M.Tech(MOCE) SPARSH SINGHAL 2023

# COMPOUND WIDEBAND RECONFIGURABLE ANTENNAS BASED ON PIN DIODES AND VO2 RF SWITCHES FOR C-BAND WIRELESS STANDARDS

A DISSERTATION

SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
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## CANDIDATE'S DECLARATION

I, Sparsh Singhal, Roll No. 2K21/MOC/05 student of M.Tech (Microwave and Optical Communication Engineering) hereby declare that the project dissertation which is titled as "Compound Wideband Reconfigurable Antennas based on PIN diodes and VO2 RF switches for C-band wireless standards", is submitted by me to the Department of Electronics and Communication Engineering(ECE) , Delhi Technological University(DTU), Delhi in partial fulfillment of the requirement for the award of the degree of Master of Technology, is original and not copied from any source without proper citation. This work has not previously formed the basis for the award of any Degree, Diploma Associateship, Fellowship or other similar title or recognition.

Place: Delhi **(Sparsh Singhal)**

Date: 13th June 2023

**ELECTRONICS AND COMMUNICATION ENGINEERING DEPARTMENT**

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## CERTIFICATE

I hereby certify that the Project Dissertation titled “Compound Wideband Reconfigurable Antennas based on PIN diodes and VO2 RF switches for C-band wireless standards” which is submitted by Sparsh Singhal, Roll No. 2K21/MOC/05, Electronics and Communication Engineering Department, DelhiTechnological University, Delhi in partial fulfillment of the requirement for the award of the degree of Master of Technology, is a record of the project work carried out by the students under my supervision. To the best of my knowledge this work has not been submitted in part or full for any Degree or Diploma to this University or elsewhere.

Place: Delhi

Date: 13th June 2023

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# ABSTRACT

Wireless technology is one of the most important fields of research in the world of communication systems today, and a study of communication systems would be incomplete without an understanding of antenna functioning and manufacturing. This was the primary reason we chose a project in this field.

Microstrip patch antennas are gaining popularity as more and more advancements are made in the wireless communication systems. They are being used in multiple fields and the scope of research and improvements is quite high in this area. A simple patch antenna is designed to work for only a single application, having frequency of operation within a certain frequency band range but a reconfigurable antenna enables us to reconfigure this frequency band based on our different requirements. It is possible to reconfigure different functionalities of an antenna, such as frequency, polarization, radiation pattern, bandwidth etc.

The common practice of making the antennas reconfigurable is by adding switches like PIN diodes and Varacter diodes in the antenna which help in changing the state of the antenna when the biasing or voltage across the diodes is changed, making it possible to observe more than one resonating state for a designed antenna. In this project, two papers

were submitted for the conference in the same field of reconfigurable antennas.

The first paper titled “Fox-Face Compound Reconfigurable Antenna for Wireless Systems” presents an antenna design of a compact structured CRA (Compound Reconfigurable antenna) in which compound reconfiguration is observed by using just two PIN diodes in the antenna structure. While the second paper titled “Bandwidth Reconfigurable Wideband Antenna with comparison between PIN diodes and Vanadium Dioxide switches” presents an approach where a bandwidth reconfiguration compact antenna is presented while also suggesting an alternate approach of using Vanadium diode switches instead of PIN diodes and comparing the results in the two approaches.

Both antenna structures were designed and simulated by making use of the Ansys HFSS software and the respective results were observed and presented in the conference papers and the project report here.

# ACKNOWLEDGEMENT

I would like to express my profound gratitude to Dr. O.P.Verma, H.O.D. of Electronics and Communication Engineering department of Delhi Technological University for their contributions to the completion of my project titled “Compound Wideband Reconfigurable Antennas Based on PIN diodes and VO2 RF Switches For C-Band Wireless Standards”.

I would like to express my special thanks to my mentors Prof. N.S.Ragava and Mr. M.Ganesh for their time and efforts they provided throughout the year. Their useful advice and suggestions were really helpful for me during the project’s completion. In this aspect, I am eternally grateful to them.

I'd want to emphasise that this project was totally finished by me and not by anyone else.

Sparsh Singhal

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# LIST OF SYMBOLS, ABBREVIATIONS

| | |
|---|---|
| IEEE | Institute of Electrical and Electronics Engineers |
| MMIC | Monolithic Microwave Integrated Circuit |
| PTFE | Polytetrafluoroethylene |
| HFSS | High-Frequency Structure Simulator |
| CRA | Compound Reconfigurable Antenna |
| MIMO | Multiple Input Multiple Output |
| RF | Radio Frequency |
| VO2 | Vanadium Dioxide |

# CHAPTER 1

# INTRODUCTION TO MICROSTRIP PATCH ANTENNAS

The software simulation of two microstrip patch antennas is the focus of our project. Understanding the different terms used to refer to antennas is a necessary first step before you can fully understand microstrip Patch Antennas. That's the topic of this first chapter.

## 1.1 Microstrip Patch Antenna

An antenna is defined as electrical conductor or network of conductors.
Transmitter – Serves the purpose of radiating electromagnetic energy into space
Receiver - Serves the purpose of collecting electromagnetic energy from space
The IEEE definition for an antenna which was given by Stutzman and Thiele is, "That part of a transmitting or receiving system that is designed to radiate or receive electromagnetic waves".
Antennas which are low profile, can be critical in high-performance aircraft, spacecraft, satellite, and missile programs where length, weight, value, overall performance, aerodynamic profile and ease of installation are all important considerations. Many other governmental and commercial uses, such as wireless communications and mobile radio, already have criteria that are comparable. These criteria might be met using microstrip antennas. These antennas have a low profile, are conformable to planar and nonplanar surfaces, are simple and inexpensive to fabricate using current revealed-circuit technology, are routinely robust when installed on rigid surfaces, and are extremely flexible in terms of resonant frequency, polarisation, pattern, and impedance depending on the patch form and mode selected. Furthermore, by connecting the patch and ground plane with loads like PIN and varactor [1].

To understand the work presented and observe the results, the knowledge of the characteristics associated with the antennas is necessary.

### 1.1.1 Basic Characteristics

As seen in Fig. 1.1, microstrip antennas are made of a metallic strip (patch) that is extremely thin (t0) and is positioned really tiny distance above a ground plane (h≈0, typically 0.003> h >0.05≈ 0). The broadside radiator is created with the microstrip patch's maximum pattern in mind. This is accomplished by carefully adjusting the mode (field configuration) of stimulation beneath the patch. Prudent mode selection can potentially result in end-fire radiation. As seen in Figure 1.1(a), a dielectric sheet i.e. dielectric substrate divides the patch from the ground plane[1].

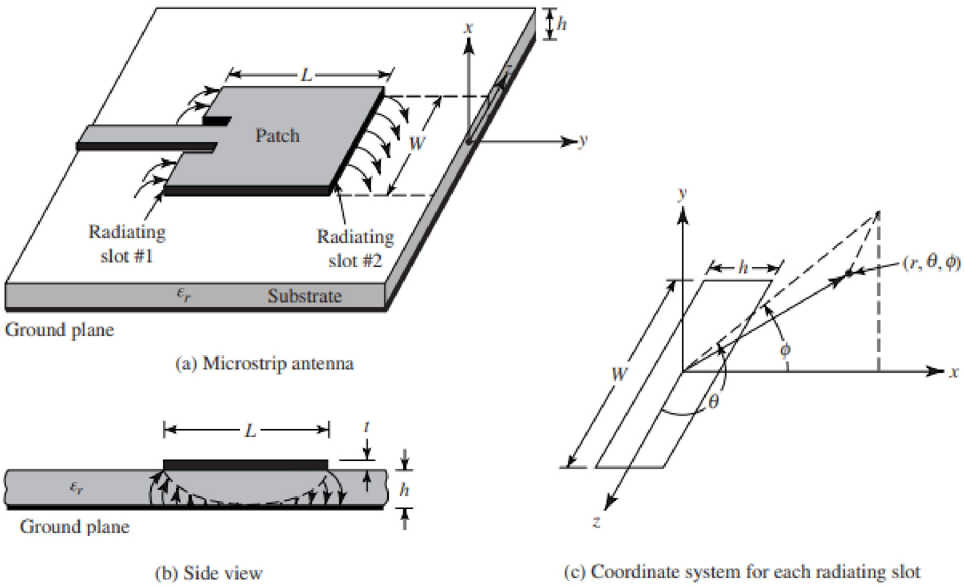



Fig.1.1 Microstrip antenna and coordinate system.

Patch antennas are some other name for microstrip antennas. commonly, the feed lines and radiating additives are photoetched onto the dielectric substrate. The radiating patch may be formed however you like: rectangular, square, thin strip (dipole), round, elliptical, triangular, etc. Microstrip dipoles are proper due to the fact they have got a broad bandwidth by way of nature and take in much less region, making them ideal for arrays. Microstrip antenna arrays and unmarried additives might also both produce linear and round polarisations. to add scanning abilties and attain better directivities, arrays of microstrip factors with one or extra feeds will also be hired. Microstrip antennas have significant operational drawbacks, such as low efficiency, low power, high Q (occasionally exceeding 100), poor polarisation purity, poor experiment performance, spurious feed radiation, and a very small frequency bandwidth, which is typically a few percent or less. Overcoming those drawbacks and creating an software-unique patch antenna is continually a trouble [1].

