5G Reconfigurable Patch Antenna using RF MEMS

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CERTIFICATE OF CORRECTIONS & APPROVAL

Certified that work contained in this thesis titled “5G Reconfigurable Patch Antenna using RF MEMS”, carried out by CSUO Waleed, SGT Kashif, GC Rizwan, GC Abdul Hanan, under the supervision of Dr. Farooq Ahmed Bhatti for partial fulfillment of Degree of Bachelors of Electrical Engineering, in Military College of Signals, National University of Sciences and Technology, Islamabad during the academic year 2016-2020 is correct and approved. The material that has been used from other sources, has been properly acknowledged / referred.

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We are appreciative towards our Creator Allah Subhana-Watala to have helped us during the process of writing our thesis by putting new ideas in our mind and then improving them. Indeed nothing could have been possible without Your inestimable aid and supervision. All the individuals who have helped us during our thesis did so because of Your will and no one is worthy of praise except You.

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As a final point, we are all very thankful to our loving parents for fulfilling all our necessities that were required to reach this stage.

Dedication

I dedicate this to my loving parents whose support paved a way for me to this wonderful accomplishment.

Abstract

The worldwide versatile information traffic is probably going to be anticipated by 45% that will bring about roughly 18 billion IoT out of all out 29 billion gadgets.5G innovation can give numerous favorable circumstances, for example, higher transmission rate and shorter latency over the current 4G framework. 5G remote correspondence frameworks request scaled down size and multifunction necessities with worthy qualities in addition, transmission capacity and radiation productivity. The progression of present day remote correspondence frameworks request receiving antenna applications in remote sensing, imaging, dielectric sensing, radar frameworks, satellite interchanges, clinical territories, remote frameworks, radio frequency identification (RFID) tags. Because of the requirements for the size of economy, the gadget makers must lessen the quantity of equipment segments and this requests an expanded number of frequency bands utilizing less complicated equipment. In this study we have achieved tri band characteristics by varying length of radiating patch, slots, partial ground and parasitic patches while frequency reconfigurability has been achieved by RF MEMS. The small size of the antenna (70x140 mm^2), and switchable frequency bands enables the antenna to be used in different wireless devices. Stimulation software HFSS 13 was used for this design and results were achieved.

Table of Contents

List of Figures

List of Tables

Chapter 1: Introduction

1.1 What is use of Antenna?

The use of antenna is to provide a connection between radio waves which are travelling in space and between the current in a metallic conductor. The reception and transmission of a signal is done by an antenna.

1.2 Types of antenna

Antennas are of many kinds. The structure and the shape of antenna determine the application for which they are designed. Log Periodic, Horn, Dipole, Vivaldi, Bowtie and Micro-strip patch antennas are some of the popular kinds of antennas. Antennas are classified into directional and Omni-directional antennas. The antenna which has the similar gain value in every direction is called the Omni-directional antenna. A dipole antenna is a kind of Omni-directional antenna which is used in mobile phones as well as wireless routers. Whereas the antenna having high gain in a particular direction is called a directional antenna. This thing makes it very unique. Balanis, C. A in his paper discusses that the parabolic dish antenna is a kind of directional antenna. This paper is mentioned in reference [1].

Figure 1.1 shown below shows the radiation pattern of Omni directional and directional antenna.

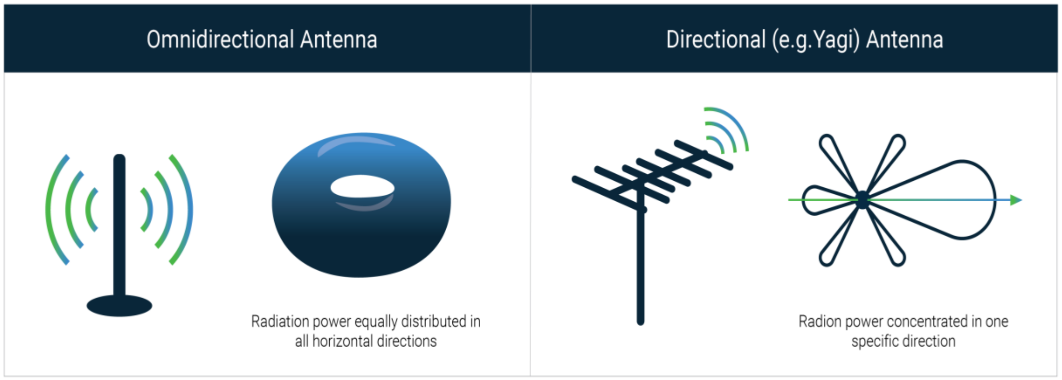


Figure 1. 1: Omni Directional and Directional Antenna

Nowadays, the Micro-strip patch antennas are suitable because of the miniaturization which is a important requirement. The other advantages are that they are very economical, have very low operating bandwidth and are having very light weight. It is because of these advantages, they are mostly used for wireless applications.

1.3 Micro-strip Patch Antenna

This antenna is manufactured by using a micro-strip technique on PCBs. It is manufactured in a way that a radiating patch is put above a substrate having a plane ground at its bottom.

1.4 Construction of Patch Antenna

A micro-strip technique is used for making a patch antenna. It is made up of a substrate of appropriate thickness and having a specific dielectric material. It has a radiating patch on its top. On its rear side, there is a ground plane. But in some cases it is present on the same side.

The complete construction of Micro-strip patch with patch on top and ground at bottom of substrate is **shown in Figure 1.2**

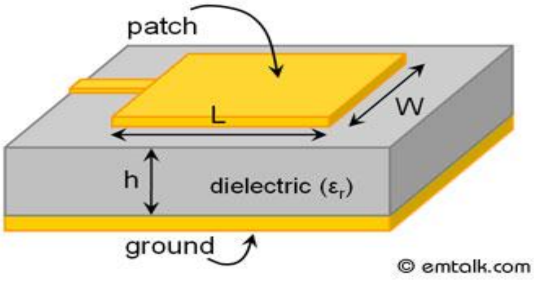


Figure 1. 2: A Micro-strip patch antenna

1.5 Constituents of Patch Antenna

The substrate, radiating patch and ground are the basic components of a patch antenna.

1.5.1 Radiating Patch

The patch can take up any structure or shape. They can be rectangular, circular, a square, a ring or elliptical. But in its basic design, it is rectangular. They may be changed as per its application.

Different shapes of patch have been shown in the **Figure 1.3**. Any shape can be taken as per the requirement of your design.

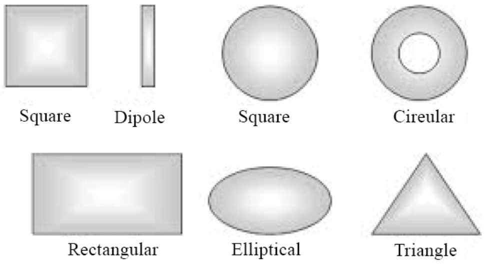


Figure 1. 3: Different structures of radiating patch

1.5.2 Substrate

The thing which supports the antenna mechanically is called substrate. The transmission line and electrical properties of substrate are affected by its characteristic properties. To select a substrate, we have to consider some basic factors. Some of these factors are dielectric material, temperature, humidity, loss tangent and surface wave excitation. The most important factors are the price and its availability.

1.5.3 Ground plane

The ground plane comprises of a conducting material. Basically, the ground plane is situated at rear of substrate. It can also be called a partial ground if it is etched to a smaller size, which increases its bandwidth. We can also increase its gain and directivity by introducing another frequency. To do this, we introduce a defect in the ground. By doing this the ground is then called the Defected Ground structure (DGs).

Some of the examples of defected ground are shown in **Figure 1.4**. There are other examples as well but these are the ones that are most commonly used.

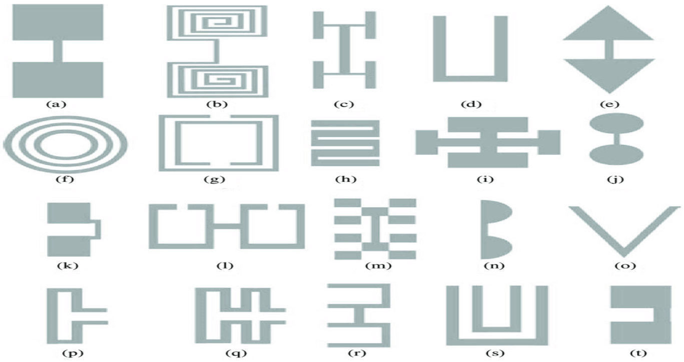


Figure 1. 4: Shapes of Defected ground structure

1.6 Feeding Procedure of Micro-strip Patch Antenna

There are five feeding mechanisms of Micro-strip patch antenna which are:

- Micro-strip Line Feed
- Inset Feed
- Aperture Coupled Feed
- Proximity Coupled Feed
- Coaxial Probe Feed

The detail of each is explained below:

1.6.1 Micro-strip Line Feed

The feed is carved on top of substrate, resulting of the same plane of feed line and radiating patch. In this type of feed, the fabrication becomes very easy.

Figure 1.5 shows the micro-strip feed line that has been inserted in the patch. This is the point where you give feed to your antenna. It should be noted that micro-strip feed line is not inserted in the radiating patch as in case of insert feed.

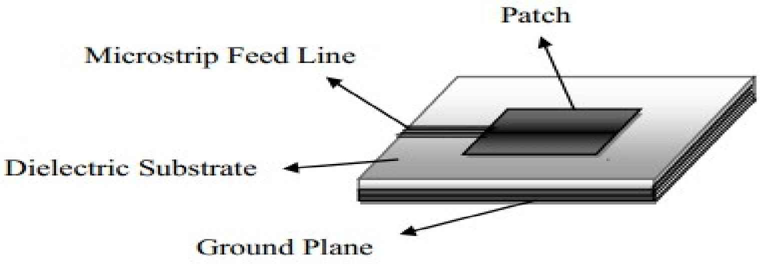


Figure 1. 5: Micro-strip Feed line

1.6.2 Insert Feed

In case of such feed, the transmission and the micro-strip line feed are same, but feed is entered into a radiating patch. It has the same advantage as of micro-strip feed and that is the ease of fabrication.

How a feed is inserted in the radiating patch is **shown in Figure 1.6**. It can easily be observed in this figure that the feed line is inside the radiating patch and the dimensions of the part of feed inside the radiating patch is denoted by **‘d’** in the figure.

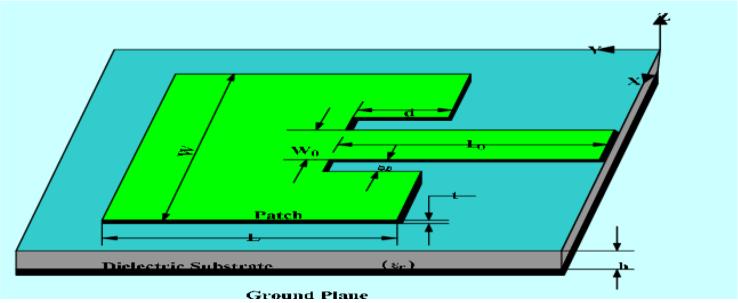


Figure 1. 6: Inset Feed

1.6.3 Aperture coupled Feed

In this method, two substrates are piled up on one another, and ground is plane in the middle of these substrates and on the top-substrate there is a radiating patch. Its advantage is that it makes the antenna optimize-able and versatile.

Figure 1.7 shows how feed line is placed on top of ground which in between the two substrates.

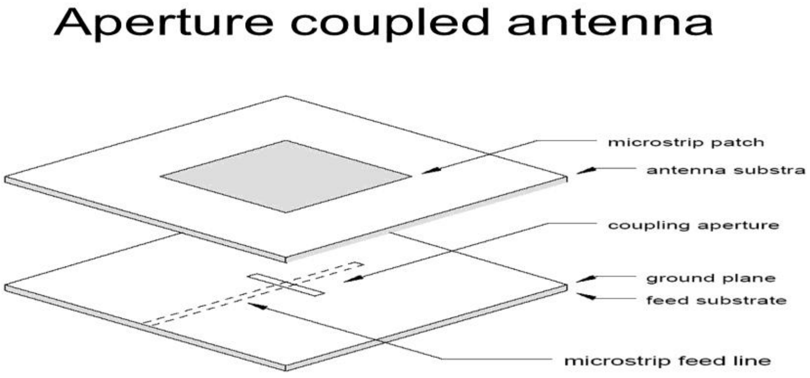


Figure 1. 7: Aperture coupled Feed

1.6.4 Proximity coupled feed

In this method, the micro-strip feed is passing in the middle of two substrates which are stacked into each other, with the radiating patch carved on the top substrate. Its advantage is that it has very low spurious radiations which increase its bandwidth.

Micro strip feed line placed between two substrates piled on one another is shown in **Figure 1.8 below**.

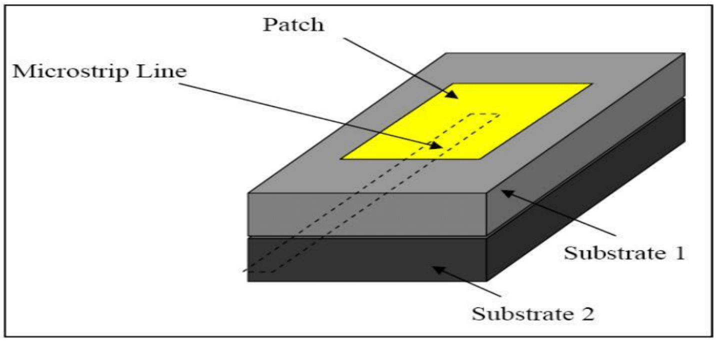


Figure 1. 8: Proximity Coupled Feed

1.6.5 Coaxial probe Feed

In case of such feed, the conducting pin is placed at the bottom of radiating patch which is on top. This pin is drilled from ground plane and is insulated from the material of substrate. Its disadvantage is that it has insertion loss.

Figure 1.9 shows how a coaxial feed is inserted.

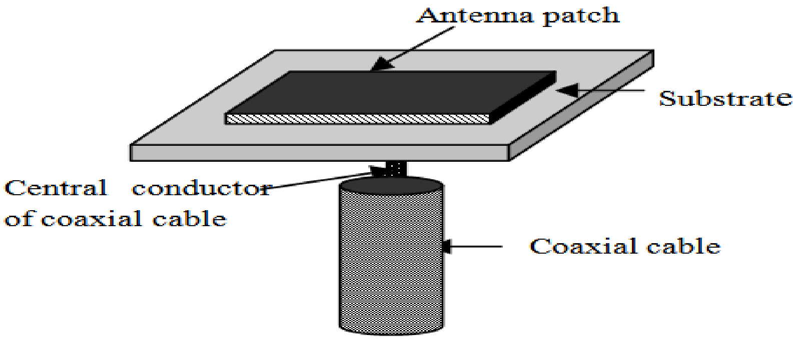
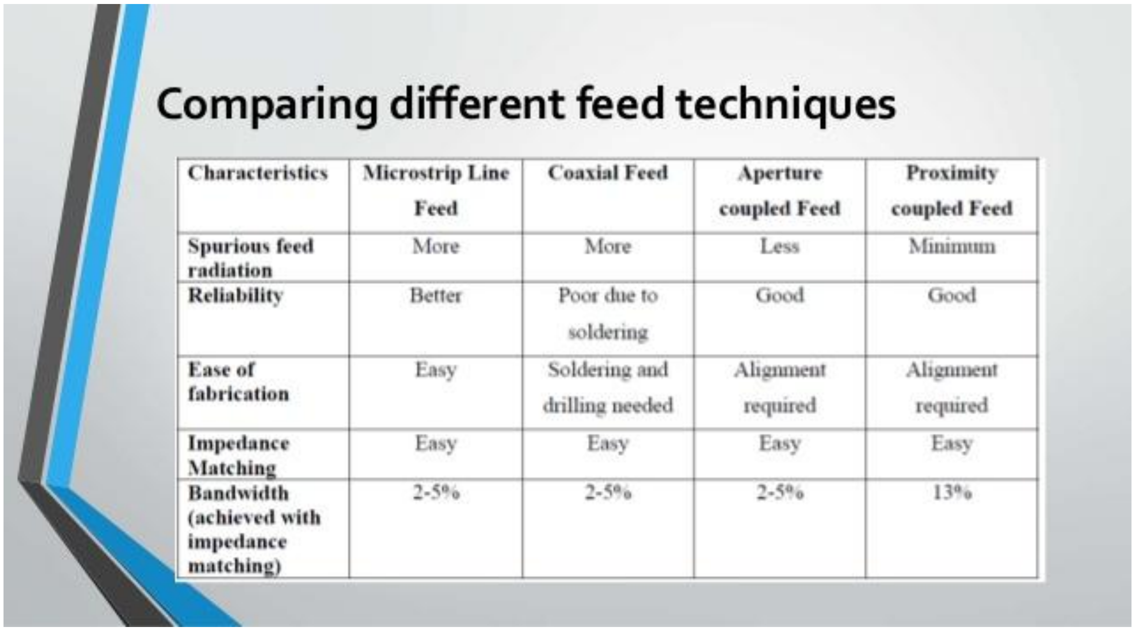


Figure 1. 9: Coaxial Probe Feed

Following **Table 1.1** shows general characteristics of feeding methods:



Comparing different feed techniques

Characteristics	Microstrip Line Feed	Coaxial Feed	Aperture coupled Feed	Proximity coupled Feed
Spurious feed radiation	More	More	Less	Minimum
Reliability	Better	Poor due to soldering	Good	Good
Ease of fabrication	Easy	Soldering and drilling needed	Alignment required	Alignment required
Impedance Matching	Easy	Easy	Easy	Easy
Bandwidth (achieved with impedance matching)	2-5%	2-5%	2-5%	13%

Table1. 1: Different feeding methods

1.7 Variables of Antenna

The parameters that are important for measuring dimensions and calculating patch are as follows:

1.7.1 Geometrical Variables:

1.7.1a Proportions of rectangular patch:

It affects bandwidth of antenna if it is a square or rectangular patch antenna. The equation for width is given below:

$$W = \frac{1}{2fr\sqrt{\mu_0\mathcal{E}_0}}\sqrt{\frac{2}{\epsilon_r+1}} = \frac{v_0}{2fr}\sqrt{\frac{2}{\epsilon_r+1}}$$

v_o is free space velocity of light.

