antenna testing. After testing, the antenna will replace the monopole antenna of the I/O module and will be used in new IOT devices for small range communication and data transfer.

5 Learning Outcome

From this thesis project, there are several technical and non-technical aspects one can evaluate. This chapter includes the important parameters and characteristics of the antenna design. Also, there are general advantages of this I/O device are included as well.

From technical point of view, important parameters such as radiation pattern, gain, reflection coefficient, VSWR are very crucial while designing the antenna. These parameters are crucial for both conventional and PCB antennas and some of them like gain and radiation pattern are depends on the application.

The characteristics of antenna change with the physical properties of the antenna. For an example, the thickness of the PCB changes the bandwidth of the antenna by the effect called fringing. The width of the trace line affects the impedance of the antenna. Resonance frequency of the antenna depends on the length of the antenna trace. Also, the gain and directivity of the antenna depend on the size of the ground plane and the placement of the ground plane. The radiation pattern changes with the surrounding environment of the antenna. These characteristics also affect by the material used to build the PCB as well. The dielectric constant affects the parameters such as gain, reflection coefficient and bandwidth. Changing the antenna trace material, changes the radiation power and return loss of the antenna. When two antennas are implemented at close distances, the scattering parameters are also important.

Mounting of the antenna also affects parameters such as radiation intensity, electromagnetic interference to nearby electrical and communication devices. Radiation intensity is crucial part when it comes to emit the radiation in prescribe limit by the government bodies. These limitations of the radiation emission differ from commercial and industrial usage. According to these government bodies, the new designed antenna should not be emit the electromagnetic radiation because the over emitted radiation is harmful to nearby humans, animals and plants.

Also, if these antennas are mounted near the other electrical/electronic devices, it will degrade the performance of the antenna because of nearby strong EMC pulse and voltage/current spikes.

6 Conclusions and future work

The printed circuit board (PCB) antenna is the better option to replace the conventional monopole antenna which is being used currently in the NIBE AB's I/O module. The PCB antennas offer better gain as the wire antenna with the wide bandwidth. The important features of these antennas are that they do not require the connector (e.g., SMA connector) so that the connection losses are very less. They are also cheap. There are thousands of PCB antenna designs available in market for different frequencies and for different specifications. Even at 2.45 GHz ISM band there are so many different designs available. PCB antennas have problem to achieve high gain. Some PCB antennas like printed Yagi-Uda and printed coil antennas have the high gain, but they are narrow band. MLA and PIFA antennas can overcome the limitation of PCB antennas by choosing the right dialectical material and with optimization.

In this project we also worked on the reduction of size of the antenna. There are two metal boxes which implemented into the module to prevent the back-side radiation and the radiation from heating unit itself. These metal boxes also help to prevent the interferences from both antennas. The proposed antenna has to be fit inside these boxes. For example, patch antenna offers higher gain and bandwidth, but its size exceeds the size of metal boxes.

NIBE AB is going to choose one or two designs and implement these proposed antennas into their module for testing. Other improvements can also be done to obtain an antenna with higher performance such as stacking the antennas with the different dielectric materials which is beyond of this project. Some of the proposed antennas in this thesis are dual band which the potential to work at both 2.45 GHz and 5.0 GHz. So, in the future NIBE AB will not have any issue of antenna designing if they wish to change their module frequency to work at 5.0 GHz. Instead of the metal boxes, one can use the EM absorber on the outside to prevent the outer interference. Also, by changing the material of the box one can improve the performance of the antennas.

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