### 1.1.2 Different Substrates and their parameters

The creation of microstrip-type antennas may be done on a variety of commercial substrates. Table 1.1 provides a list of some popular substrates together with the most important details.

Table 1.1 Substrates commercially available and their parameters [1]

| Company | Substrate | Thickness (mm) | Frequency (GHz) | $\varepsilon_r$ | $\tan\delta$ |
|---|---|---|---|---|---|
| Rogers Corporation | Duroid® 5880 | 0.127 | 0 – 40 | 2.20 | 0.0009 |
| | RO 3003 | 1.575 | 0 – 40 | 3.00 | 0.0010 |
| | RO 3010 | 3.175 | 0 – 10 | 10.2 | 0.0022 |
| | RO 4350 | 0.168<br>0.508<br>1.524 | 0 – 10 | 3.48 | 0.0037 |
| — | FR4 | 0.05 – 100 | 0.001 | 4.70 | — |
| DuPont | HK 04J | 0.025 | 0.001 | 3.50 | 0.005 |
| Isola | IS 410 | 0.05 – 3.2 | 0.1 | 5.40 | 0.035 |
| Arlon | DiClad 870 | 0.091 | 0 – 10 | 2.33 | 0.0013 |
| Polyflon | Polyguide | 0.102 | 0 – 10 | 2.32 | 0.0005 |
| Neltec | NH 9320 | 3.175 | 0 – 10 | 3.20 | 0.0024 |
| Taconic | RF-60A | 0.102 | 0 – 10 | 6.15 | 0.0038 |

This is only a tiny selection; there are many different substrate types available from various businesses, like the Rogers Corporation. The Rogers substrates, which are woven glass laminates and widely used in microstrip patch antenna designs, are often known as PTFE (polytetrafluorethylene). Another widely used substrate is FR4.

### 1.1.3 Feeding Methods

There are several ways to feed microstrip antennas. The four most common are coaxial probe, aperture coupling, proximity coupling, and microstrip line. In Fig. 1.2, they are shown. Fig. 1.3 displays a single set of comparable circuits for each of them.

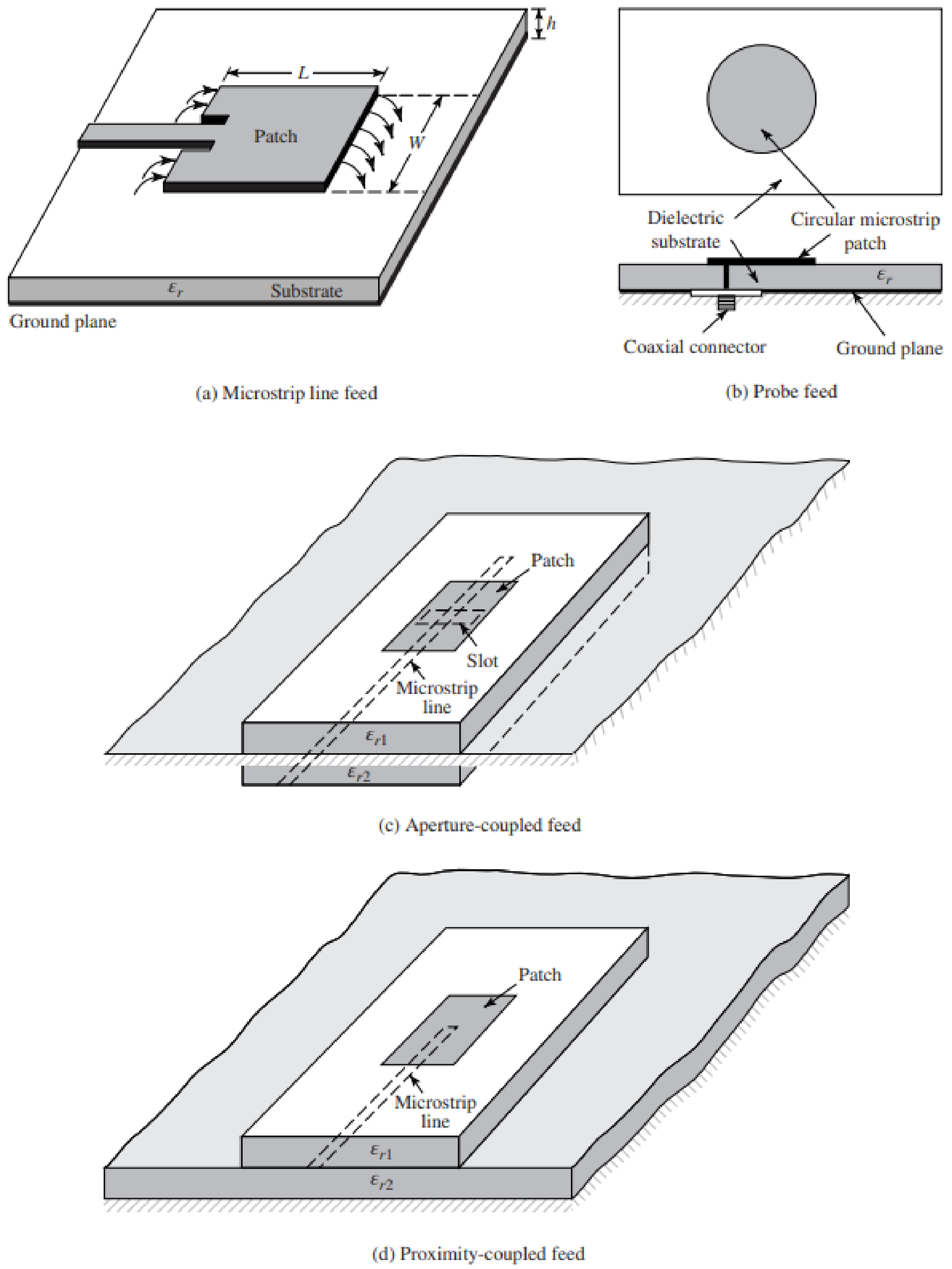



Fig.1.2 Different Feeding Methods[1]

The microstrip line feed strategy, as shown in Fig. 1.2(a), involves connecting a conducting strip directly to the border of the patch. Despite the fact that the achieving strip is narrower than the patch, this form of feed arrangement offers the benefit of allowing the feed to be etched on the same substrate to give a planar structure. Without the use of any extra matching additives, the patch's inset cut is designed to match the impedance of the patch's feed line.

The co-axial feed is a non-planar feeding method that feeds the patch using a z-co-axial cable. The cable's outer conductor is attached to the floor plane, as illustrated in Fig. 1.2(b), while the co-axial connection's internal conductor extends through the dielectric and makes steel contact with the patch. The probe is in direct contact with the antenna and is situated at 50 ohms at the antenna entrance. This feed machine produces significantly less spurious radiation and is easy to construct. However, the fact that it got connected to the floor plane connection was a big negative.

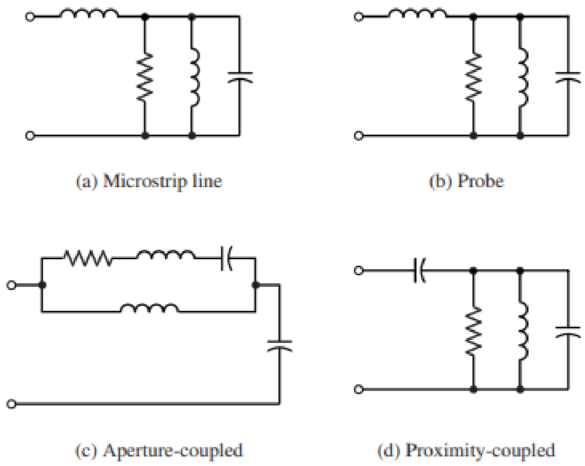



Fig.1.3 Equivalent circuits for feeds of Fig.1.2[1].

The aperture feed technique has two dielectric substrates: the antenna dielectric substrate and the feed dielectric substrate. These two dielectric substrates are separated by a ground plane with a slit in the centre. The metal patch is attached to the antenna substrate, as shown in Fig. 1.2 (c). The ground plane is located on the other side of the antenna dielectric. The feed line and feed dielectric are placed on the opposite side of the ground plane to generate isolation. Aperture feed provides excellent polarisation purity, which is not attainable with other feed techniques. An aperture-fed antenna provides more bandwidth. It comes in handy when we don't want to utilise wires to link one layer to another. The downside of this feed is that it necessitates multilayer construction.

The feed line in proximity feed is positioned between two dielectric substrates. Because the impedance at the edges will be rather high when using the edge-fed approach, a feed point of 50 ohms will be difficult to find. To avoid this, the feed line is placed below the patch at a lower level. The feed line's edge is situated at 50 ohms of antenna input impedance. In this situation, power is transferred from the feed to the patch via electromagnetic field coupling. Relocating the feed line to a lower level lowered feed line radiation significantly, in addition to improving planar feeding. Furthermore, it makes better use of bandwidth than the other approaches. The drawback of this approach is that multilayer production is required, and the polarisation purity is subpar.