1.7.1b Radius of circular patch:

Its effect is given from the following equation:

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

Where $F = \frac{8.791\times10^9}{f_r\sqrt{\epsilon_r}}$

1.7.1c Height of Substrate:

It is important in the antenna bandwidth. Its relation with respect to length is given.

$$\frac{\boldsymbol{\Delta L}}{\boldsymbol{h}} = \mathbf{0.412}\frac{(\boldsymbol{\epsilon_{reff}}+\mathbf{0.3})(\frac{\boldsymbol{W}}{\boldsymbol{h}}+\mathbf{0.264})}{(\boldsymbol{\epsilon_{reff}}-\mathbf{0.258})(\frac{\boldsymbol{W}}{\boldsymbol{h}}+\mathbf{0.8})}$$

1.7.2 Performance Parameters

The performance parameters are given below:

1.7.2a Reflection Coefficient

It is also called the S11 parameter. It gives the resonant frequency and reflected amount of power which is obtained from an antenna. Its A0 dB shows that it has reflected all of its power and nothing is radiated. So it is a ratio of incident to reflected power.

$$r = 10log_{10}\frac{p_i}{p_r}$$

1.7.2b Return Loss

The loss in a signal, returned after the dissipation in load.

$$RL = -20log_{10}r\ (dB)$$

An example of a return loss plot is presented in the **Figure 1.10**

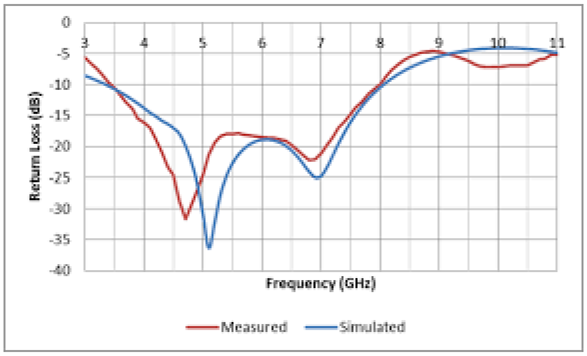


Figure 1. 10: S11 plot of antenna

1.7.2c Voltage Standing Wave Ratio

VSWR value should become one for impedance-matching but 2 is also acceptable at resonant frequencies. This is also a criterion which has to be fulfilled for the acceptable case characteristics. It shows the power that is bounced back from antenna and it's a reflection coefficient function.

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

1.7.2d Gain

When we divide the power which is generated by antenna from a source of long distance on its beam axis with the power which is produced by isotropic hypothetical omni-directional antenna, we get gain. A gain of very high value is desired.

This **Figure 1.11 shows** that gain of directional antenna is in a particular direction whereas in case of isotropic antenna it is equal in every direction.

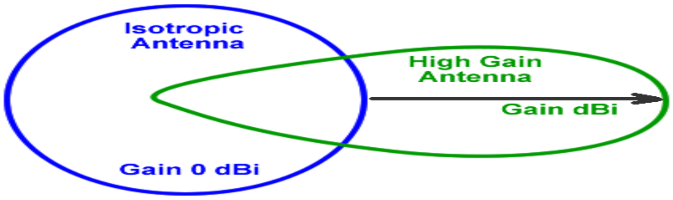


Figure 1. 11: Gain of an isotropic antenna vs. directional antenna

1.7.2e Radiation Patten

The fashion in which the antenna radiates in H plane and the E plane is described by radiation pattern. The cross polarization and the co-polarization is also found with the help of this plot.

An example of radiation pattern plot is **shown in Figure 1.12**

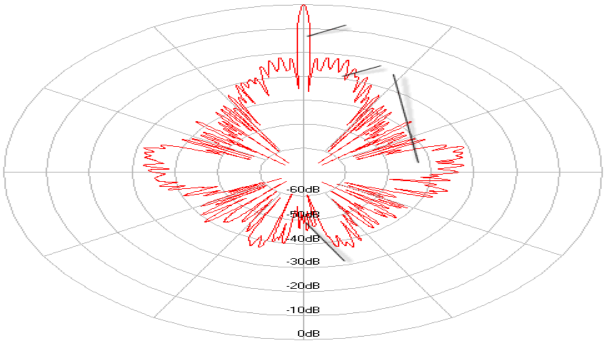


Figure 1. 12: Plot of Radiation pattern

1.7.2f Directivity

This is also a very important variable of an antenna. It gives the direction an antenna would radiate in. It may have the Broadside radiation, in which the antenna will radiate perpendicular to the radiating patch. Or it may have the End fire, in which it radiates parallel to its patch.

Now the main lobe in **Figure 1.13** shows that in which direction the antenna will radiate in.

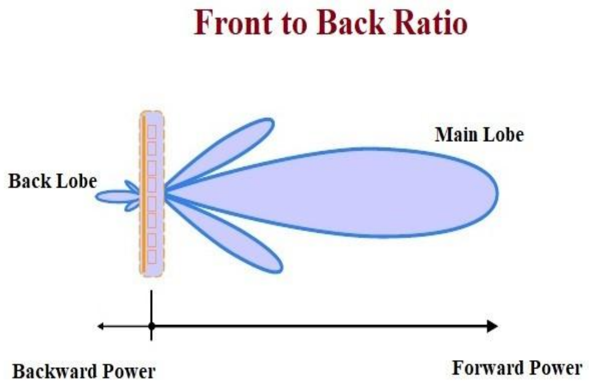


Figure 1. 13: Directivity of antenna

1.7.2g Polarization

The path or pattern which is followed by electromagnetic waves, when it passes through the radiating structure of the antenna is called polarization. It may be linear or circular polarization.

Linear polarization:

In linear polarization, antenna will radiate in only one plane that is parallel to the direction of propagation of signal. Its types are as follows:

Vertical polarization:

It is when the electric field makes an angle perpendicular with the surface of earth.

Horizontal polarization:

It is when the electric field makes an angle that is parallel with the surface of earth

Circular polarization:

When the polarization plane rotates in a circle in a single duration of a wave, it is called circular polarization. Its types are as follows:

RHCP:

It is when wave rotates in clockwise manner, while looking in propagation direction.

LHCP:

It is when wave rotates in an anti- clockwise manner, while looking in propagation direction.

Different patterns of polarization are **shown in Figure 1.14**. It shows the difference between RHCP and LHCP as well as vertical and horizontal polarization.

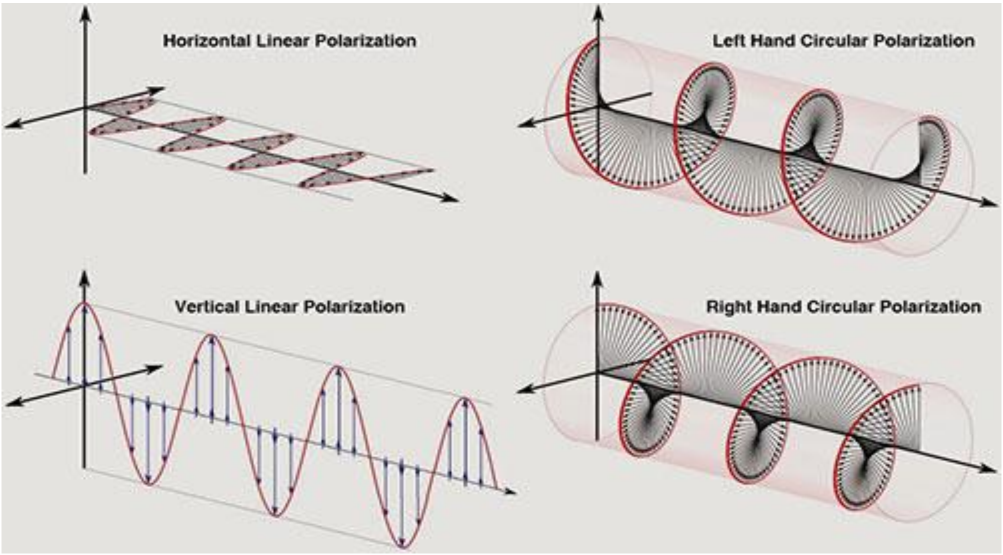


Figure 1. 14: Linear vs. Circular Polarization

1.7.2h Bandwidth

It gives the operating frequency range. In Microstrip patch antennas, basically there is a narrow bandwidth. The bandwidth is increased up to a required frequency range by specific techniques. One of these techniques is the partial ground.

1.8 Multiband Antennas:

The antenna which operates on more than one frequency is called a multiband antenna. Its purpose is to acquire the required frequency components for which it is designed for**.**

Chapter 2: Reconfigurable Antennas

Changing in one or more parameters in such a way that their characteristics or properties are altered is called Reconfigurability.

2.1 What is Reconfigurable Antenna?

An antenna that can change its radiation pattern or frequency in a reversible manner. This change is controlled in a manner that the result which we need are obtained.

2.2 Why Reconfiguration was required?

The purpose of the reconfigurable antennas is that it can handle several standards at the same time due to their switching operation, whereas the multiband antennas have the disadvantage that they can operate on a single wireless standard.

2.3 Advantages of Reconfigurable Antennas:

These advantages are as follows:

2.3.1 Multi Standard Suitability

It has the advantage that it has very low cost and it has very low space requirements. Its fabrication is also very easy and there is a good isolation between many standards.

2.3.2 Eliminate filtering Requirement at front end of system

In these, no filtering is required and these antennas need simple end case. The band rejection is also more than the average.

2.3.3 Adaptive Applications

These antennas are most suitable for the adaptive applications due to the reason that they have automation via microcontroller or FPGA.

2.3.4 Versatility

These are versatile antennas. They may be operate for narrow and wide operations as well as a single antenna or as an array.

2.4 Types of Reconfiguration

Reconfiguration is of four types. These are:

- Frequency Reconfiguration
- Polarization Reconfiguration
- Pattern Reconfiguration
- Compound Reconfiguration

There types are explained below:

2.4.1 Frequency Reconfiguration

In this type of reconfiguration the geometry of the antenna is changed and in doing so resonant frequency of antenna shifts. Huff, G. H in his paper talks about the reconfiguration of resonant frequency bands. It is shown in reference [2].

The Figure 2.1 shows how frequency bands are shifted by switching modes of switch and how frequency reconfiguration is achieved.

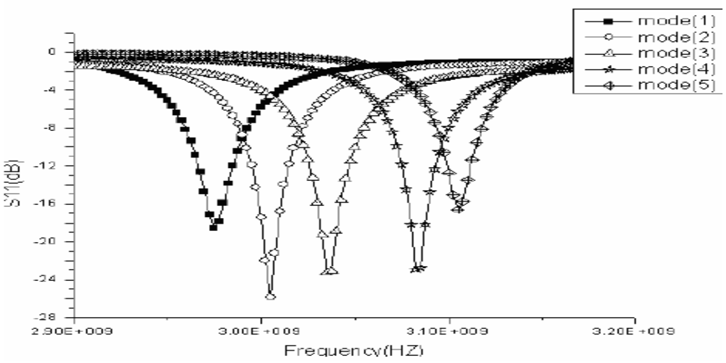


Figure 2. 1: Frequency Reconfiguration

2.4.2 Polarization Reconfiguration

In this type of reconfiguration the antenna alters its polarization pattern. It may do this by switching from RHCP or LHCP or it can also do this from the horizontal to vertical in case of the linear polarization.

Figure 2.2 below shows the polarization characteristics and the direction of propagation. A typical polarization reconfigurable antenna displays LHCP in off state of switch and a RHCP in the on state of switch.

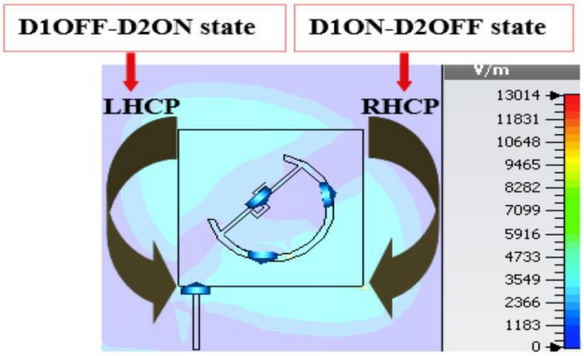


Figure 2. 2: Polarization Reconfiguration

2.4.3 Radiation Pattern Reconfiguration

In this type of reconfiguration the radiation pattern is changed which is controlled by controlling mechanism.

YanNan Jiang, Rui Yuan, Xi Gao, Jiao Wang have talked about pattern reconfiguration in an UWB antenna which was based on graphene coating. It is shown in reference [3].

This **Figure 2.3** explains how the radiation pattern changes its value when being controlled by some controlling mechanism.

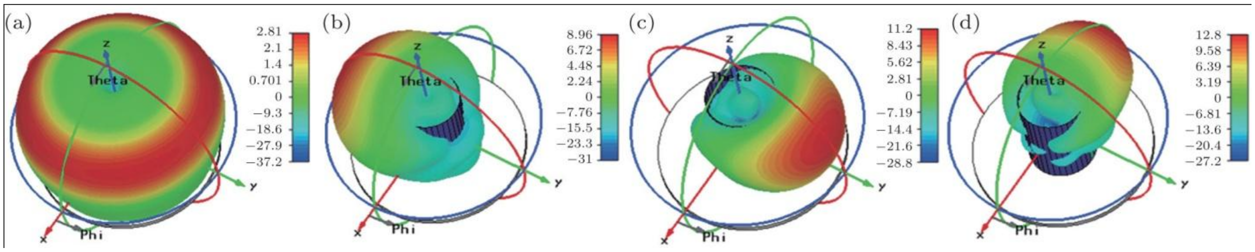


Figure 2. 3: Pattern Reconfiguration

2.4.4 Compound Reconfiguration

In this type of reconfiguration, other reconfiguration methods are mixed or combined to obtain the desired result.

Chapter 3: Frequency Reconfiguration Techniques

The simple and most important reason of a reconfigurable antenna is that it covers a number of frequencies within a range so that several independent antennas are not required to operate on those frequencies. If we don't make use of such antennas then we will have to use many antennas placed adjacent to each other, covering a lot of space, to operate on the same frequency bands. In this case all the antennas will have poor isolation making them unsuitable for any wireless device.

Just because of this issue frequency reconfiguration is the most important requirement in this new era of communication.

3.1 Frequency Reconfiguration Techniques

There are many techniques through which the frequency reconfigurability is achieved. To case a multi band antenna for specific frequency is one of the first steps in its evolution.

The structures which are used for achieving the multiple resonant frequencies are:

- Patch antennas
- wire antennas
- PIFA structure

They are described below:

3.1.1 Patch antennas

In these antennas the reconfigurability is achieved When the current path is divided by varying the geometry of the antenna, or slots. By using the switches, this variation can be achieved.

3.1.2 Wire antennas

In these type of antennas, the only geometrical parameter is the length and the reconfigurablity is a introduced with the variation of this length. A monopole is an example of this type of antenna.

At a quarter of a wavelength, its first resonant frequency is obtained. So by using switches in two states, the length of the antenna can be altered.

3.1.3 PIFA structures

A Famous technique to obtain multiple bands in a patch antenna is the PIFA structure.

An antenna by Dr. Hattan Abutarboush, operating on three frequencies 2.09,3.74, and 5 Ghz for DMB/GSM/DCS applications. It is a compact and ultra thin case. Two frequency bands have been individually managed in this antenna. It can be seen in reference [4].

Figure 3.1 shows the structure of PIFA used in this design and its dimensions are **mentioned in Table 3.1**.