### 1.1.4 Fringing Effect

The fields which are along the patch's boundaries experience fringing as the patch's dimensions are limited along its dimensions. This is shown for the two radiating slots of the microstrip antenna over its length in Fig. 1.4(a,b), which is same holds true for the breadth. The patch's size and substrate height both have significance in deciding how much fringing occurs. Fringing is a function of the substrate's dielectric constant (εr) and the ratio of the patch's length L to its height h for the major E-plane (xy-plane). Although fringing is lessened for microstrip antennas because of L/h >>1, it must still be considered since it affects the resonance frequency of the antenna. The same applies for the width.

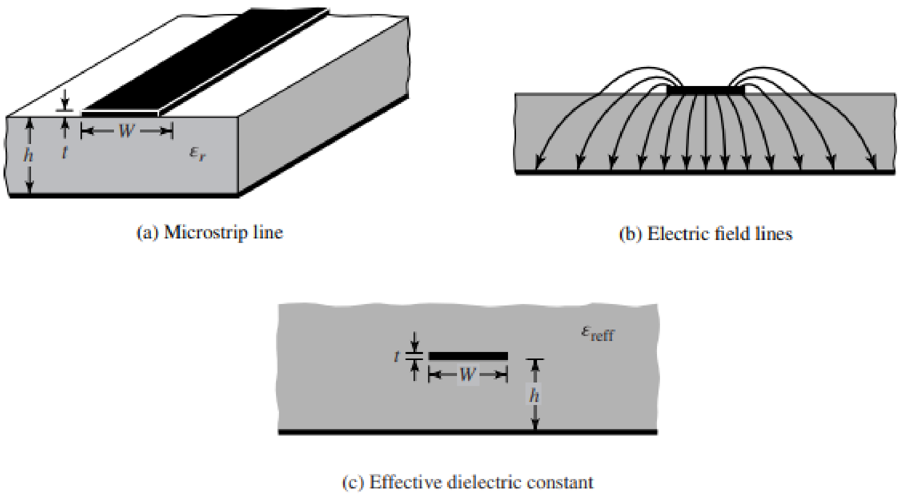



Fig.1.4 Microstrip line and its electric field lines, and effective dielectric constant geometry[1].

Typical electric field lines are depicted in Fig. 1.4(b) for a microstrip line in Fig. 1.4(a). A substrate and air are the typical dielectrics in this nonhomogeneous line. As can be observed, the majority of the electric field lines are found in the substrate, while some lines also have portions in the air. The electric field lines are largely concentrated in the substrate as W/h and $\varepsilon_r$ are highly greater than unity. In this instance, the microstrip line's electrical appearance is broader than its actual dimensions due to the presence of fringes.

An effective dielectric constant ($\varepsilon_{reff}$) is included to account for fringing and wave propagation in the line since some waves travel in the substrate and others in the air.

To introduce the effective dielectric constant, assume that the microstrip line's centre conductor is submerged in one dielectric with its original dimensions and height above the ground plane, as illustrated in Fig. 1.4(c). The effective dielectric constant is defined as the dielectric constant of the uniform dielectric material, therefore the line in Fig. 1.4(c) has the same electrical characteristics as the real line in Fig. 1.4(a), most notably the propagation constant. For an antenna where air is above the substrate, the effective dielectric constant has values in the range of $1 < \varepsilon reff < \varepsilon r$. The value of $\varepsilon reff$ will be closer to the value of the actual dielectric constant i.e., $\varepsilon r$ of the substrate for most applications where the dielectric constant of the substrate is much greater than unity ($\varepsilon_r \gg 1$). The effective dielectric constant is also affected by frequency. As the operating frequency increases, the majority of the electric field lines congregate in the substrate. As a result, the effective dielectric constant approaches the value of the dielectric constant of the substrate, and the microstrip line behaves more like a homogeneous line with a single dielectric (the substrate). At low frequencies, the effective dielectric constant is generally constant. Its values begin to rise monotonically at intermediate frequencies, eventually approaching the dielectric constant of the substrate. The static values are the starting values of the effective dielectric constant (at low frequencies).

$$\varepsilon_{reff} = \frac{(\varepsilon_r + 1)}{2} + \frac{\varepsilon r - 1}{2} \left[ 1 + 12 \frac{h}{W} \right]^{-1/2} \quad (1.1)$$

### 1.1.5 Effective Length, Resonant Frequency, and Effective Width

The patch of the microstrip antenna seems larger than its actual size electronically due to the effects of fringing. This is seen in Fig. 1.5 for the main E-plane, where the patch's dimensions along its length have been stretched on either end by a distance L, which is a function of the effective dielectric constant and the width-to-height ratio (W/h). A widely used and useful approximation for the normalised extension of length is

$$\frac{\Delta L}{h} = 0.412 \frac{(\varepsilon_{reff} + 0.3)\,(\frac{W}{h} + 0.264)}{(\varepsilon_{reff} - 0.258)\,(\frac{W}{h} + 0.8)} \quad (1.2)$$

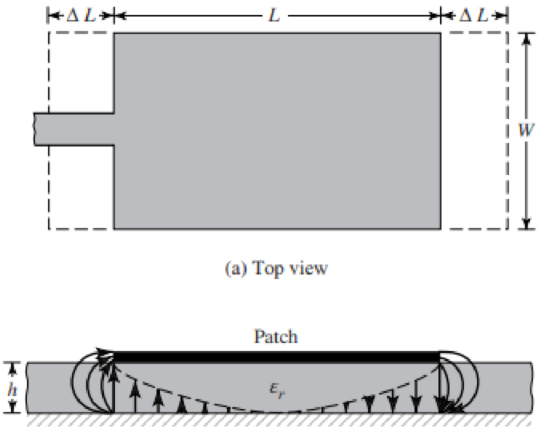



Fig.1.5 Physical and effective lengths of rectangular microstrip patch[1].

Since the length of the patch has been extended by ΔL on each side, the effective length of the patch is now (L = λ/2 for dominant TM010 mode with no fringing)

$$Leff = L + 2\Delta L \quad (1.3)$$

For the dominant TM010 mode, the resonant frequency of the microstrip antenna is a function of its length. Usually it is given by

$$(f_r)_{010} = \frac{1}{2L\sqrt{\varepsilon r}\sqrt{\mu 0 \varepsilon 0}} = \frac{\upsilon 0}{2L\sqrt{\varepsilon r}} \quad (1.4)$$

where $\upsilon 0$ is the speed of light in free space. Since (1.4) does not account for fringing, it must be modified to include edge effects and should be computed using

$$(f_r)_{010} = q \frac{\upsilon 0}{2L\sqrt{\varepsilon r}} \quad (1.5)$$

where

$$q = \frac{(f_{rc})_{010}}{(f_r)_{010}} \quad (1.6)$$

The fringe factor (length reduction factor) is another name for the q factor. Fringing grows along with substrate height, resulting in wider gaps between radiating edges and lower resonance frequencies. As the patch seems longer, the planned resonant frequency, based on fringing, decreases, as seen in Figure 14.7. Typically, fringing reduces resonance frequency by 2–6%.

## 1.2 Design Specific Calculations

In the proposed designs the formulas for both rectanguar patch as well as circular patch are utilised as in different cases, the resonating patch shape is different. The thickness of the substrate, h is very small compared to wavelength($\lambda_0$) of resonate frequency($f_{rc}$) i.e. h<$0.05\lambda_0$, so the following formulas for first dominant mode for patch can be considered.

For rectangular patch:

$$W = \frac{1}{2f_{rc}\sqrt{\mu_0\varepsilon_0}}\sqrt{\left(\frac{2}{\varepsilon_r + 1}\right)} = \left(\frac{\upsilon_0}{2f_{rc}}\right)\sqrt{\left(\frac{2}{\varepsilon_r + 1}\right)} \tag{1.7}$$

$$L = \frac{1}{2f_{rc}\sqrt{\varepsilon_{reff}}\sqrt{\mu_0\varepsilon_0}} - 2\Delta L \tag{1.8}$$

$$L \approx \frac{(0.47 - 0.49)\lambda_0}{\sqrt{\varepsilon_r}} = (0.47 - 0.49)\lambda_d \tag{1.9}$$

where W is the width of patch, L is length of patch, $v_0$ is speed of electromagnetic wave in free space, ΔL is extension length and $\lambda_d$ is wavelength in dielectric.

For circular patch:

$$(f_{rc})_{110} = \frac{1.8412\upsilon_0}{2\pi a_e\sqrt{\varepsilon_r}} = \frac{8.791 \times 10^9}{(a_e\sqrt{\varepsilon_r})} \tag{1.10}$$

$$a = \frac{F}{\left\{1 + \left(\frac{2h}{\pi\varepsilon_r F}\right)\left[\ln\left(\frac{\pi F}{2h}\right) + 1.7726\right]\right\}^{1/2}} \tag{1.11}$$

where,

$$F = \frac{8.791 \times 10^9}{(f_{rc}\sqrt{\varepsilon_r})} \tag{1.12}$$

where $f_{rc}$ resonant frequency is traveling at speed of light, $v_0$=c; $a_e$ is the effective radius of patch and a is actual radius of patch.