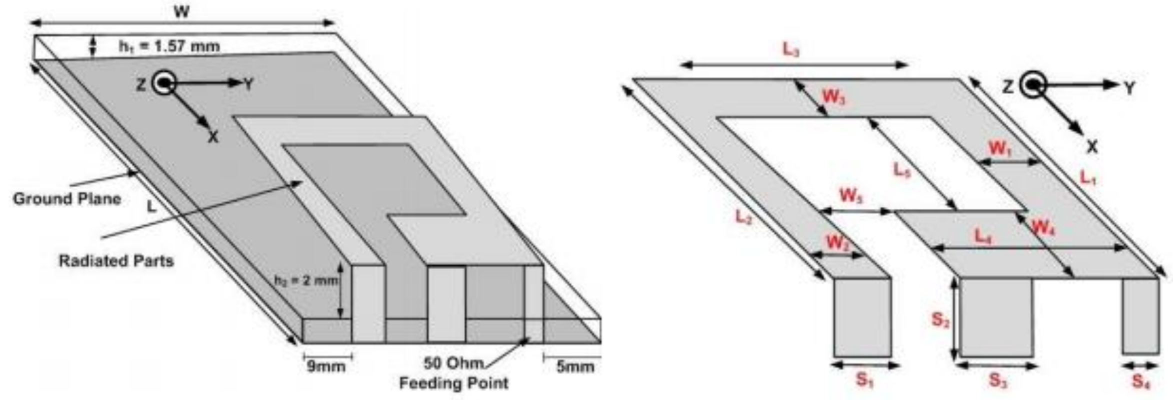


Figure 3. 1: PIFA Structure

Parameter	W	W_1	W_2	W_3	W_4	W_5
Dimension	40	6	2	2	11.6	4
Parameter	L	L_1	L_2	L_3	L_4	L_5
Dimension	40	25.6	25.6	20	20	12
Parameter	S_1	S_2	S_3	S_4	Ground Plane	
Dimension	2	3.57	4	3	40 x 40	

Table 3. 1: Detailed proportions of the planned antenna (mm)

In the PIFA structure, the reconfigurability is obtained by the use of its feed and the ground location. The impedance is matched by the variation of both the parameters.

Micro-strip patch antenna is our foremost choice for antenna structure due to its numerous advantages such as light, small size, narrow bandwidth, simplicity of fabrication and broadside radiation pattern.

3.2 Switches for Reconfigurability

The switches that can be used to achieve reconfigurability are;

- Reed Switches
- Varactor Diodes
- RF PIN Diodes
- FET Based Switches
- PIFA Structures

3.2.1 Reed Switches

A switch that can be controlled by a magnetic field which can also make a way into the ground. The most important and the biggest advantage for using this switch for reconfigurability is that its controlling circuit could be placed below the ground and yet its radiation performance is not affected.

Qiang Liu, Naizhi Wang, Changying Wu, Gao Wei, and A. B. Smolders developed an antenna that operates at frequency bands of 0.3 to 3 GHz and has used a number of reed switches and has achieved reconfigurability. It can be seen in reference [5].

Figure 3.2 shows 24 reed switch antenna design with a controlling circuit.

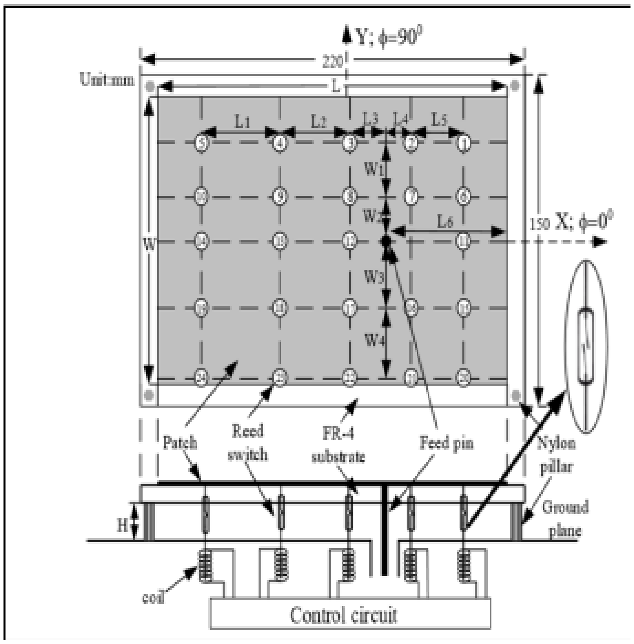
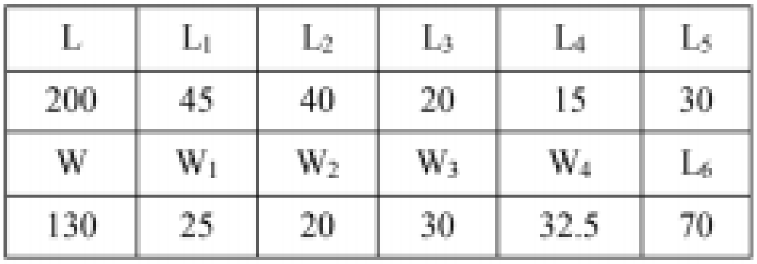


Figure 3. 2: An Antenna with Reed switches

Table 3.2 shows the detailed dimensions of the design.



L	L_1	L_2	L_3	L_4	L_5
200	45	40	20	15	30
W	W_1	W_2	W_3	W_4	L_6
130	25	20	30	32.5	70

Table 3. 2: Detailed proportions of antenna (mm)

Figure 3.3 shows the S11 parameters of stimulated and measured results of the antenna in reference [5].

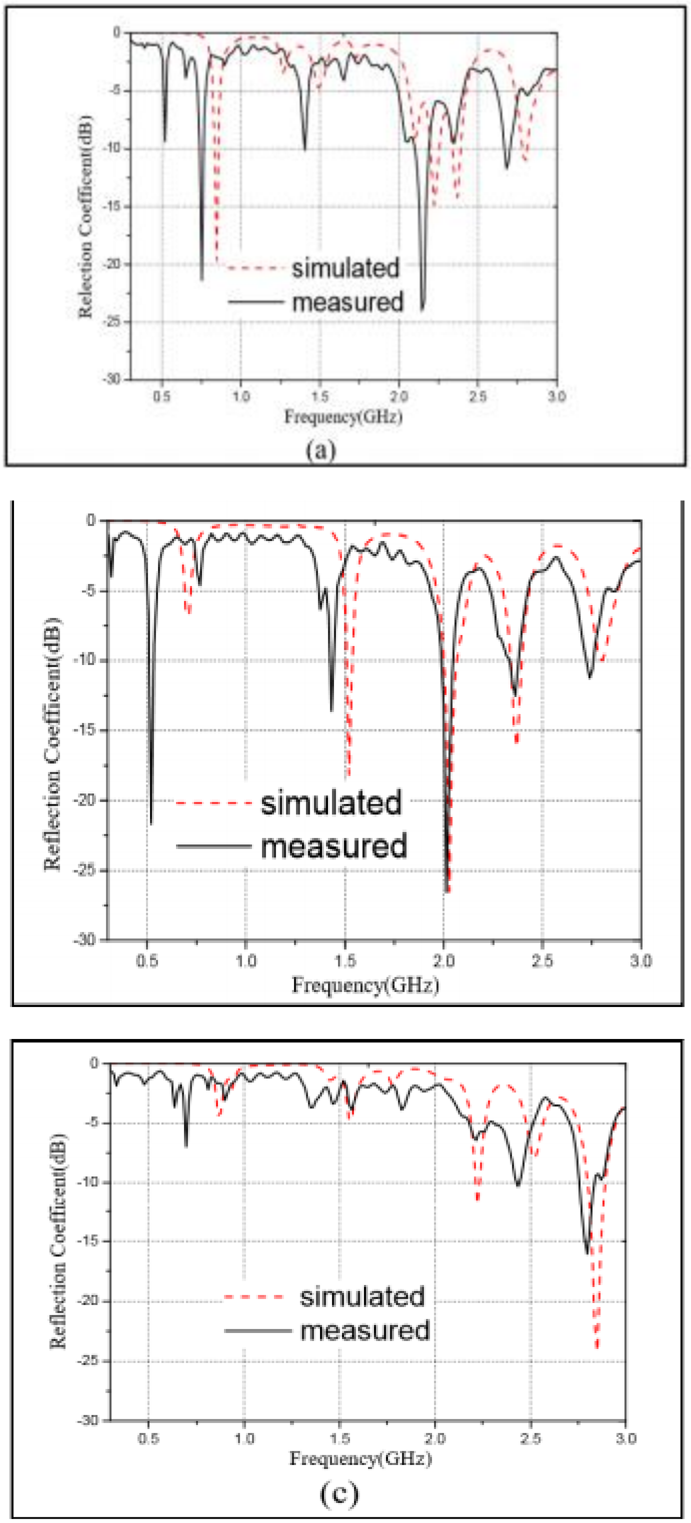


Figure 3. 3: Measured vs simulated S11 parameters

3.2.2 Varactor Diodes

Varactor diodes are special kinds of switches having a built-in capacitance. The value of capacitance can be changed and can be set between two extremes. It is also called a variable capacitance diode A wide range of values can be switched between maximum and minimum values due to this variable capacitance and because of this we get smooth switching.

Abu Tarboush and Hattan F developed an antenna in which varactor diodes have been used in order to obtain a reconfigurable antenna. In this paper the varactor diodes are used to link and disengage as well as provide different values of capacitance between the two lower strips. Due to this visible change can be seen in results and geometry which in return alters the resonant frequency bands shown in reference [6].

Geometry of this antenna is shown in **Figure 3.4**. It has two lower strips of length L_6. Dimensions are discussed in the reference [6].

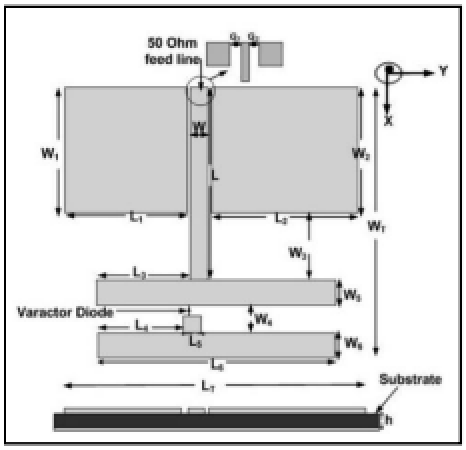


Figure 3. 4: Geometry of multiband reconfigurable antenna

Measured and stimulated results of S11 parameter of this paper is **shown in Figure 3.5**.

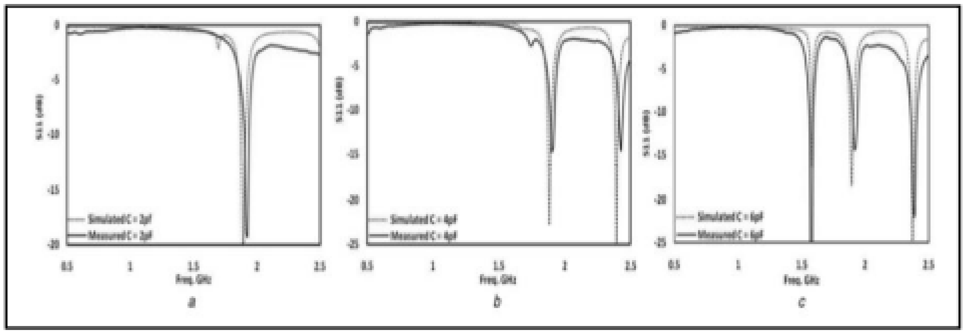


Figure 3. 5: S11 results for separate values of capacitance 9(a)c=2pF (b)c=4pF (c)c=6pF tri-band operation

3.2.3 RF PIN Diodes

These are switches that operate in two states i.e. on and off. The On state usually provides connection whereas off state provides disconnection. For this purpose it is positioned in slots.

Borhani, M., P. Rezaei, and A. Valizade constructed a reconfigurable antenna using 3 RF PIN Diodes for reconfigurability. These pin diodes provide connection and disconnection in the partial ground slot. The complete reconfiguration is controlled by varying the dimensions of this ground slot. Three variable frequency bands at different switch states combinations are achieved and shown in reference [7].

Top and bottom view of reference [7] is shown in **Figure 3.6**. The modes of reconfiguration and S11 parameters of stimulated and measured results of this paper are **shown in Figure 3.7-3.9.**

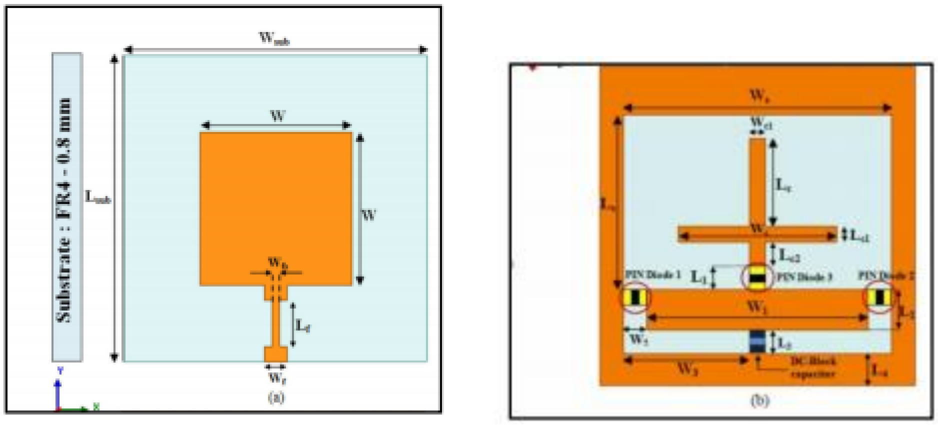


Figure 3. 6: A Multiband reconfigurable antenna (a) top (b) bottom

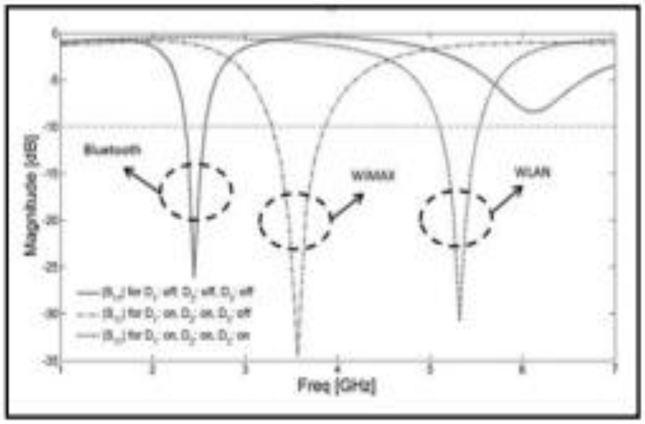


Figure 3. 7: S11 parameter

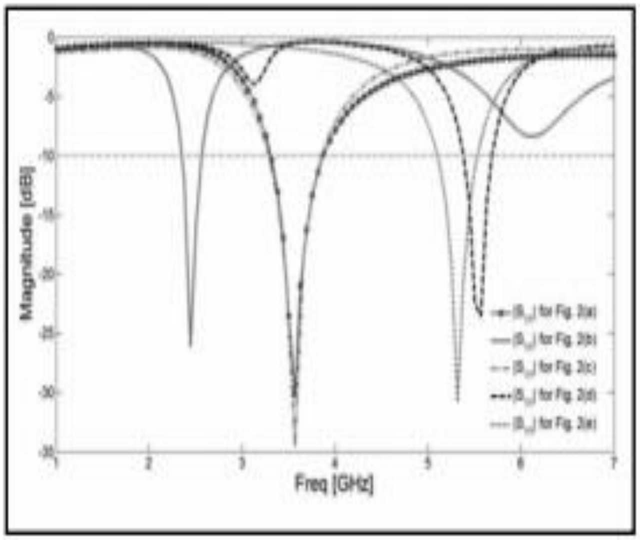


Figure 3. 8: Modes of reconfigurable multiband antenna

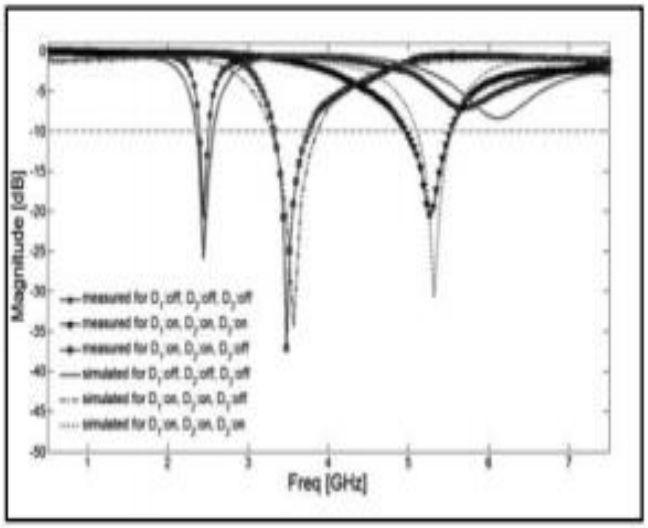


Figure 3. 9: Reflection coefficient simulated and measured

3.2.4 FET Based Switches

A switch that can be operated by digital signals and thus requires no external bias network. This is its main advantage along with the fact that it is easy to formulate and operate. It has little insertion losses, better switching speed and is suitable for miniature sized antennas.

Figure 3.10 shows a reconfigurable GaAs FET Switch Antenna made by Yang, Xiao-lin & Lin, Jian-cheng & Chen, Gang & Kong, Fang-ling that is operating on two different modes. One is narrowband mode, for WLAN (2.4-2.48GHz) and WiMax (2.5-2.69GHz) applications whereas the second is the wide band mode for PCS (1.85-1.99GHz) and WiMAX (3.4-3.69GHz) frequencies. It is shown in reference [8].

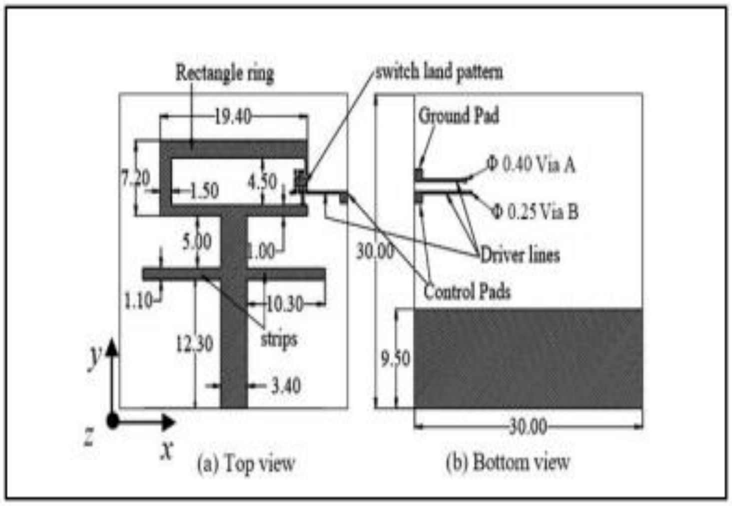


Figure 3. 10: An FET- based Antenna

The stimulated and measured S11 parameters of reference [8] with and without strips are shown in **Figure 3.11**.

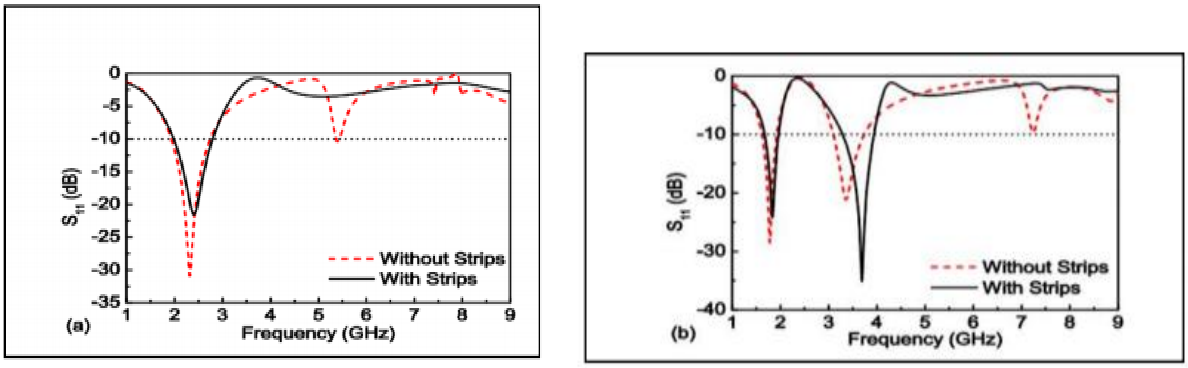


Figure 3. 11: Simulated vs. Measured S11 with and without strips

3.2.5 PIFA Structures

A popular method to achieve multiband characteristics is the Planar Inverted F structures. Switches can be used to achieve reconfigurability in PIFA structures. There use is popular in mobile devices.

Jong-Hyuk Lim, Gyu-Tae Back, Young-Il Ko, Chang-Wook Song, and Tae-Yeoul Yun developed an antenna that is using PIN Diode and Varactor diodes. This antenna utilizes PIN diode for connecting with a separate radiator whereas it uses Varactor diode to provide connection between the two layers of the antenna. It is Planar Inverted F Case. This antenna operates on three frequencies i.e. 1.95GHz, 3.5GHz and 5.5GHz and has reconfigurable characteristics. It is shown in reference [9].

Figure 3.12 shows the PIFA design used in reference [9].

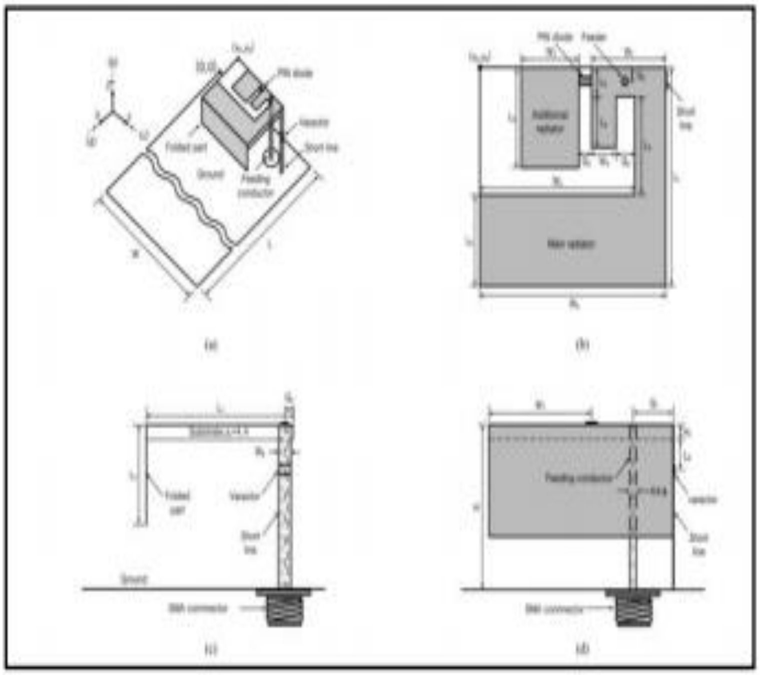


Figure 3. 12: PIFA Design

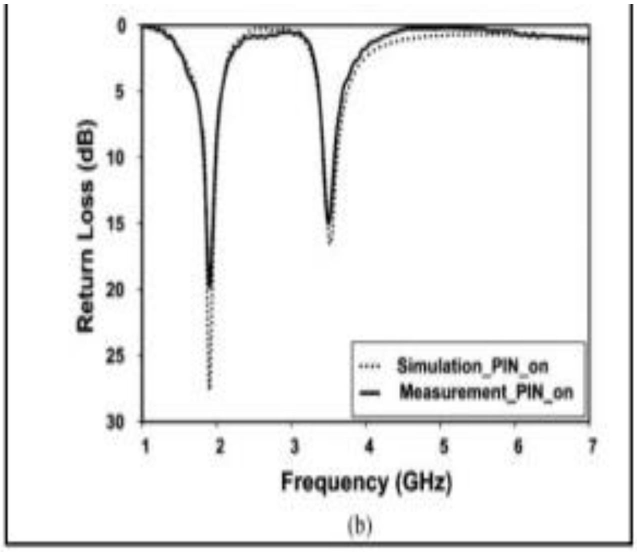


Figure 3.13 shows the S11 results of the antenna designed in reference [9].

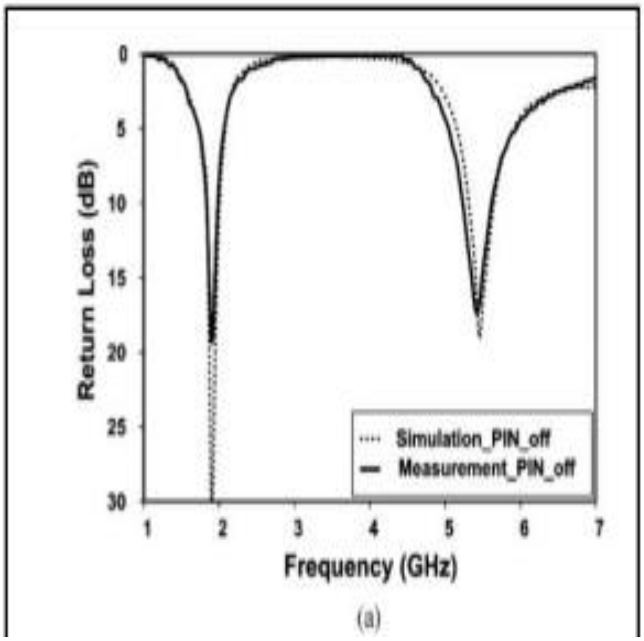


Figure 3. 13: S11 results

Chapter 4: RF MEMS

4.1 Background

Wherever high frequency operation in communication is required RF devices are used. One of the most common and popular RF device known as RF switch is used for this purpose which provides high speed switching for its use in RF communication. One such switch is the RF MEMS. It is both an electrical as well as mechanical device which is exposed to contamination and suffers from limited life time.

4.2 Introduction

It is our latest technology. It has its precedence like small size, little cost, high isolation, and little power dissipation and low insertion loss as compared to other switches. Due to these factors we can use this switch in components like power dividers, inductors, capacitors etc.

For better understanding of RF MEMS a reference paper is shown in which a two layer reconfigurable antenna by A. Zohur, H. Mopidevi, D. Rodrigo, M. Unlu, L. Jofre, and Bedri A. Cetiner using RF switch as a current divider device, operating in two different modes is shown. In each mode different antenna geometry is used and due to this two different current paths are followed, one for each mode (on and off). It is shown in reference [10].

PIFA structure with RF MEMS (on state) used in reference [10] is shown in **Figure 4.1**.

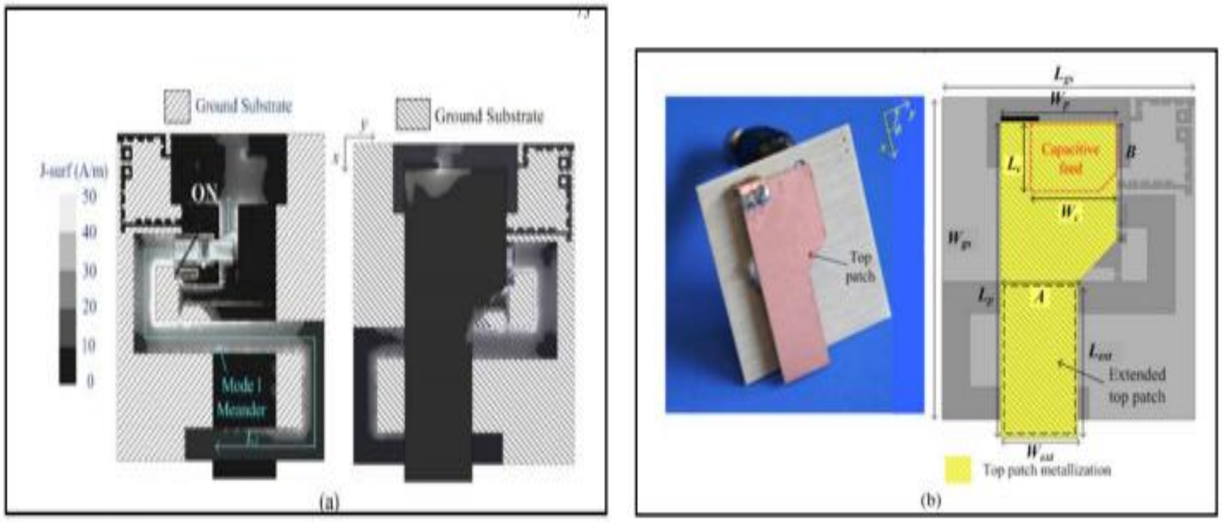


Figure 4. 1: PIFA with RF MEMS (on state)

In **Figure 4.2** PIFA structure with RF MEMS (off state) used in reference [10] is shown.

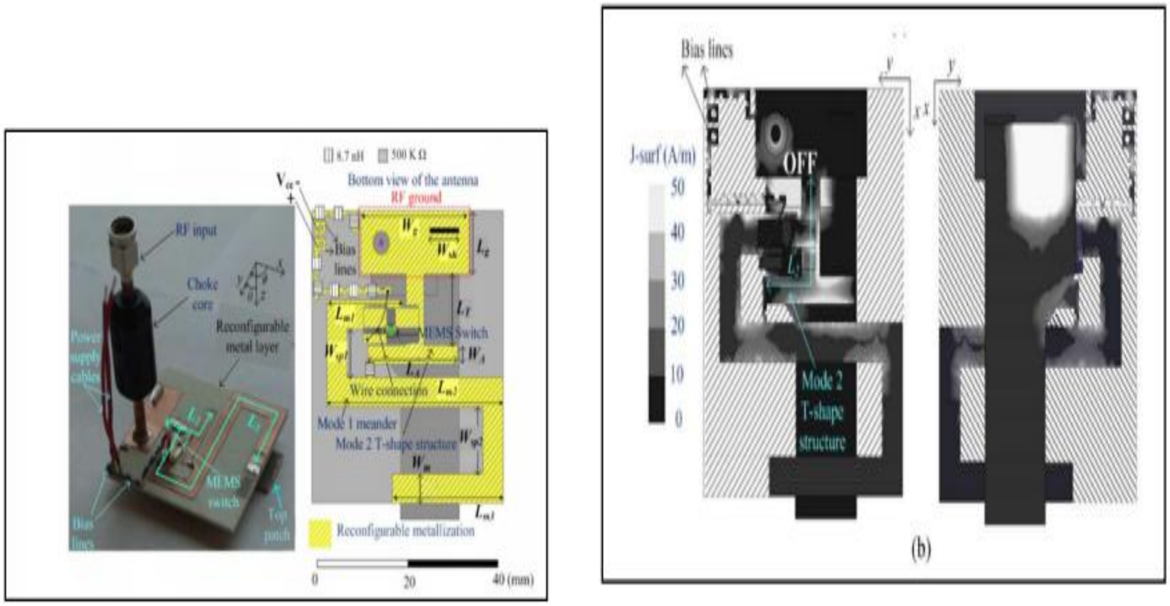


Figure 4. 2: PIFA with RF MEMS (off state)

This reconfigurable antenna is operating on 718 MHz and 4970 MHz

The model of RF MEMS that we would be using will be ADGM1004. It is a new technology and it can ideal y be used in extensive variety of RF and precision apparatus because of its very less insertion loss and broad RF bandwidth. It can function from 0 Hz/dc to 13 GHz.

4.3 Applications

It has the following applications;

- It can be used as replacement of relays
- It can be used in reconfigurable attenuators and filters
- It can be used in components that require high performance RF switching.

4.4 Features

It has the following features;

- It can wholly operate till 0 Hz/dc. Its resistance in on state is 2.9 **Ω** (max) and its leakage current in off state is 0.5 nA (max).
- It has 0.45 dB insertion loss and 24 dB isolation at 2.5 GHz.
- It has airtight switch contacts. Its lifetime is of 1 billion cycles (min) and the switching time in on state is 75 µs.
- 3-3.6 V is the supply voltage and has switches that can be managed individually

4.5 ADGM1004 Pin Configuration and Description of Functions

The Pin configuration of the switch is shown in **Figure 4.3**.

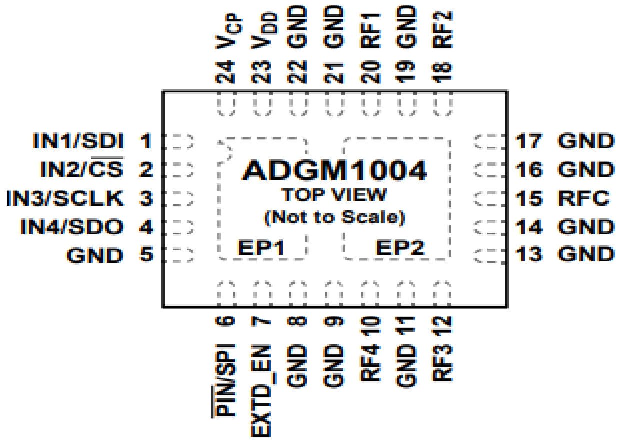


Figure 4. 3: ADGM1004 Pin Configuration

Figure 4.4 shows the complete circuit of ADGM1004 (RF MEMS).