## 1.3 Antenna Parameters

The following sections outline the key parameters connected with an antenna.

### 1.3.1 Antenna Gain

Gain is evaluated at the radiation's highest intensity and describes how well an antenna can convert input power into radiation in a certain direction. The power density radiated by an isotropic antenna with input power $P_0$ at a distance R which is given by S = $P_0/4\pi R^2$[1]. By dividing the radiated power by the sphere's surface area ($4\pi R^2$), one may calculate the radiated power density S of an isotropic antenna, which radiates equally in all directions. The efficiency of an isotropic radiator is 100 percent[1]. The power density in the direction of peak radiation is increased by a real antenna's gain:

$$S = \frac{P_0 G}{4\pi R^2} = \frac{|\mathbf{E}|^2}{\eta} \quad \text{or} \quad |\mathbf{E}| = \frac{1}{R}\sqrt{\frac{P_0 G \eta}{4\pi}} = \sqrt{S\eta} \tag{1.13}$$

Gain is obtained by diverting the radiation in the radiation sphere away from other areas. Gain is often described as the antenna's gain-biased pattern[1].

$$\begin{aligned} S(\theta,\phi) &= \frac{P_0 G(\theta,\phi)}{4\pi R^2} \qquad \text{power density} \\ U(\theta,\phi) &= \frac{P_0 G(\theta,\phi)}{4\pi} \qquad \text{radiation intensity} \end{aligned} \tag{1.14}$$

### 1.3.2 Antenna Efficiency

The antenna efficiency, or relative power radiated, is computed as the surface integral of the radiation intensity throughout the radiation sphere divided by the input power P0.

$$\frac{P_r}{P_0} = \int_0^{2\pi} \int_0^{\pi} \frac{G(\theta, \phi)}{4\pi} \sin\theta \, d\theta \, d\phi = \eta_e \tag{1.15}$$

where Pr denotes the power radiated. Radiated power is reduced by material losses in the antenna or reflected power owing to poor impedance matching[1].

### 1.3.3 Effective Area

A portion of the power that antennas harvest from passing waves is sent to the terminals. The power provided to the terminals is the result of the incident wave's power density and the antenna's effective area.

$$P_d = SA_{\text{eff}} \tag{1.16}$$

The effective area of an aperture antenna, such as a horn, parabolic reflector, or flat-plate array, is calculated by multiplying the physical area by the aperture efficiencyThe effective area to physical area ratio is frequently reduced as a result of distribution, material, and mismatch losses. The average aperture efficiency of a parabolic reflector is reported to be 55%. Because they drain energy from passing waves, even antennas with extremely tiny physical surfaces, such as dipoles, have effective areas[1].

### 1.3.4 Directivity

The concentration of radiation in the direction of maximal directivity is measured.

$$\text{directivity} = \frac{\text{maximum radiation intensity}}{\text{average radiation intensity}} = \frac{U_{\max}}{U_0} \tag{1.17}$$

Gain and directivity merely differ in their efficiency, although directivity may be readily inferred from patterns. Gain must be calculated as directivity times efficiency. A surface integral across the radiation sphere of the radiation intensity divided by the area of the sphere in steradians i.e. 4π, may be used to get the average radiation intensity[1]:

$$\text{average radiation intensity} = \frac{1}{4\pi}\int_0^{2\pi}\int_0^{\pi} U(\theta,\phi)\sin\theta\, d\theta\, d\phi = U_0 \tag{1.18}$$

This is the radiated power divided by the area of a unit sphere. The radiation intensity U(θ,φ) separates into a sum of co- and cross-polarization components:

$$U_0 = \frac{1}{4\pi}\int_0^{2\pi}\int_0^{\pi}[U_C(\theta,\phi) + U_\times(\theta,\phi)]\sin\theta\, d\theta\, d\phi \tag{1.19}$$

Both co- and cross-polarization directivities can be defined:

$$\text{directivity}_C = \frac{U_{C,\max}}{U_0} \qquad \text{directivity}_\times = \frac{U_{\times,\max}}{U_0} \tag{1.20}$$

Directivity can alternatively be defined as radiation intensity divided by average radiation intensity for any arbitrary direction D(θ,φ), however since the coordinate angles are not supplied, we compute directivity at Umax. [1].

### 1.3.5 Path Loss

We combine the gain of the transmitting antenna with the effective area of the receiving antenna to determine delivered power and route loss. The power density at the receiving antenna is given by equation 1.14, while the received power is given by equation 1.16. Combining the two results, we arrive at the route loss shown below[1].

$$\frac{P_d}{P_t} = \frac{A_2 G_1(\theta,\phi)}{4\pi R^2} \tag{1.21}$$

For Antenna 1 transmitting and antenna 2 receiving, the transmission and receiving patterns are identical if the materials used to construct the antennas are linear and isotropic. The path loss is when we consider antenna 1 as the receiving antenna and antenna 2 as the broadcasting antenna:

$$\frac{P_d}{P_t} = \frac{A_1 G_2(\theta,\phi)}{4\pi R^2} \tag{1.22}$$

Using the method, we quickly calculate route loss for various units of distance R and frequency f in megahertz[1]

$$\text{path loss(dB)} = K_U + 20\log(fR) - G_1(\text{dB}) - G_2(\text{dB}) \quad (1.23)$$

where $K_U$ depends on the length units as shown in table 1.2

Table1.2 Dependency of $K_U$ on units of lengths

| Unit | $K_U$ |
|---|---|
| km | 32.45 |
| nm | 37.80 |
| miles | 36.58 |
| m | −27.55 |
| ft | −37.87 |

### 1.3.6 Input Impedance

The input impedance of an antenna is defined as "the impedance presented by the antenna at its terminals, the voltage to current ratio at the pair of terminals, or the ratio of the appropriate components of the electric to magnetic fields at a point." As a consequence, the antenna's impedance may be expressed as follows. [1]:

$$Z_{in} = R_{in} + jX_{in} \quad (1.24)$$

where Zin is the terminal antenna impedance, Rin is the terminal antenna resistance, and Xin is the terminal antenna reactance

The imaginary component of the input impedance, Xin, indicates the power stored in the near field of the antenna. Rin, the resistive component of the input impedance, is composed of two components: the radiation resistance Rr and the loss resistance RL. While the power lost in the loss resistance is lost as heat in the antenna as a result of dielectric or conducting losses, the power linked with the radiation resistance is the power that the antenna actually emits[1].

### 1.3.7 Antenna Factor

Field strength E is measured by the technical community using an antenna coupled to a receiver such as a spectrum analyzer, network analyzer, or RF voltmeter. The load resistor $Z_L$ in these devices typically matches the antenna impedance[1].

The received voltage $V_{rec}$ multiplied by the antenna factor AF results in the incident field strength $E_i$. This is related to the effective antenna height.

$$\mathrm{AF} = \frac{E_i}{V_{\mathrm{rec}}} = \frac{2}{h} \tag{1.25}$$

AF is measured in meters$^{-1}$ but is generally reported in decibels (dB(m-1). The antenna factor, often known as the open-circuit voltage, is one-half the value given by equation 1.25. We assume that the antenna is parallel to the electric field; in other words, the observed electric field component is the antenna polarisation:

$$\mathrm{AF} = \sqrt{\frac{\eta}{Z_L A_{\mathrm{eff}}}} = \frac{1}{\lambda}\sqrt{\frac{4\pi}{Z_L G}} \tag{1.26}$$

A poor impedance match between the antenna and receiver and any cable loss that lowers the voltage and lowers the computed field strength can both skew this reading[1].

### 1.3.8 Return Loss

It's a setting that specifies how much power is given to the load and then "lost" since it's not reflected back. As a consequence, the RL may be used to assess how closely matched the transmitter and antenna are. In a nutshell, it is an antenna's S11. The return loss curve is a graph that shows the s11 of an antenna as a function of frequency. Such a graph must have a dip at the operating frequency and a minimum dB value at this frequency in order to perform properly[1],[2]. We discovered that changing the antenna size at a particular operating frequency (say, 1.8 GHz) was crucial to our research. Fig. 1.6 depicts the RL curve simply.

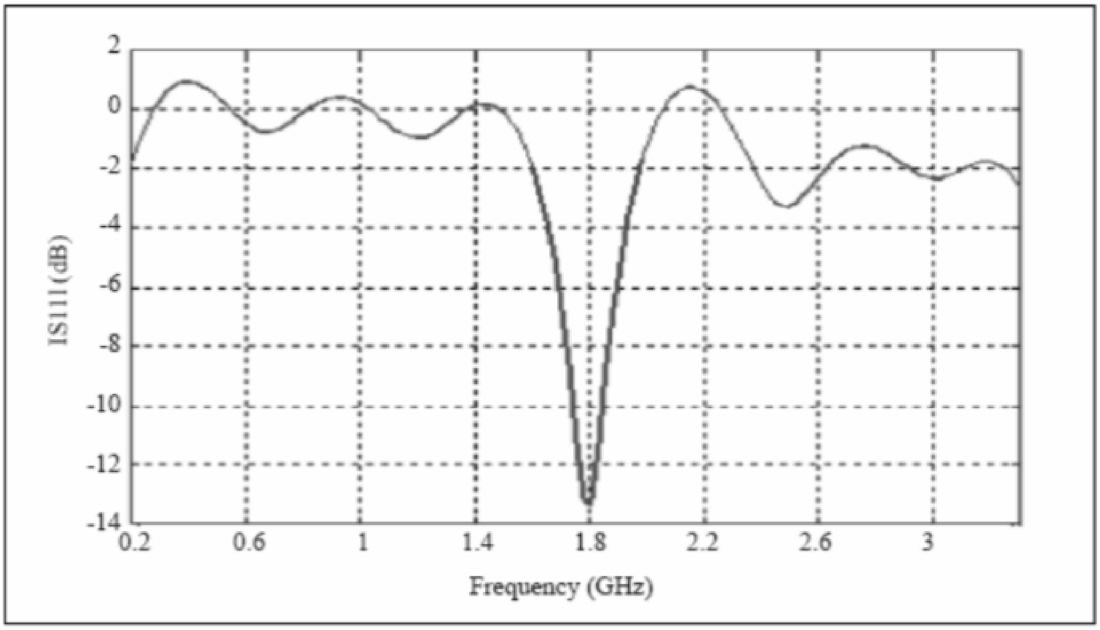



Fig.1.6 Return Loss Curve for an Antenna

### 1.3.9 Radiation Pattern

An antenna radiation pattern depicts the far-field radiation properties of an antenna as a function of the spatial co-ordinates represented by the elevation angle (θ) and azimuth angle (φ). More specifically, it is a plot of an antenna's power emitted per unit solid angle, which is simply the radiation intensity. This 3D graph can alternatively be represented as a 2D polar or Cartesian slice. It is a crucial feature since it displays the antenna's gain and directivity at various positions in space. Because it serves as the antenna's signature, a single glance at it is usually enough to identify the antenna that made it. We needed to properly understand this parameter since it was critical to our software simulations.. The general 3D plot and 2D plot for a rectangular patch antenna are shown below in Fig. 1.7.

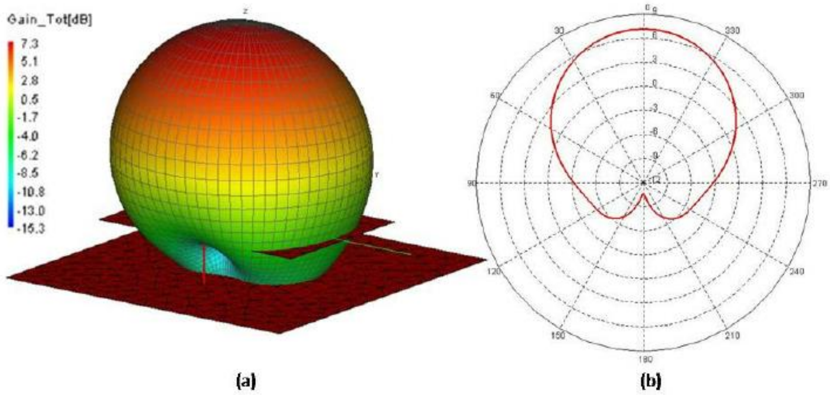



Fig.1.7 Radiation pattern for a Rectangular Patch Antenna

### 1.3.10 Beamwidth

An antenna's beamwidth, which is also a crucial parameter, may be simply estimated from its 2D radiation pattern. The distance between the half-power points of the radiated pattern is measured in beamwidth. Figure 1.8 depicts beamwidth.

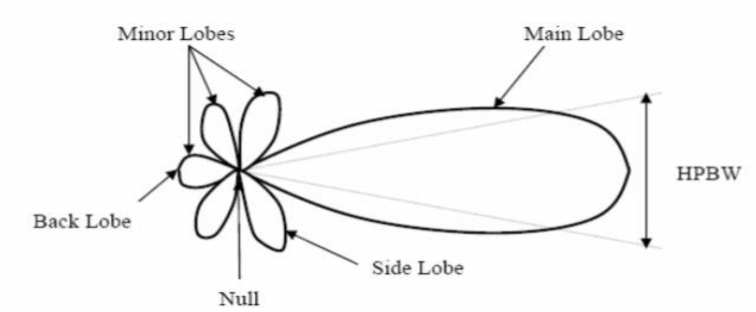



Fig.1.8 Determination of HPBW from radiation pattern

# CHAPTER 2

# RECONFIGURABLE PATCH ANTENNAS

A reconfigurable antenna is one that can alter its frequency and radiation parameters dynamically, controllably, and irreversibly. Reconfigurable antennas include an inner mechanism (such as RF switches, varactors, mechanical actuators, or tunable materials) that allows for the intentional redistribution of RF currents across the antenna surface and produces reversible changes in its properties to provide a dynamic response. Smart antennas use an external beamforming network, whereas reconfigurable antennas use an internal reconfiguration mechanism. Reconfigurable antennas are used to optimise antenna performance in a changing environment or to satisfy changing operating demands[2].

## 2.1 Types of antenna reconfiguration

The operating frequency, radiation pattern, or polarisation are frequently the antenna parameters that may be changed dynamically using reconfigurable antennas.

### 2.1.1 Frequency reconfiguration

Antennas with frequency reconfigurability may alter their operational frequency on the fly. They are especially useful in cases where many communications systems converge because the numerous antennas required may be substituted with a single reconfigurable antenna. To enable frequency reconfiguration, RF switches, impedance loading, tunable materials, or other physical or electrical alterations to the antenna's size are frequently employed[2][3].

### 2.1.2 Radiation pattern reconfiguration

The radiation pattern's reconfigurability is based on the intentional modification of its spherical dispersion. The most sophisticated use, beam steering, involves controlling the greatest radiation direction to maximise antenna gain in a link with mobile devices. Pattern-reconfigurable antennas are often built with switchable and reactively loaded parasitic components or moveable or rotatable structures. Because of its wireless uses, small form factor, and extensive beam steering range, reconfigurable antennas based on metamaterials have sparked attention in the last 10 years. Plasma antennas have also been studied as alternatives with changeable directivities. [4].

### 2.1.3 Polarization reconfiguration

Polarisation reconfigurable antennas can switch between multiple polarisation modes. Polarisation mismatch losses in mobile devices can be decreased by enabling them to switch between horizontal, vertical, and circular polarisations. Polarisation reconfigurability may be achieved by adjusting the balance between the various modes in a multimode structure[5].

### 2.1.4 Compound reconfiguration

Compound reconfiguration refers to the ability to modify numerous antenna parameters at the same time, such as frequency and radiation pattern. To improve spectrum efficiency, frequency agility and beam scanning are typically coupled in compound reconfiguration. Combining numerous single-parameter reconfiguration procedures in the same structure or dynamically rebuilding a pixel surface yields compound reconfigurability.[7].

## 2.2 Reconfiguration techniques

There are several techniques for reconfiguring antennas. They are largely electrical (for example, employing RF-MEMS, PIN diodes, or varactors), optical, physical (mostly mechanical), and material-based. Solid, liquid crystal, or liquid (dielectric liquid or liquid metal) materials may be used in reconfiguration procedures.

# CHAPTER 3

# PAPER 1

The title of the first published paper is "Fox-Face Compound Reconfigurable Antenna for Wireless Systems". A compact multiband Fox-Face compound reconfigurable antenna is proposed in this paper using two PIN diodes. On switching the states of the PIN diodes, the reconfigurable antenna resonates at multiple bands, having one band in each case for which the bandwidth is highest and is considered as the primary band. Primary frequency band is reconfigurable from 5.5GHz (used in 5G services) to 6.7GHz (used in digital high-capacity fixed point-to-point links), while a secondary band is present at around 9GHz (used in satellite and military applications) in all the four configurations possible in the design.

## 3.1 Introduction

Microstrip patch antennas are gaining popularity as more and more advancements are made in the wireless communication systems. They are being used in multiple fields and the scope of research and improvements is quite high in this area. A simple patch antenna is designed to work for only a single application, having frequency of operation within a certain frequency band range but a reconfigurable antenna enables us to reconfigure this frequency band based on our different requirements[2]. It is possible to reconfigure different functionalities of an antenna, such as frequency[3], polarization[4],[5], radiation pattern, bandwidth etc[6]. A simple designing methodology for a reconfigurable antenna include using RF switches in the antenna design[6].

The reconfigurable antenna proposed here, is made quite compact and only 2 PIN diodes were used. The proposed design is a Compound reconfigurable antenna (CRA), capable of reconfiguring multiple characteristic parameters of the antenna, which gives it more advantages over a single parameter specific reconfigurable antenna.