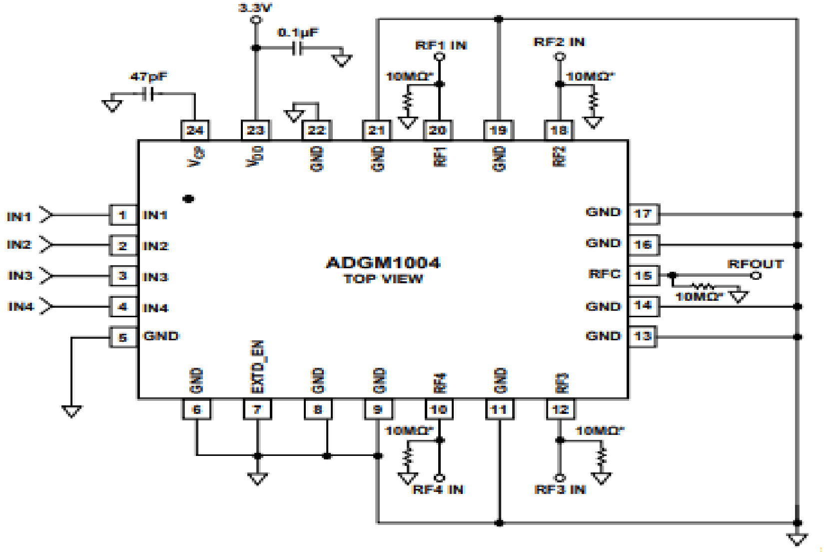
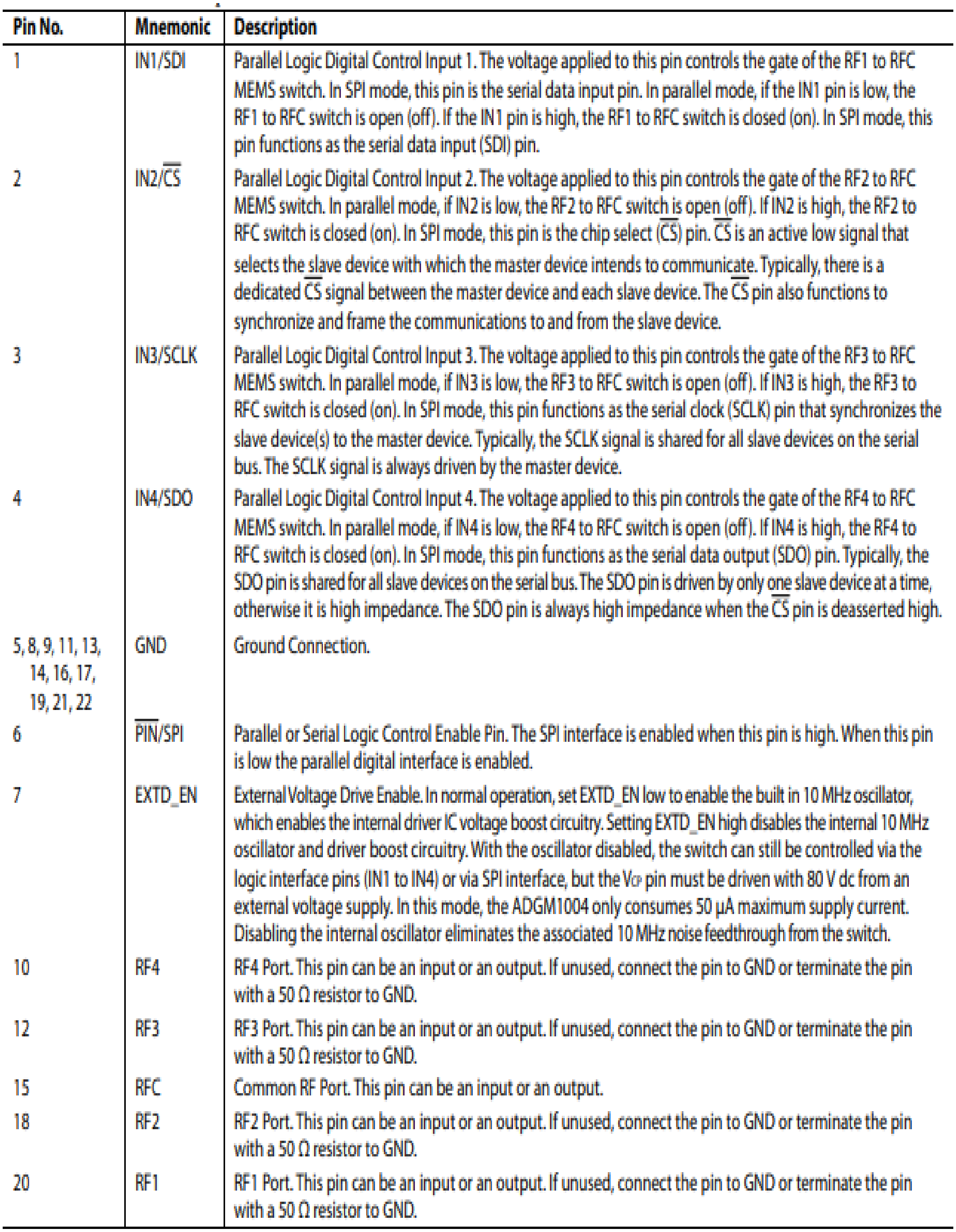
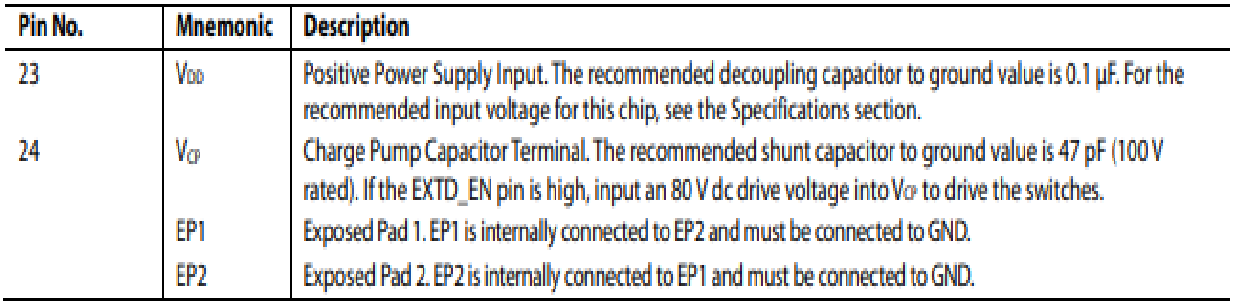


Figure 4. 4: ADGM1004 Circuit

Table 4.1 shows detailed description of Pin functions of RF MEMS.



Pin No.	Mnemonic	Description
1	IN1/SDI	Parallel Logic Digital Control Input 1. The voltage applied to this pin controls the gate of the RF1 to RFC MEMS switch. In SPI mode, this pin is the serial data input pin. In parallel mode, if the IN1 pin is low, the RF1 to RFC switch is open (off). If the IN1 pin is high, the RF1 to RFC switch is closed (on). In SPI mode, this pin functions as the serial data input (SDI) pin.
2	IN2/$\overline{\text{CS}}$	Parallel Logic Digital Control Input 2. The voltage applied to this pin controls the gate of the RF2 to RFC MEMS switch. In parallel mode, if IN2 is low, the RF2 to RFC switch is open (off). If IN2 is high, the RF2 to RFC switch is closed (on). In SPI mode, this pin is the chip select ($\overline{\text{CS}}$) pin. $\overline{\text{CS}}$ is an active low signal that selects the slave device with which the master device intends to communicate. Typically, there is a dedicated $\overline{\text{CS}}$ signal between the master device and each slave device. The $\overline{\text{CS}}$ pin also functions to synchronize and frame the communications to and from the slave device.
3	IN3/SCLK	Parallel Logic Digital Control Input 3. The voltage applied to this pin controls the gate of the RF3 to RFC MEMS switch. In parallel mode, if IN3 is low, the RF3 to RFC switch is open (off). If IN3 is high, the RF3 to RFC switch is closed (on). In SPI mode, this pin functions as the serial clock (SCLK) pin that synchronizes the slave device(s) to the master device. Typically, the SCLK signal is shared for all slave devices on the serial bus. The SCLK signal is always driven by the master device.
4	IN4/SDO	Parallel Logic Digital Control Input 4. The voltage applied to this pin controls the gate of the RF4 to RFC MEMS switch. In parallel mode, if IN4 is low, the RF4 to RFC switch is open (off). If IN4 is high, the RF4 to RFC switch is closed (on). In SPI mode, this pin functions as the serial data output (SDO) pin. Typically, the SDO pin is shared for all slave devices on the serial bus. The SDO pin is driven by only one slave device at a time, otherwise it is high impedance. The SDO pin is always high impedance when the $\overline{\text{CS}}$ pin is deasserted high.
5, 8, 9, 11, 13, 14, 16, 17, 19, 21, 22	GND	Ground Connection.
6	$\overline{\text{PIN}}$/SPI	Parallel or Serial Logic Control Enable Pin. The SPI interface is enabled when this pin is high. When this pin is low the parallel digital interface is enabled.
7	EXTD_EN	External Voltage Drive Enable. In normal operation, set EXTD_EN low to enable the built in 10 MHz oscillator, which enables the internal driver IC voltage boost circuitry. Setting EXTD_EN high disables the internal 10 MHz oscillator and driver boost circuitry. With the oscillator disabled, the switch can still be controlled via the logic interface pins (IN1 to IN4) or via SPI interface, but the V_{CP} pin must be driven with 80 V dc from an external voltage supply. In this mode, the ADGM1004 only consumes 50 µA maximum supply current. Disabling the internal oscillator eliminates the associated 10 MHz noise feedthrough from the switch.
10	RF4	RF4 Port. This pin can be an input or an output. If unused, connect the pin to GND or terminate the pin with a 50 Ω resistor to GND.
12	RF3	RF3 Port. This pin can be an input or an output. If unused, connect the pin to GND or terminate the pin with a 50 Ω resistor to GND.
15	RFC	Common RF Port. This pin can be an input or an output.
18	RF2	RF2 Port. This pin can be an input or an output. If unused, connect the pin to GND or terminate the pin with a 50 Ω resistor to GND.
20	RF1	RF1 Port. This pin can be an input or an output. If unused, connect the pin to GND or terminate the pin with a 50 Ω resistor to GND.



Pin No.	Mnemonic	Description
23	V_{DD}	Positive Power Supply Input. The recommended decoupling capacitor to ground value is 0.1 µF. For the recommended input voltage for this chip, see the Specifications section.
24	V_{CP}	Charge Pump Capacitor Terminal. The recommended shunt capacitor to ground value is 47 pF (100 V rated). If the EXTD_EN pin is high, input an 80 V dc drive voltage into V_{CP} to drive the switches.
	EP1	Exposed Pad 1. EP1 is internally connected to EP2 and must be connected to GND.
	EP2	Exposed Pad 2. EP2 is internally connected to EP1 and must be connected to GND.

Table 4. 1: Description of Pin Functions

As shown in Fig 4.4, we will apply 3.3 V to Pin 23 (V_{DD}) of the switch. We will be using two of the total four input states i.e. Pin 1 and 2. Moreover Pin 15 (RF out) will be used to see output.

4.6 Results

The analysis of the design implemented is discussed below:

4.6.1 Case 1: An inverted L and F design with RF MEMS.

In this design the value of capacitance given at Pin 1 is 9 pF and at Pin 2 is 13 pF. Rest of the two input states are not included and will be used as open circuit.

The design of the proposed antenna with RF MEMS is shown in **Figure 4.5**. The position of RF MEMS is:

Position: X= -70, Y=2.5, Z=0

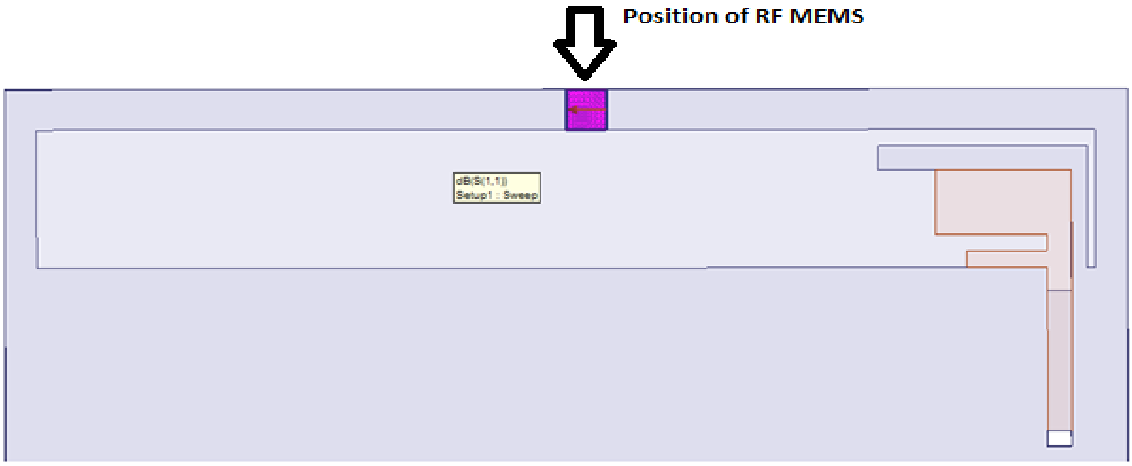
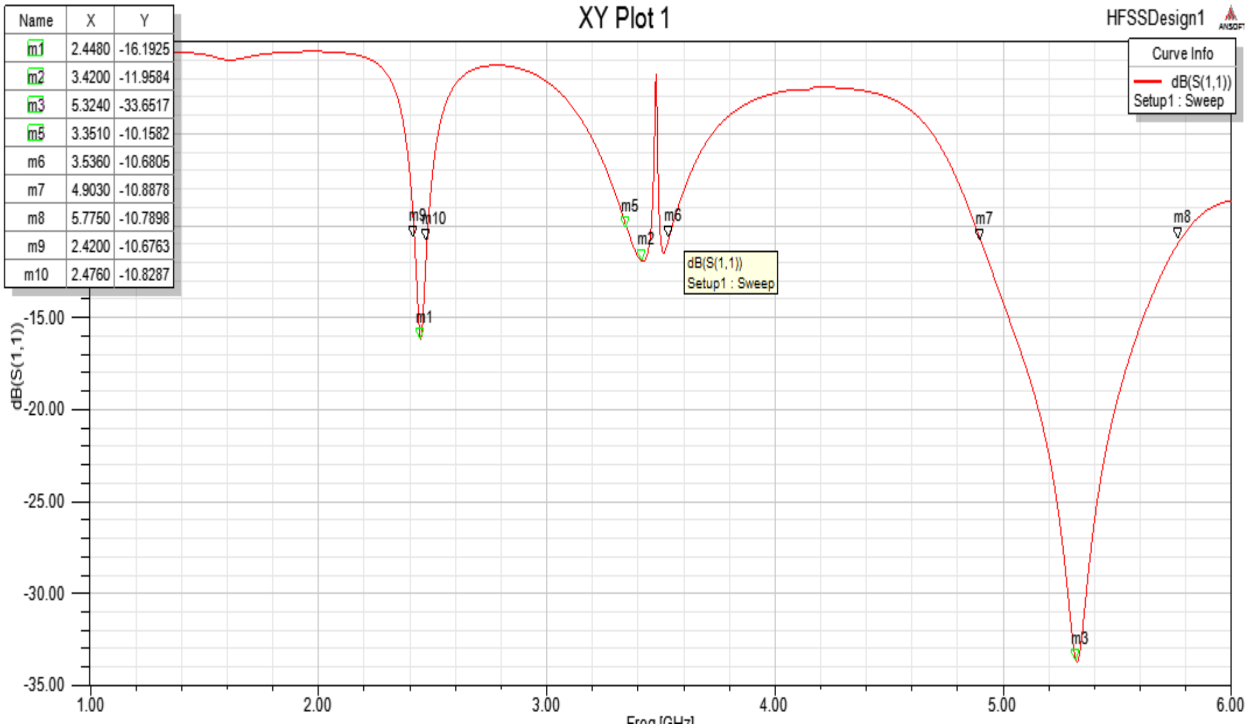


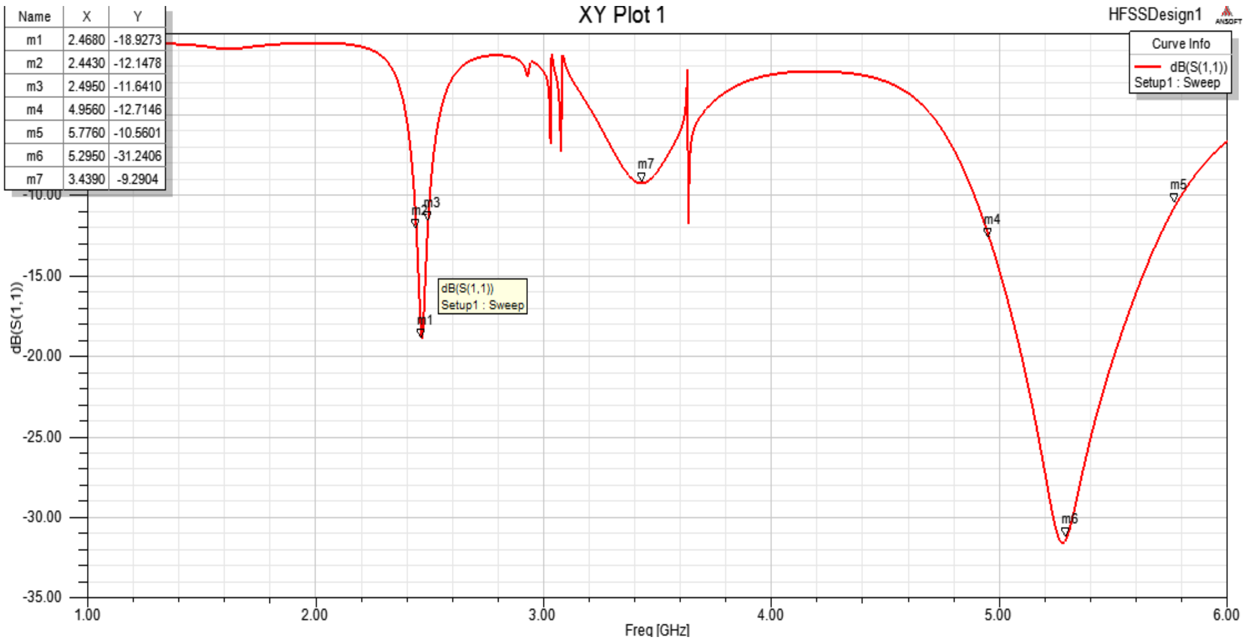
Figure 4. 5: Design with location of RF MEMS

Figure 4.6 and Figure 4.7 show the S11 results of this design in on and off state of RF MEMS.