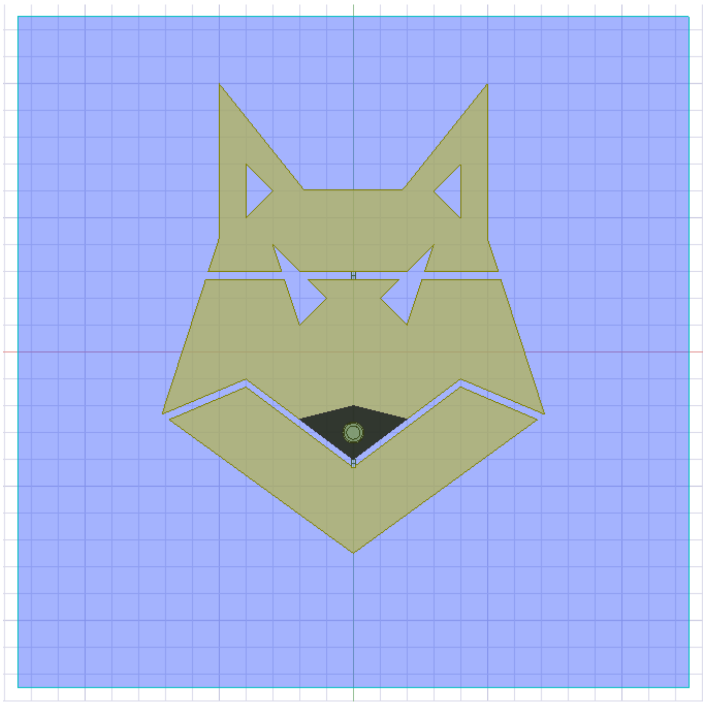
Reconfigurable antenna designs performing frequency reconfiguration are reported in [3], operating only for a single band with tunable frequency, while only polarization reconfiguration designs are reported in [4] and [5] over a single fixed frequency band. The design that was reported in [6], reconfigure the bandwidth of the proposed antenna with other characteristics remaining the same.

Very few designs such as the one that is reported in [6] is capable of acting as a CRA, making use of PIN diodes and reconfiguring frequency as well as polarization using a single structure, but the number of PIN diodes used is still a lot, contributing to increase in fabrication complexity and cost especially when biasing circuitry is taken into consideration.

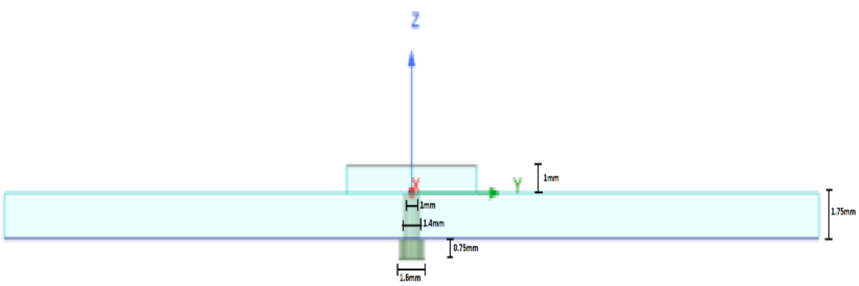
This paper proposes a simple and compact multiband CRA antenna structure. Two PIN diodes are utilized here in the antenna, making four different cases possible on switching the biasing across the two diodes. With authors' best cognition, this is the first co-axially fed compact multiband CRA using two PIN diodes, having the ability to reconfigure frequency, polarization, radiation pattern and gain together in a single design.

## 3.2 ANTENNA STRUCTURE

Fig.3.1 presents the structural design of the antenna. An FR-4 substrate of thickness 1.75 mm, dielectric constant ($\varepsilon_r$) 4.4 and loss tangential (tan $\delta$) 0.02 is mounted over a metallic ground plane. A pentagon patch structure is then constructed over the substrate at the middle using the Ansys HFSS software. Two triangles are added to the patch at the upper edge of the pentagon to maintain symmetry of the patch. Four triangular slots are made in the patch structure. The patch is divided into three uneven parts, where the PIN diodes D1 and D2 connect top part and bottom part respectively to the central part of the patch. A co-axial method of feeding is given to the central part of the patch. Over the patch where the feed reaches, an FR4 substrate of thickness 1mm shaped like kite is mounted, followed by another patch over the newly added substrate. The antenna so designed gives it a Fox-face like look.

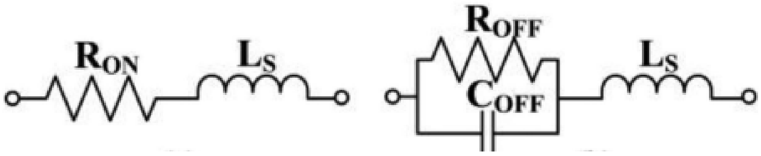


(i)




(ii)

Fig.3.1. Design of the Fox-face CRA displaying (i) top and (ii) side view.



(i) (ii)

Fig.3.2. Circuit equivalence of the PIN diodes in (i) ON state and (ii) OFF state. For which, $R_{ON}$ = 5 Ω, $L_S$ = 0.5nH, $R_{OFF}$ = 5 kΩ and $C_{OFF}$ = 0.2 pF for both D1 and D2.

The design employs two PIN diodes, namely D1 and D2. The reason for utilizing PIN diodes is that they can be utilized as switches, i.e., ON state or OFF state is attained by the diodes based on the biasing given to the diode. The comparable circuit diagram of the PIN diodes in displayed in Fig.3.2[7].

The proposed design of the antenna is capable of reconfiguration to resonate at different frequencies because the pentagon shaped patch is divided into three segments and these segments are connected to each other using PIN diodes. In different configurations, different combinations of joining these patch segments via PIN diodes results in different resonating patches, which have different shapes and sizes. In designing the patches, the size of the patch suitable for resonating at frequency of interest is determined using the formulas for rectangular patch or circular patch[1] as per which shape is closest to the proposed patch shape. To the best of authors' knowledge, there no other patch shape specific general formulas.

In the proposed design the formulas for both rectanguar patch as well as circular patch are utilised as in different cases, the resonating patch shape is different and then some approximation is done for design convenience. The thickness of the substrate, h is very small compared to wavelength($\lambda_0$) of resonate frequency($f_{rc}$) i.e. $h<0.05\lambda_0$, so the following formulas for first dominant mode for patch can be considered[1].

For rectangular patch:

$$W = \frac{1}{2f_{rc}\sqrt{\mu_0\varepsilon_0}}\sqrt{\left(\frac{2}{\varepsilon_r+1}\right)} = \left(\frac{\upsilon_0}{2f_{rc}}\right)\sqrt{\left(\frac{2}{\varepsilon_r+1}\right)} \quad (3.1)$$

$$L = \frac{1}{2f_{rc}\sqrt{\varepsilon_{reff}}\sqrt{\mu_0\varepsilon_0}} - 2\Delta L \tag{3.2}$$

$$L \approx \frac{(0.47 - 0.49)\lambda_0}{\sqrt{\varepsilon_r}} = (0.47 - 0.49)\lambda_d \tag{3.3}$$

where W is the width of patch, L is length of patch, $v_0$ is speed of electromagnetic wave in free space, ΔL is extension length and $\lambda_d$ is wavelength in dielectric.

For circular patch:

$$(f_{rc})_{110} = \frac{1.8412\upsilon_0}{2\pi a_e\sqrt{\varepsilon_r}} = \frac{8.791 \times 10^9}{(a_e\sqrt{\varepsilon_r})} \tag{3.4}$$

$$a = \frac{F}{\left\{1 + \left(\frac{2h}{\pi\varepsilon_r F}\right)\left[\ln\left(\frac{\pi F}{2h}\right) + 1.7726\right]\right\}^{1/2}} \tag{3.5}$$

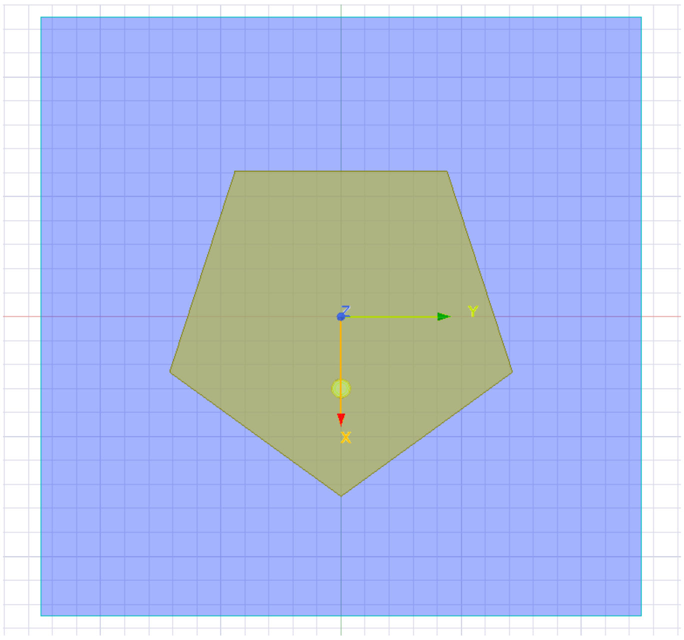
where,

$$F = \frac{8.791 \times 10^9}{(f_{rc}\sqrt{\varepsilon_r})} \tag{3.6}$$

where $f_{rc}$ resonant frequency is traveling at speed of light, $v_0$=c; $a_e$ is the effective radius of patch and a is actual radius of patch.

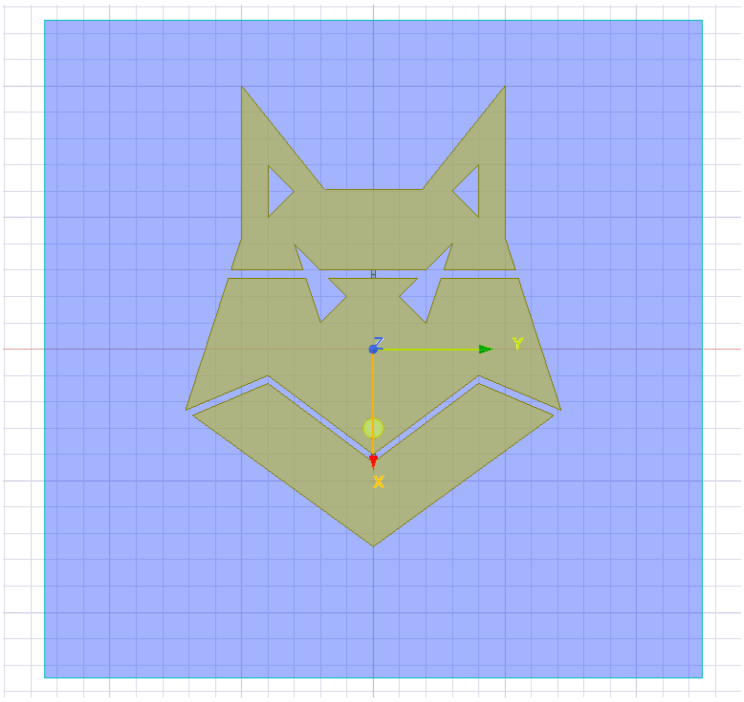
## 3.3 DESIGNING STEPS AND ASSESSMENT

The designing procedure for the proposed CRA is split into 4 steps which are represented in the Fig.3.3.

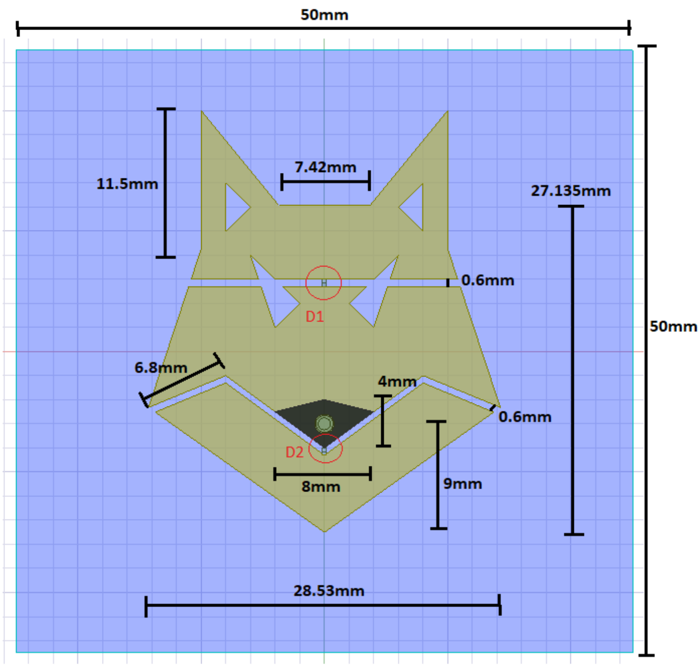



(i)


(ii)



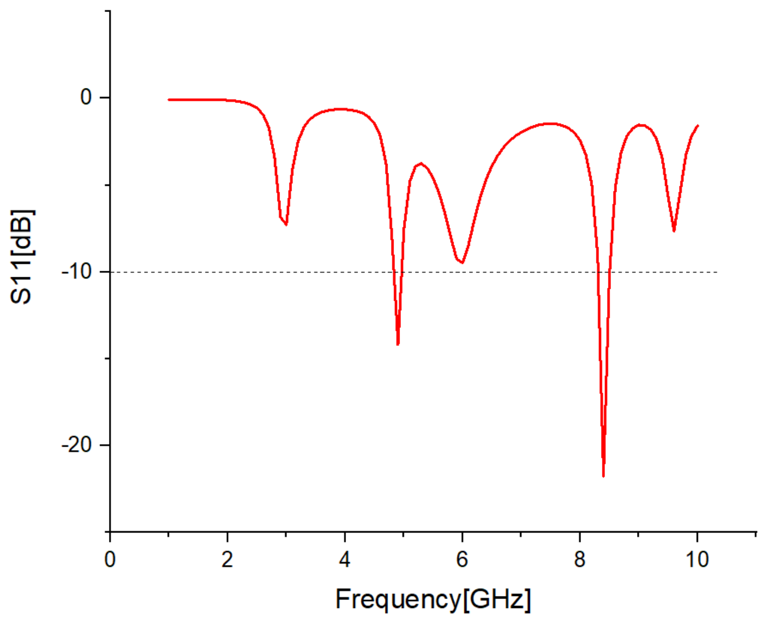

(iii)



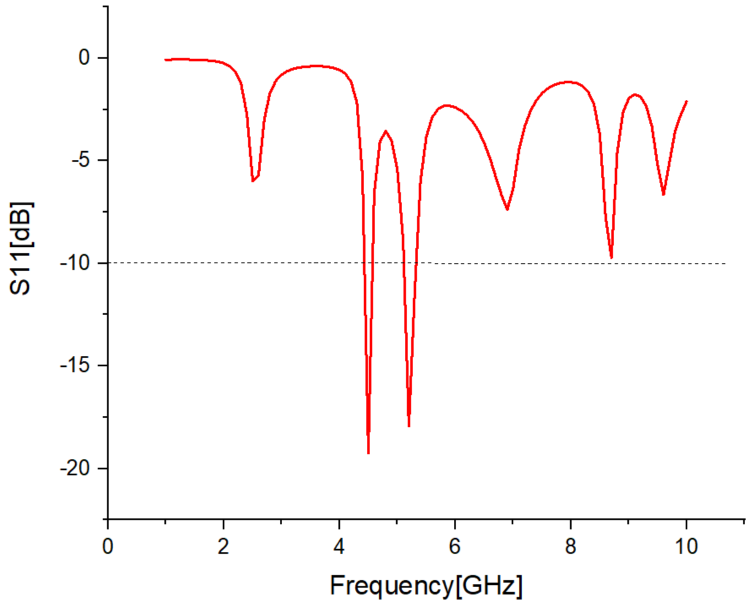

(iv)

Fig.3.3. Structural steps in designing Antenna: (i) Pentagon patch, (ii) Patch with slots, (iii) Reconfigurable patch and (iv) Final design

As seen in the Fig.3.3.(i), the first step involves making a normal patch antenna in the shape of a pentagon at the center of the substrate with co-axial type of feeding given to antenna. The problem with this design were that the antenna was not reconfigurable nor it gives good gain at the frequency of interest as shown in Fig.3.4.(i). To improve the design and still keep the structure symmetrical, two triangular structures are added along with adding slots in the design to increase the bandwidth and shift the frequency of resonance as seen in Fig.3.3.(ii). This new structure enables the antenna to resonate at around 5GHz frequency but it still lacks reconfigurability, as represented in Fig.3.4.(ii). To make this structure reconfigurable, passages were to be created to the design along with incorporating PIN diodes in the design; this is achieved in the structure shown in Fig.3.3.(iii). This structure seemed to give good gain and bandwidth at the frequencies of interest when operated with both the diodes (D1 and D2) in ON state but lack this efficiency when one of the diodes is switched OFF which can be seen in Fig.3.4.(iii) and (iv). The final design includes an additional kite structure mounted over the patch structure over the region where the antenna gets co-axial feed as in Fig.3.3.(iv). This structure is the final design for the proposed CRA.

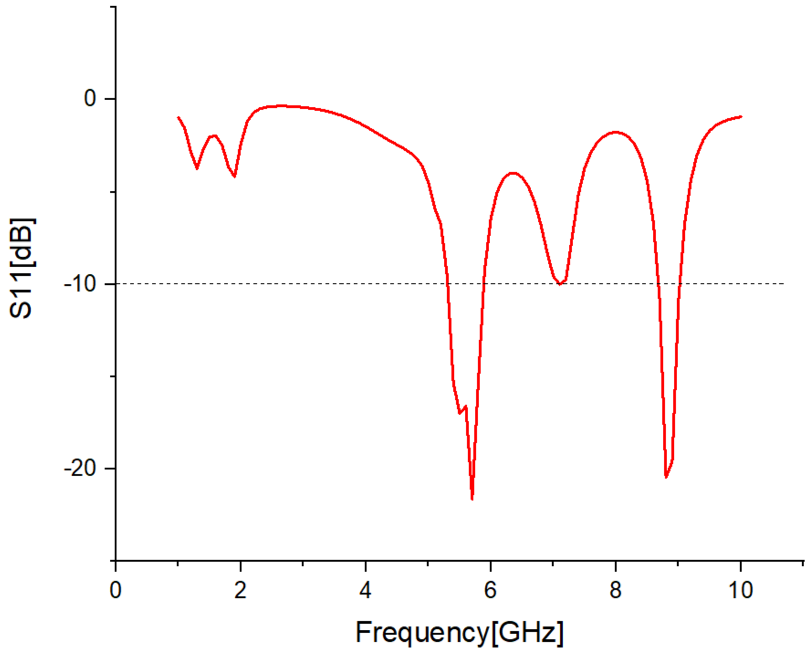



(i)