Name	X	Y
m1	2.4480	-16.1925
m2	3.4200	-11.9584
m3	5.3240	-33.6517
m5	3.3510	-10.1582
m6	3.5360	-10.6805
m7	4.9030	-10.8878
m8	5.7750	-10.7898
m9	2.4200	-10.6763
m10	2.4760	-10.8287

Figure 4. 6: Result when Pin 1 is used at 9 pF (on state)



Name	X	Y
m1	2.4680	-18.9273
m2	2.4430	-12.1478
m3	2.4950	-11.6410
m4	4.9560	-12.7146
m5	5.7760	-10.5601
m6	5.2950	-31.2406
m7	3.4390	-9.2904

Figure 4. 7: Result when Pin 2 is used at 13 pF (off state)

You can clearly see as we switch from Pin 1 to Pin 2 the 3.5 GHz is turned on and off and hence achieving reconfigurability. Further results will be discussed in great detail in chapter 6.

4.6.2 Case 2: MIMO Design

In this design the value of capacitance given at Pin 1 is 30 pF and at Pin 2 is 9 pF. Rest of the two input states are not included and will be used as open circuit.

The complete MIMO design with dimensions is shown in **Figure 4.8**.

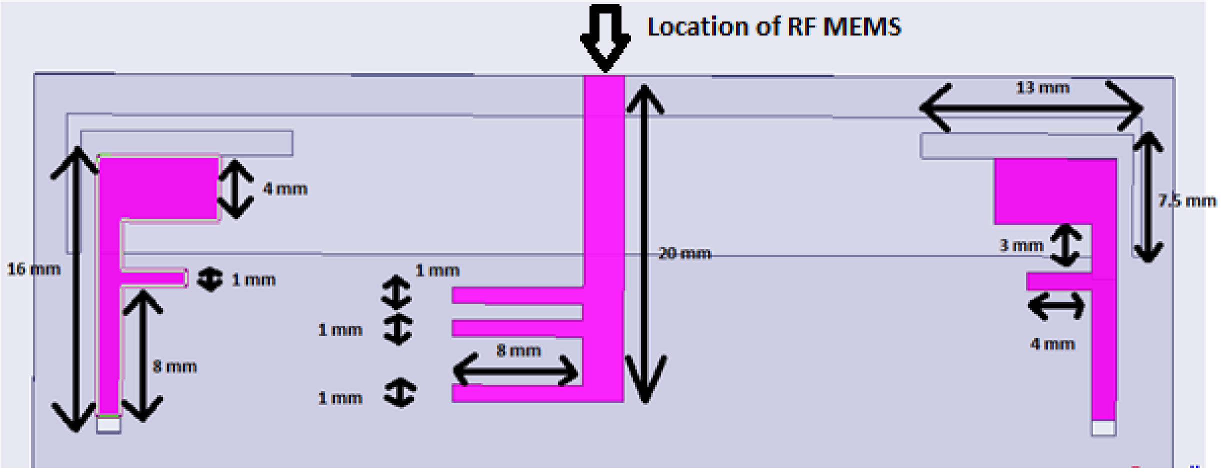
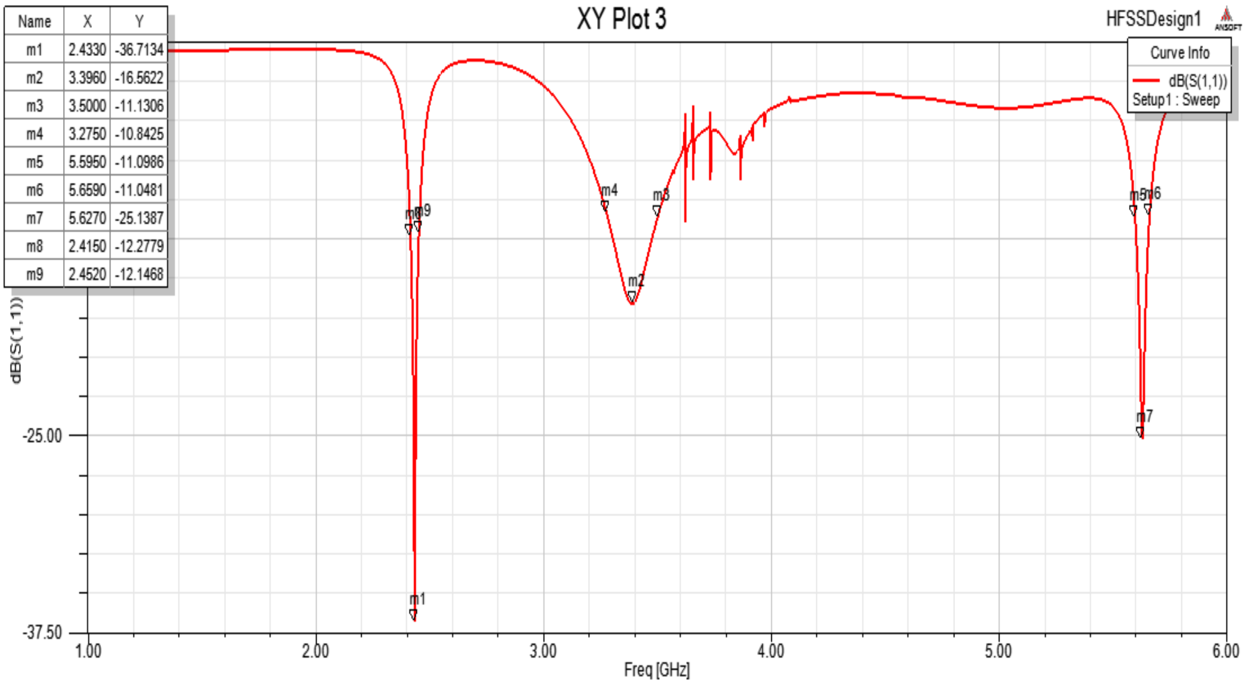


Figure 4. 8: MIMO Design with location of RF MEMS

Figure 4.9 and Figure 4.10 show the S11 results of this MIMO design in on and off state of RF MEMS.



Name	X	Y
m1	2.4330	-36.7134
m2	3.3960	-16.5622
m3	3.5000	-11.1306
m4	3.2750	-10.8425
m5	5.5950	-11.0986
m6	5.6590	-11.0481
m7	5.6270	-25.1387
m8	2.4150	-12.2779
m9	2.4520	-12.1468

Figure 4. 9: Result when Pin 1 is used at 30 pF (on state)

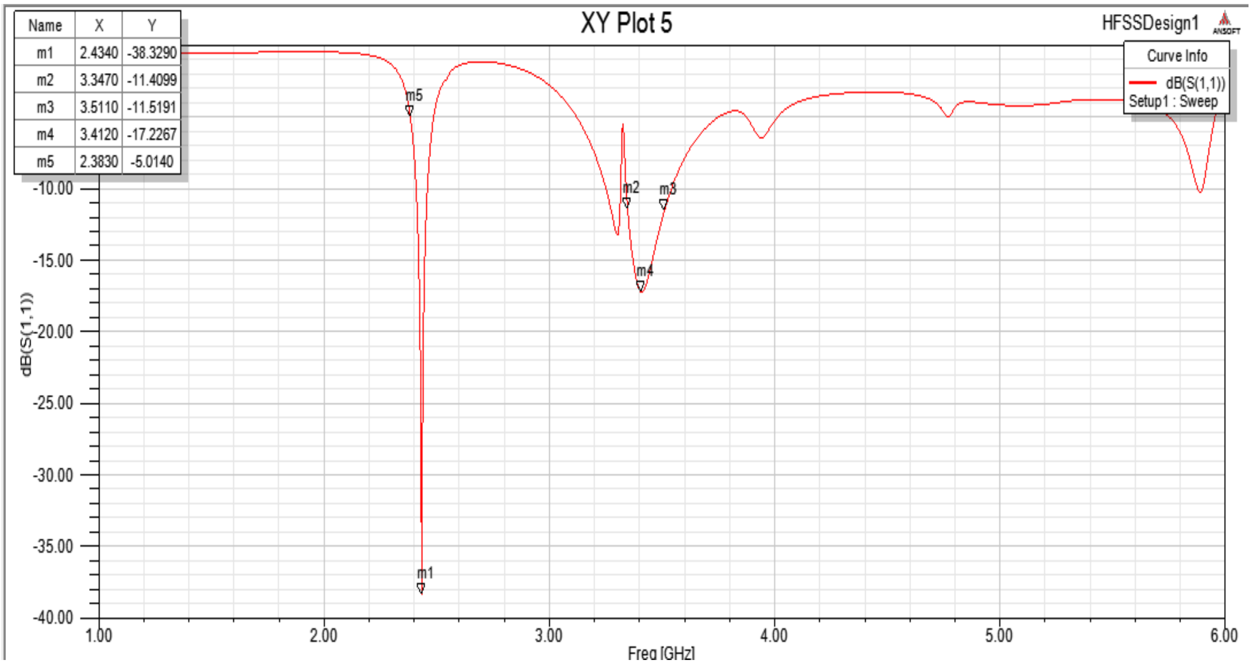


Figure 4. 10: Result when Pin 2 is used at 9 pF (off state)

You can clearly see that the 5.5 GHz band is switched on and off when RF MEMS switches from Pin 1 to Pin 2 thus achieving reconfigurability. Further results will be discussed in great detail in chapter 6.

Chapter 5: Antenna Geometry

Whenever you think of designing an antenna for any frequency, the first and foremost important thing that comes to you mind is the design and the material. As you move along design is altered according to the need of the antenna and the results are stimulated again and again till the desired result is achieved. So you can easily say that the first thing to when you think of designing an antenna is the selection of substrate. The substrate we took was FR4.

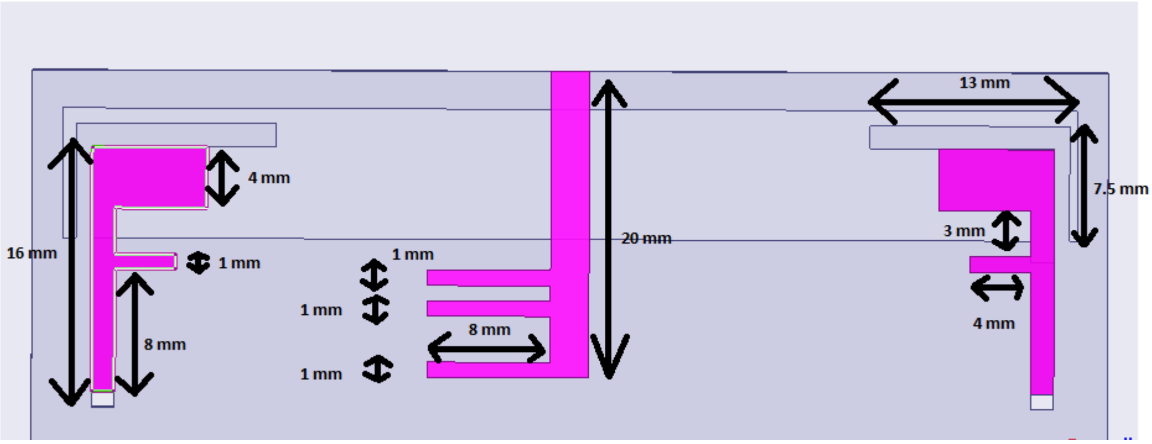
The thickness of FR4 substrate is 1mm and the rate of its dielectric constant is 4.4. The depth of micro strip feed line is 1mm and the value is 50 Ω.

Then antenna size is 70x140 mm^2. This is the appropriate size for achieving multiple bands and can meet the wireless applications and miniaturization needs.

Partial ground is introduced in the design to improve impedance matching, efficiency and to enhance bandwidth. The main part of the ground is 70x129 mm^2 with some additional parts which were added later on.

The proposed MIMO design with complete dimensions is shown in **Figure 5.1**

(a)



(b)

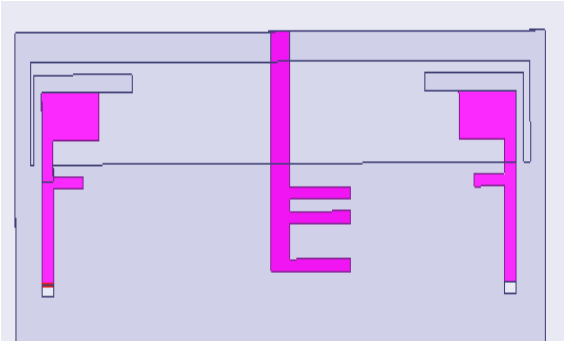


Figure 5. 1: Proposed Antenna (a) front view (b) rear view.

5.1 Progression of Antenna Geometry

The anticipated antenna was achieved by changing the design a great number of times till this design with satisfactory results was achieved. The different stages which were passed after which this design was achieved are given below.

5.1.1 Stage 1: An inverted F and L design with RLC Component.

With this initial design of an inverted F and a RLC component which we used as the replacement of RF MEMS in HFSS, we got three frequencies at which the antenna was resonating i.e. 2.45 and 3.5, 5.5 GHz..

Figure 5.2 shows the initial design with RLC component located at:

RLC Position: X= -60.5, Y=32.5, Z=0

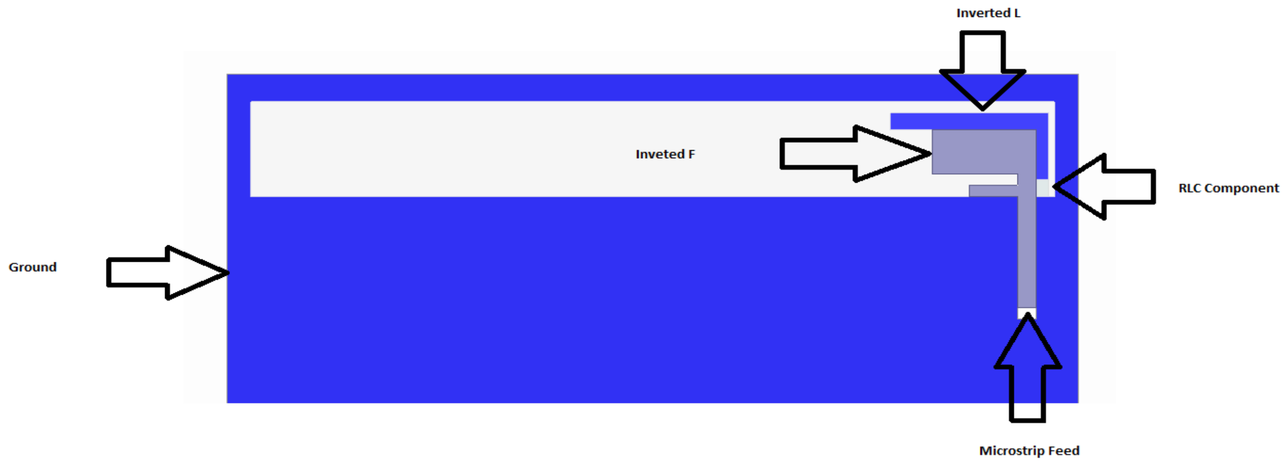


Figure 5. 2: Proposed Antenna Design at Stage 1

Figure 5.3 shows the S11 parameter results of this design.

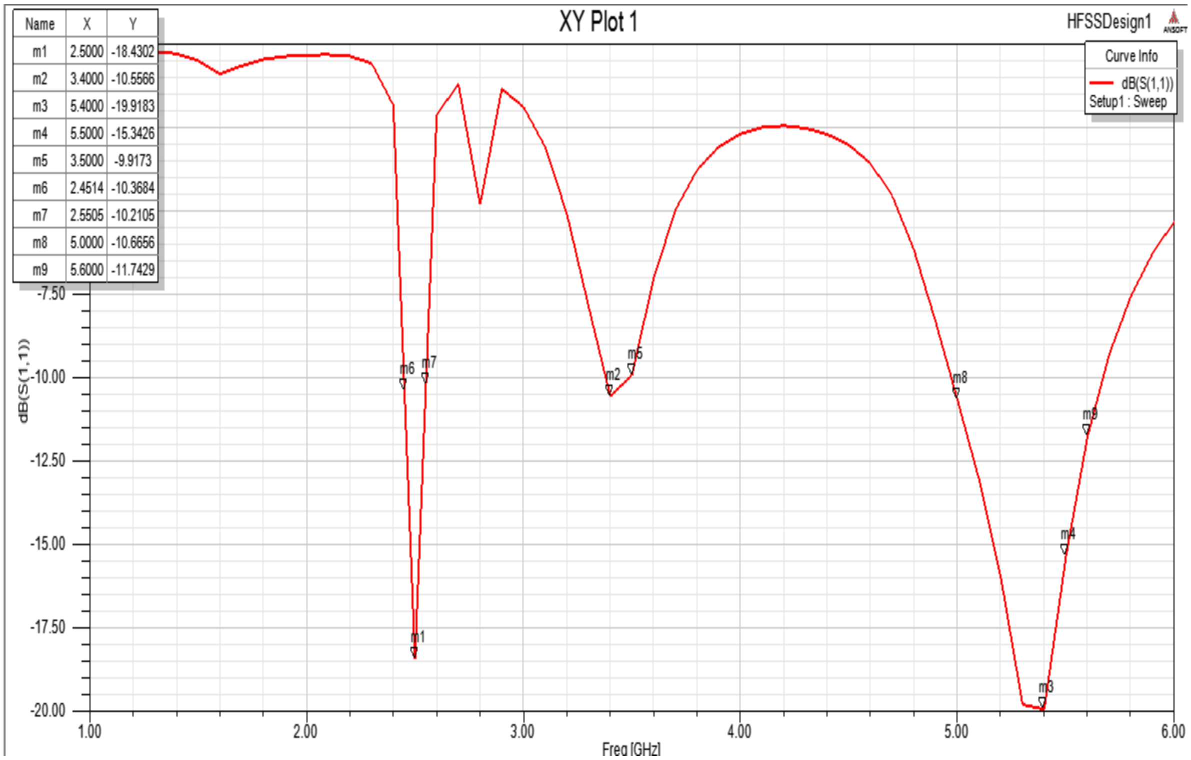


Figure 5. 3: S11 Results

From this result you can see that we achieved the narrow band from 2.45 to 2.55 GHz with the best S11 value of -18.43 dB at 2.5 GHz but the result of 3.5 GHz frequency band was not satisfactory. We also achieved a wide band from 5 to 5.6 GHz with the best S11 value -19.9 dB at 5.4 GHz. The value of RLC component was 11pF.

5.1.2 Stage 2: An inverted F design with changed location of RLC Component.

After a great number of stimulations run on the initial design (by changing slot sizes and RLC value), a new design with a changed position of RLC component was achieved. At this point by varying value of RLC and slots of inverted F and L we achieved satisfactory results of all three 5G bands.

Proposed design with centre RLC is **shown in Figure 5.4**. The position of RLC in this design is:

RLC Position: X= -70, Y=2.5, Z=0

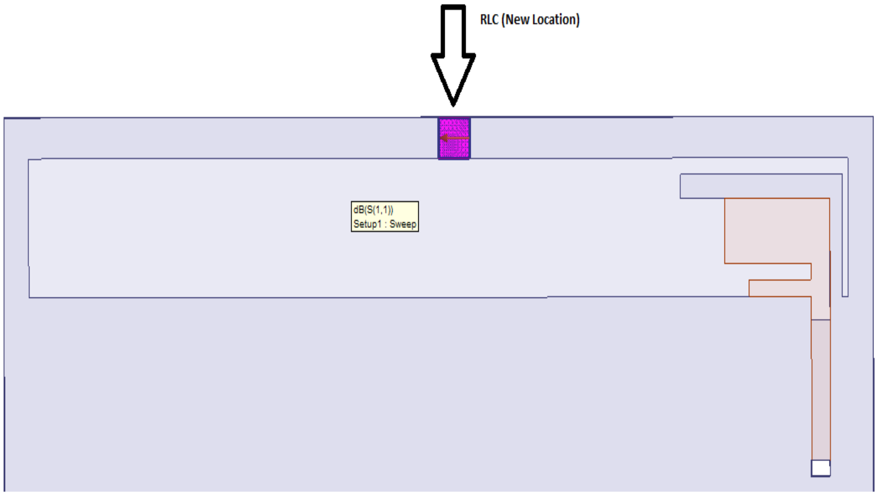
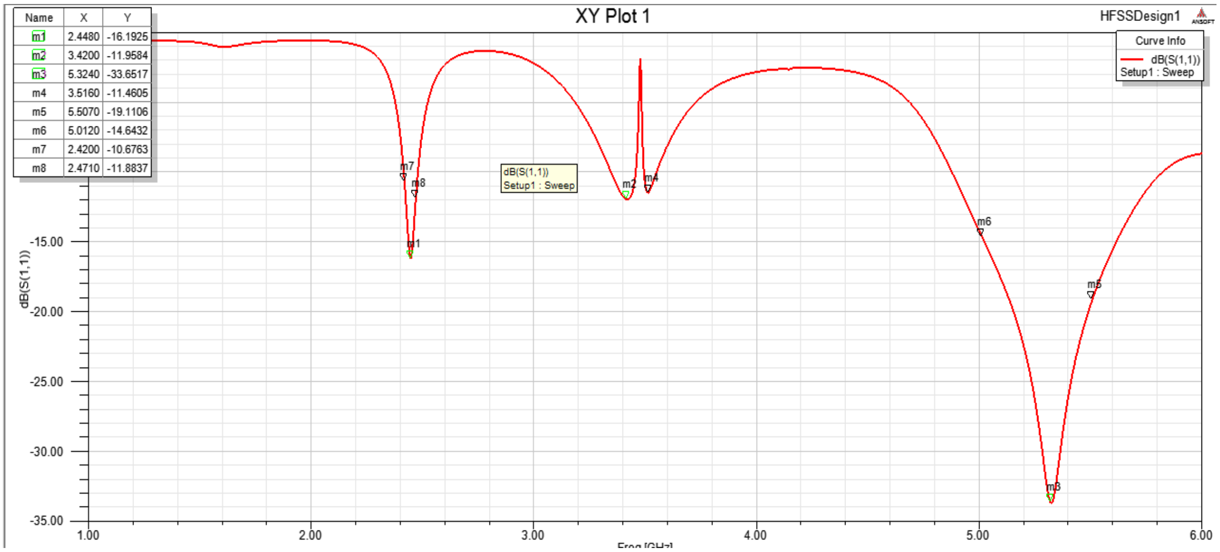


Figure 5. 4: Proposed Antenna Design at Stage 2

Figure 5.5 shows S11 parameter results of the proposed antenna design in stage 2



Name	X	Y
m1	2.4480	-16.1925
m2	3.4200	-11.9584
m3	5.3240	-33.6517
m4	3.5160	-11.4605
m5	5.5070	-19.1106
m6	5.0120	-14.6432
m7	2.4200	-10.6763
m8	2.4710	-11.8837

Figure 5. 5: S11 Results

We achieved a narrow band i.e. 2.42 to 2.47 GHz with best value of S11 variable -16.1 dB at 2.44 GHz. We got a band from 3.42 to 3.51 GHz with the best value of S11 variable -11.95 dB at 3.42 GHz and finally we got a wide band from 5 to 5.76 GHz with best value of S11 variable-33.65 dB at 5.32 GHz. **The value of RLC component is 9 pF.**

5.1.3 Stage 3: Implementing MIMO Design.

After achieving the results in the design, an attempt was made to implement the concept of MIMO in the design. This was not originally in our scope but a fine attempt was made and satisfactory results were obtained still leaving some room for improvement. In this design a mirror image of the inverted **F** and **L** was taken and results were achieved.

Complete proposed MIMO Design with dimensions is shown in **Figure 5.6** with RLC position:

RLC Position: X= -70, Y=2.5, Z=0

Figure 5.7 shows the S11 parameter results of this MIMO design.

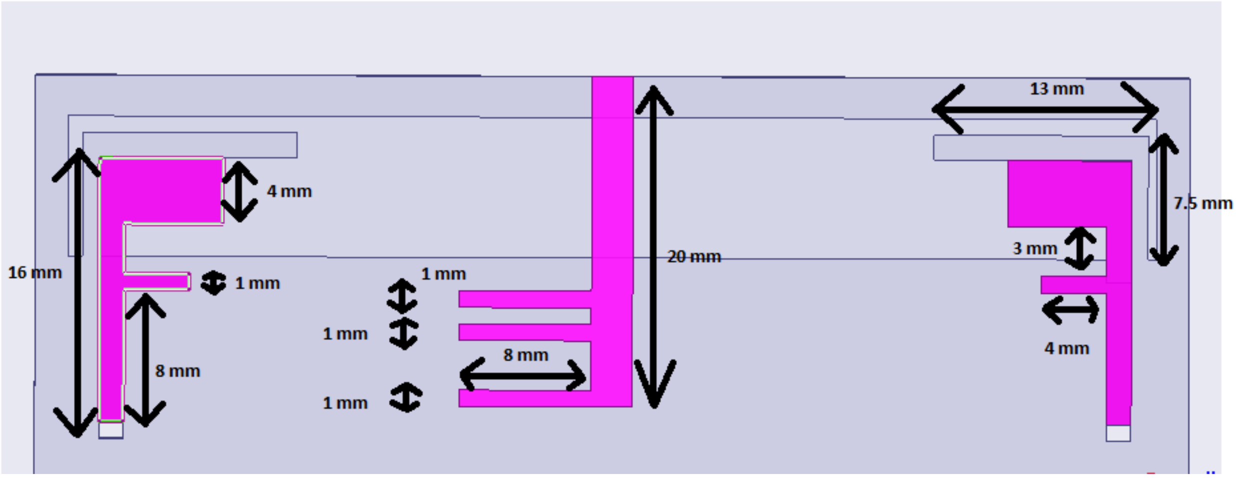
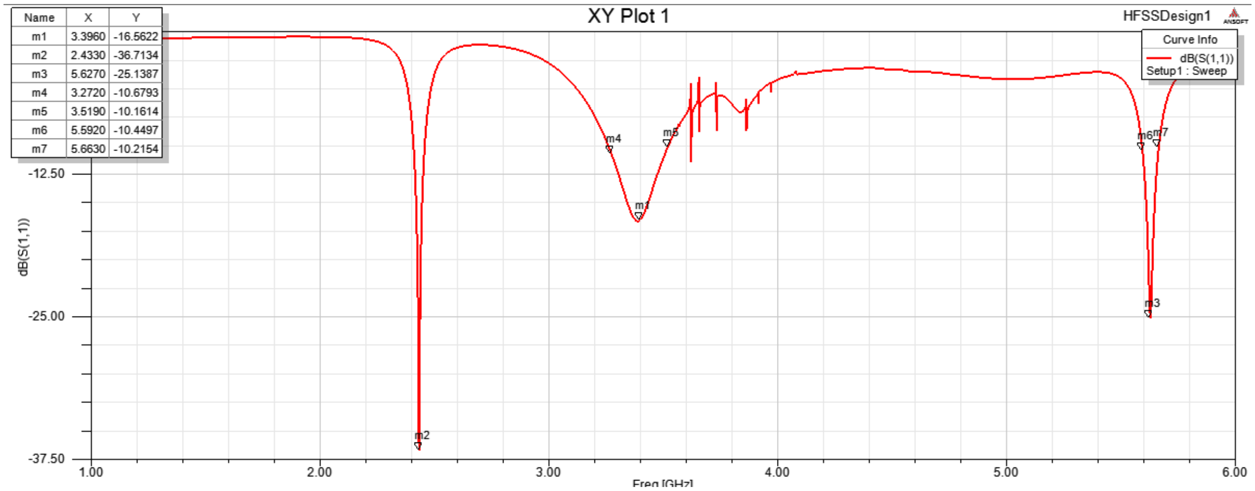


Figure 5. 6: Geometrical Dimensions of Proposed Antenna



Name	X	Y
m1	3.3960	-16.5622
m2	2.4330	-36.7134
m3	5.6270	-25.1387
m4	3.2720	-10.6793
m5	3.5190	-10.1614
m6	5.5920	-10.4497
m7	5.6630	-10.2154

Figure 5. 7: S11 Result

We have achieved satisfactory results in this MIMO design by obtaining a tri band result. At 2.43 GHz S11 value is -36.71 dB, at 3.4 GHz S11 value is -16.5 dB and at 5.62 GHz S11 value is -25.1 dB. The value of RLC in this stage is 30 pF.

5.2 Frequency Reconfigurability

Frequency reconfigurability was achieved after it was observed from various stimulations that the factors that help us achieve frequency reconfiguration are;

a) Changing Value of RLC component
b) Changing the slot size of inverted L
c) Changing the slot size of inverted F

As these factors play an important role, we will see the different results obtained by varying their values in the next chapter.

.

Chapter 6: Results and Discussion

As we have discussed in the previous chapter that we achieved the result we wanted to in stage 2. Now since reconfigurability was achieved in this design and the factors that it depended upon are already listed. We will talk about results of stage 2 and stage 3 in this chapter.

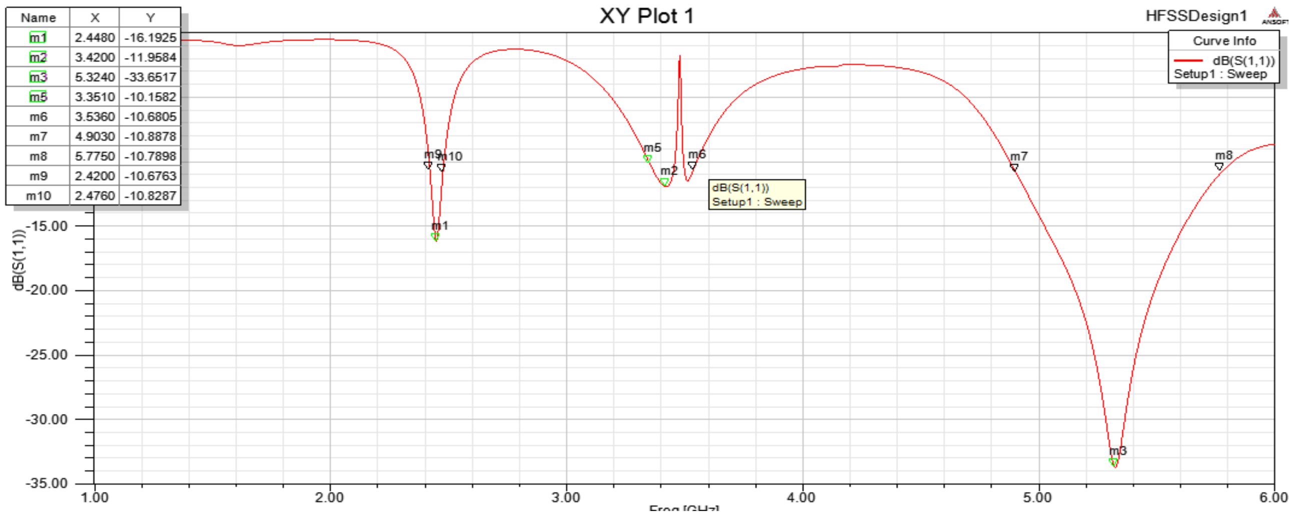
6.1 Stage 2

The purpose of this antenna is to exhibit tri band characteristics. The bands that were targeted were the 5G bands i.e. 3.5 GHz and 5.5 GHz and also the wireless band of 2.45 GHz. The 3.5 GHz 5G band is used for the reconfiguration purpose in the design and therefore the state of the antenna can be decided as per the requirement of 3.5 GHz component.

6.1.1 Reflection Coefficient

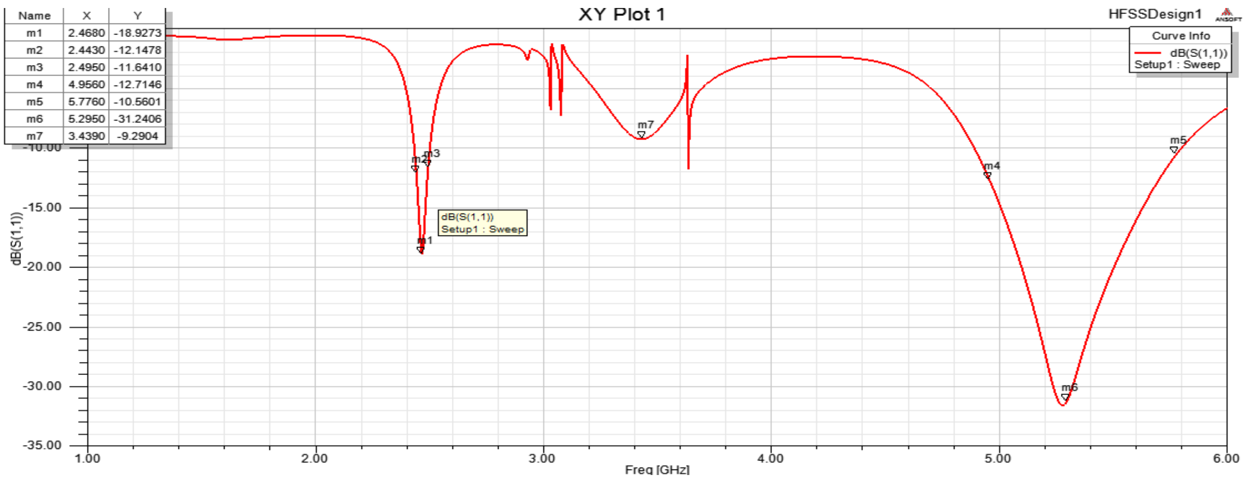
We have a narrow band from 2.42-2.47 GHz, where the best S11 result for this band is -16.19 dB at 2.448 GHz. We then have another band from 3.35-3.53 GHz, where the best S11 result for this band is -11.95 dB at 3.42 GHz. The antenna shifts this band on and off with the changing value of the capacitor. When we'll place the RF MEMS in the physical structure and then by switching it among different value of capacitance we can switch this band on and off and thus achieving reconfigurability. The third band is the wide band from 4.9-5.7 GHz, where the best S11 result for this band is -33.65 dB at 5.32 GHz. When the switch switches among the different values of capacitance there's nearly no effect on the 2.44 GHz band except the S11 value drops to -18.89 dB thus giving better result. The 5.5 GHz band shifts to 4.95-5.77 GHz but still safely covers the 5.5 GHz frequency.

The result of this stage in which RLC component is in centre position and varies its value from 9 pF to 13 pF is **shown in Figure 6.1 and 6.2.**



Name	X	Y
m1	2.4480	-16.1925
m2	3.4200	-11.9584
m3	5.3240	-33.6517
m5	3.3510	-10.1582
m6	3.5360	-10.6805
m7	4.9030	-10.8878
m8	5.7750	-10.7898
m9	2.4200	-10.6763
m10	2.4760	-10.8287

Figure 6. 1: S11 Results with Switch at 9pf (on)



Name	X	Y
m1	2.4680	-18.9273
m2	2.4430	-12.1478
m3	2.4950	-11.6410
m4	4.9560	-12.7146
m5	5.7760	-10.5601
m6	5.2950	-31.2406
m7	3.4390	-9.2904

Figure 6. 2: S11 Results Switch at 13pf (off)

It can be clearly seen that 3.5 GHz band is switched off at 13 pF and is operational at 9 pF.

6.1.2 Gain

- **ON state**

  The **Figure 6.3** show the antenna gain. It has acceptable values of 3.77 dB at 2.45 GHz, 5.06 dB at 3.5 GHz and 7.52 dB at 5.5 GHz.

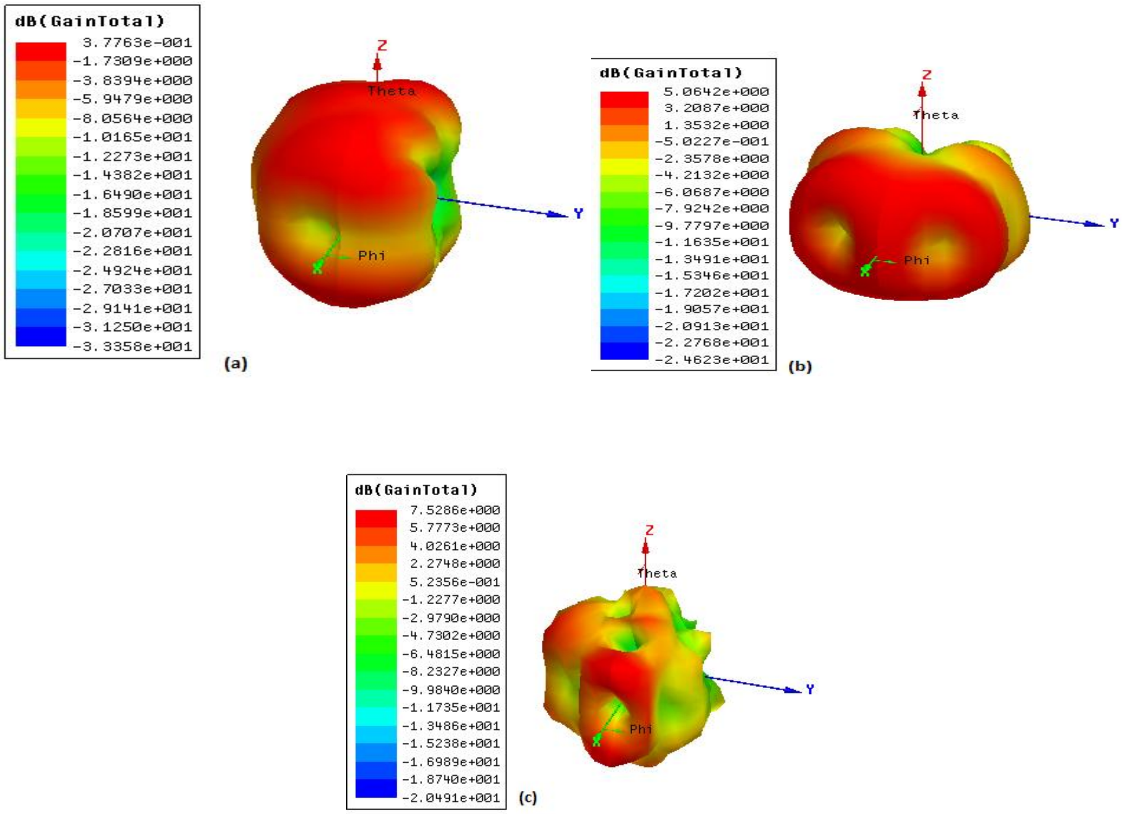


Figure 6. 3: Total Gain in On state (a) 2.45 GHZ (b) 3.5 GHZ (c) 5.5 GHZ

- **OFF State**
  Acceptable values of gain were recorded and are shown in **Figure 6.4**. A value of 3.36 dB was recorded at 2.45 GHz and 8.05 dB at 5.5 GHz

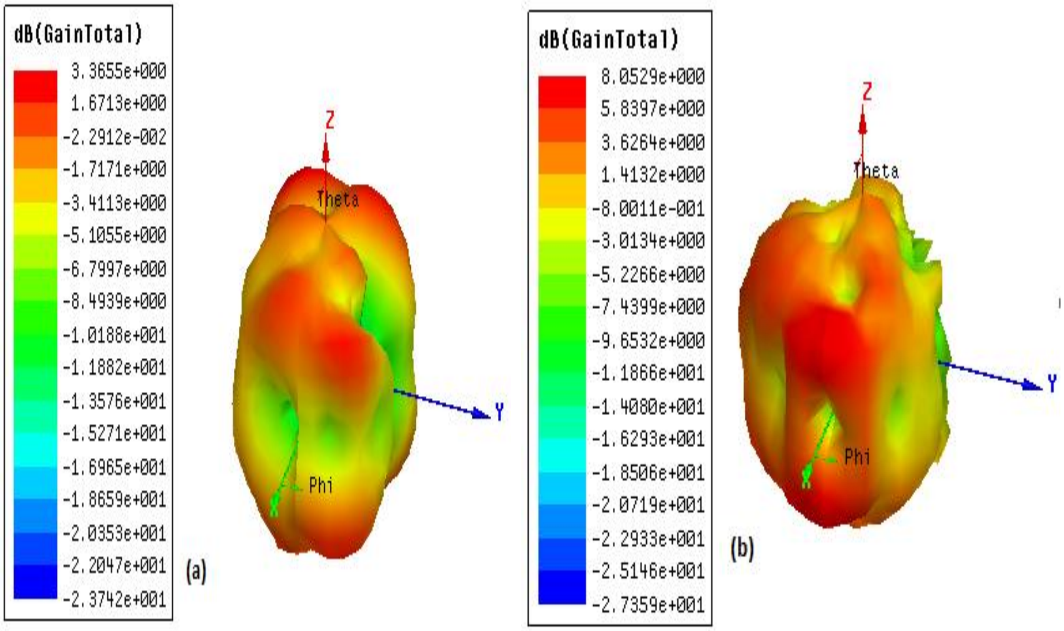


Figure 6. 4:Total Gain in On state (a) 2.45 GHZ (b) 5.5 GHZ

6.1.3 Result Summary

Table 6.1 shows the summary of complete results at this stage

State	Operating Frequency (GHz)	Ref Coeff S11 (dB)	Tot Gain (dB)	Operating Frequency (GHz)	Ref Coeff S11 (dB)	Tot Gain (dB)	Operating Frequency (GHz)	Ref Coeff S11 (dB)	Tot Gain (dB)
On	2.45	-16.19	3.77	3.5	-11.95	5.06	5.5	-20	7.52
Off	2.46	-18.19	3.36	-	-	-	5.29	-31.2	8.05

Table 6. 1: Summary

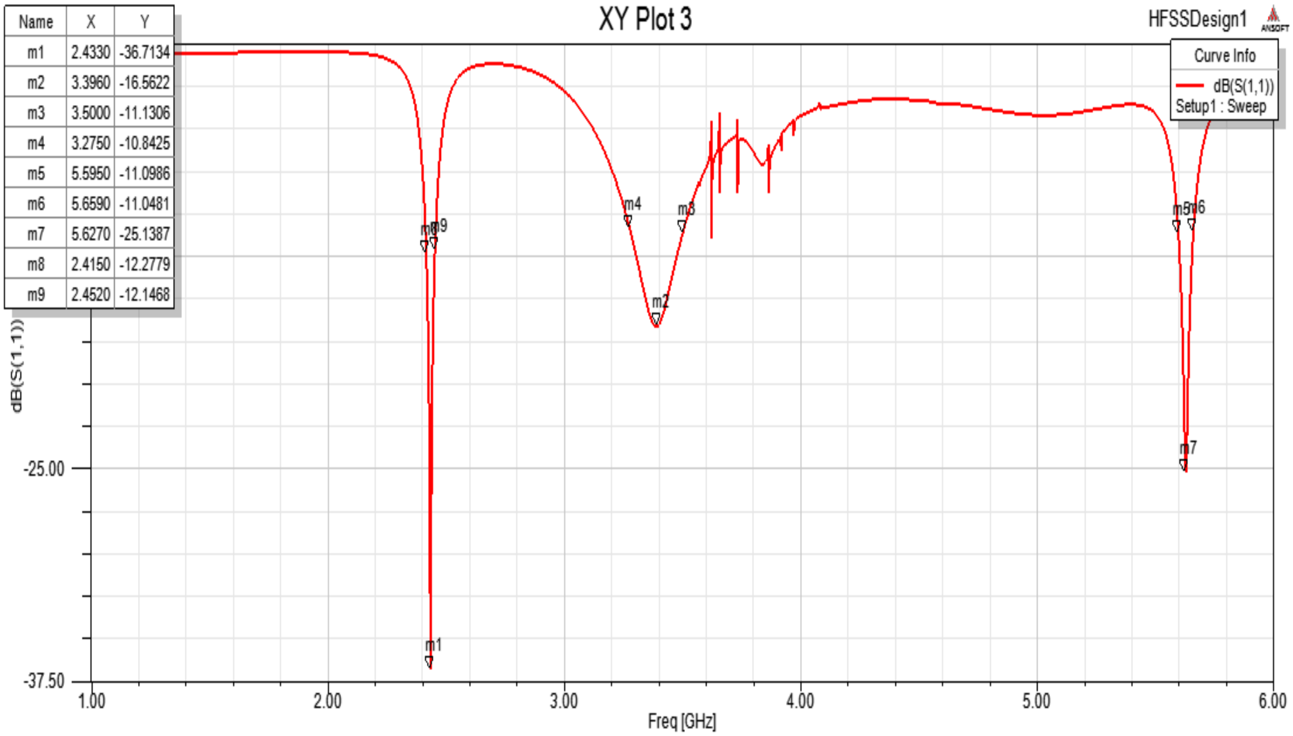
6.2 Stage 3: MIMO Design

Just like stage 2 the purpose of this design was to target the same bands and achieve reconfigurability. In this design the 5.5 GHz 5G band is used for the reconfiguration purpose and therefore the state of the antenna can be decided as per the requirement of 5.5 GHz component.

6.2.1 Reflection Coefficient

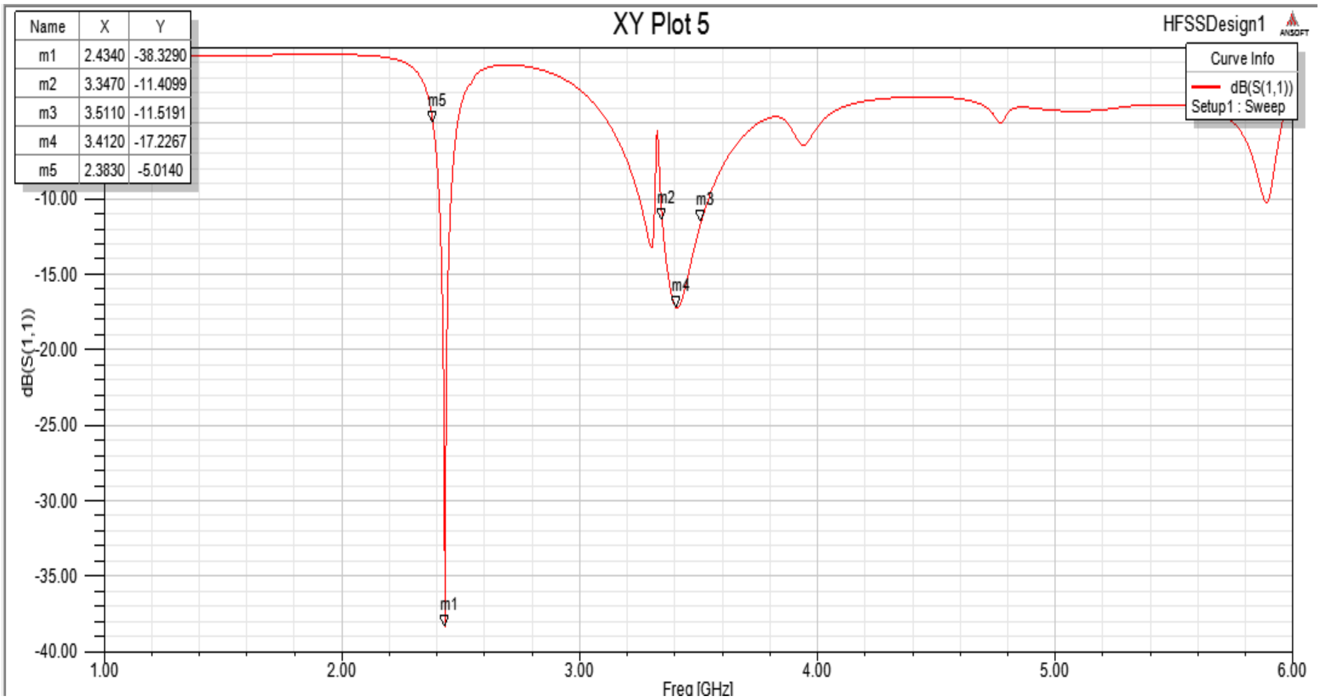
In this design we have a narrow band from 2.41-2.452 GHz, with the best value of S11 parameter -36.71 dB at 2.433 GHz. Another band that was achieved was from 3.27-3.50 GHz, with the best value of S11 parameter -16.56 dB at 3.4 GHz. The third band that we have is from 5.59-5.65 GHz, with the best value of S11 parameter -25.13 dB at 5.62 GHz. This is the band in which we have achieved reconfigurability when we place RF MEMS and it switches the value of capacitance and this third band switches on and off. With this switching there is negligible effect on 2.45 GHz band and it just gives better S11 parameter value -38.32 dB at 2.43 GHz but the 3.5 GHz band is slightly shifted i.e. from 3.34-3.51 with the best value of S11 parameter -17.22 dB at 3.41 GHz.

The result of this stage in which RLC component is in centre position and varies its value from 30 pF to 9 pF is **shown in Figure 6.5 and 6.6.**



Name	X	Y
m1	2.4330	-36.7134
m2	3.3960	-16.5622
m3	3.5000	-11.1306
m4	3.2750	-10.8425
m5	5.5950	-11.0986
m6	5.6590	-11.0481
m7	5.6270	-25.1387
m8	2.4150	-12.2779
m9	2.4520	-12.1468

Figure 6. 5: S11 result with Switch at 30 pF



Name	X	Y
m1	2.4340	-38.3290
m2	3.3470	-11.4099
m3	3.5110	-11.5191
m4	3.4120	-17.2267
m5	2.3830	-5.0140

Figure 6. 6: S11 result with Switch at 9 pF

Observation:

It can be clearly seen that the 5.5 GHz band is switched off at 9 pF and is operational at 30 pF.

Chapter 7: Conclusion

After a great number of stimulations were run and after careful observation we have achieved tri-band reconfigurable 5G antenna and the designed antenna is with maximum gain and satisfactory performances for return loss, radiation pattern, and isolation characteristics. It is based to be used in the modern 5G devices which are the need of this modern era of communication. Its reconfigurable frequency bands allow it to be used in different states according to the need thus making it suitable for many applications like smart phones, autonomous driving, smart cities, IoT etc.

Chapter 8: Potential Enhancements

8.1Implementing 2x2 and 4x4 MIMO for Enhanced Efficiency, Bandwidth and Performance

The antenna can be converted into 2x2 or 4x4 MIMO for better bandwidth and performance. It will also improve the antenna throughput and efficiency. It is also worthwhile to adopt better isolation techniques so that in MIMO structure one patch does not affect the performance of other patch.

8.2 Increase Amount of Resonant Frequency Bands

The amount of resonant bands can be incremented by addition of more slots to patch and ground. It is also possible to modify the partial ground by shape modification or other modification techniques for the purpose of increasing the number of resonant bands.

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