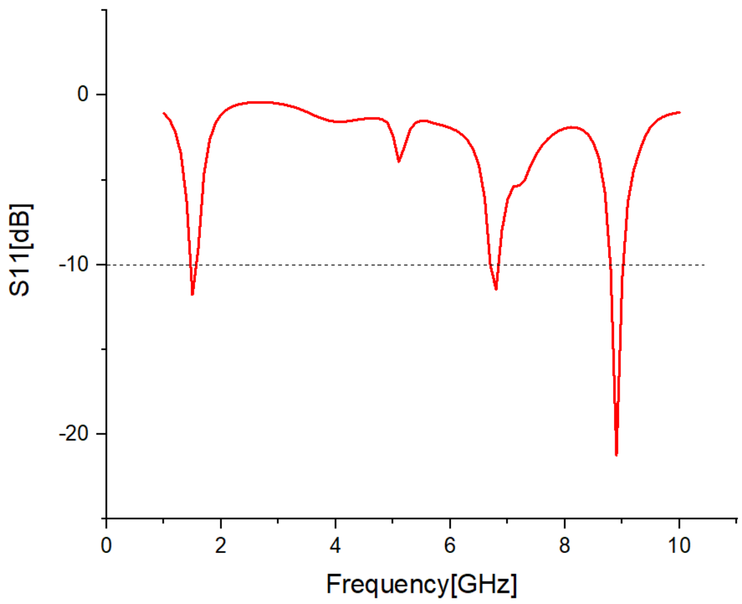
S11[dB]
0
-5
-10
-15
-20
0
2
4
6
8
10
Frequency[GHz]


(ii)



S11[dB]
0
-10
-20
0
2
4
6
8
10
Frequency[GHz]


(iii)




(iv)

Fig.3.4. $S_{11}$ plot at each structural step: (i) Pentagon patch, (ii) Patch with slots, (iii) Reconfigurable patch with both D1 and D2 in ON state and (iv) Reconfigurable patch with one PIN diode in OFF state.

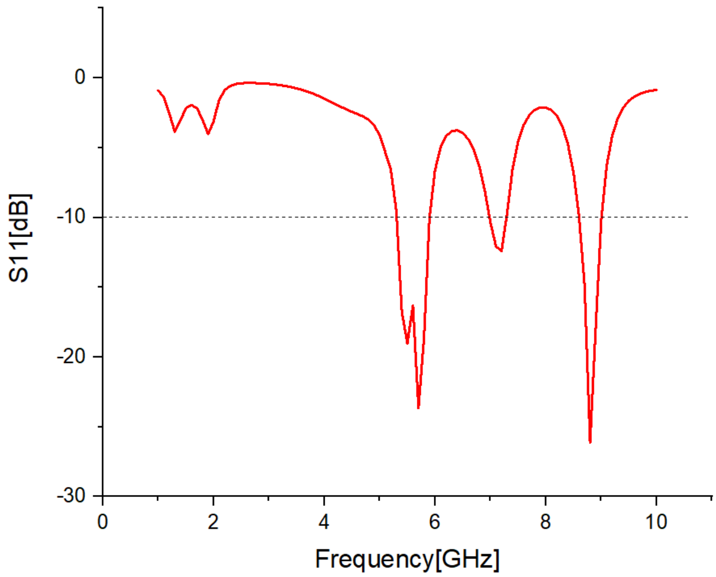
## 3.4 RESULT ANALYSIS

The Fox-face CRA so designed was then analyzed using the Ansys HFSS software and the radiation patterns so plotted were based on the gain frequencies as observed by the respective $S_{11}$ plots for each state. Table 3.1 shows the plotting frequency in each case.

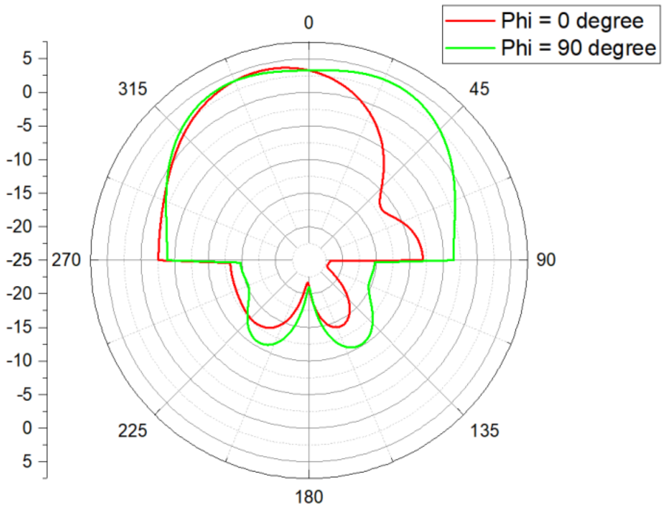
TABLE 3.1 OPERATING FREQUENCY IN EACH CASE

| Case | Diode 1 D1 | Diode 2 D2 | Frequency of operation (in GHz) |
|---|---|---|---|
| 1 | ON | ON | 5.5 |
| 2 | ON | OFF | 6.7 |
| 3 | OFF | ON | 9.1 |
| 4 | OFF | OFF | 9.1 |

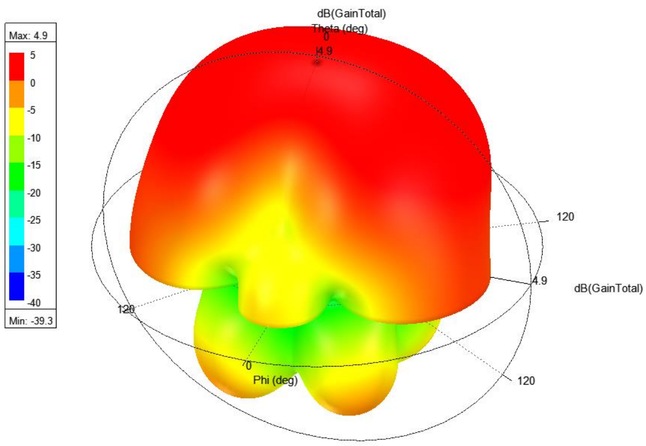
For case 1, when D1 and D2 both are in ON state, the S11 plot of the CRA has three bands for which the band having the highest bandwidth is considered as the primary band, with the central frequency at about 5.5GHz as shown in Fig.3.5(i). On plotting the 2D and 3D radiation plots at this centralized frequency, Fig.3.5(ii) and (iii), the CRA radiation pattern is single lobed unidirectional with slight oriented towards left side.




(i)



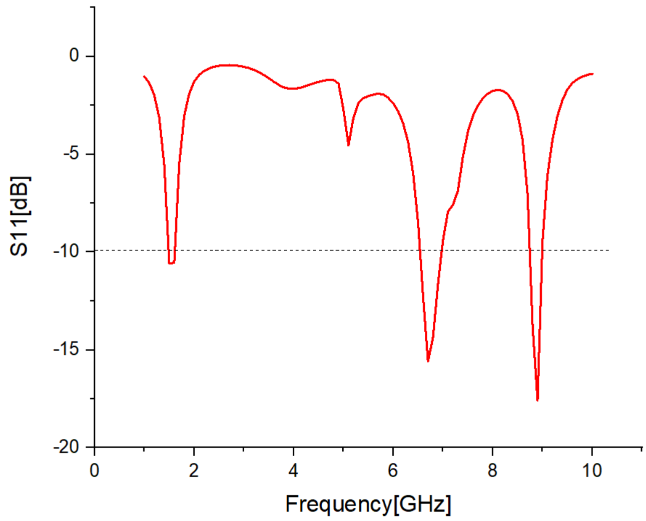

(ii)



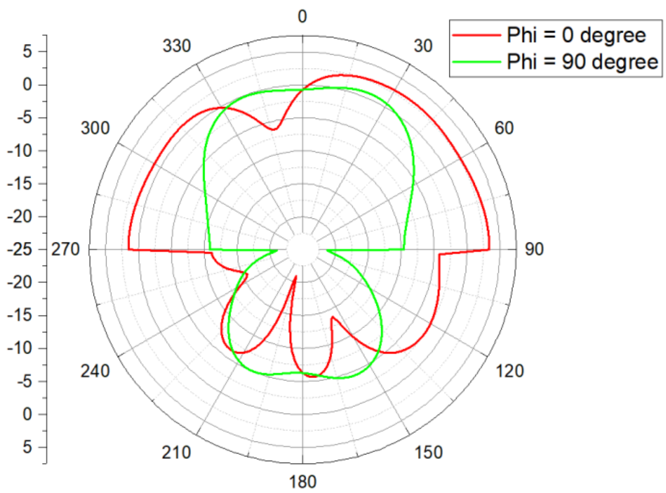

(iii)

Fig.3.5. Plots for case 1: (i) S11 plot, (ii) 2D plot and (iii) 3D plot

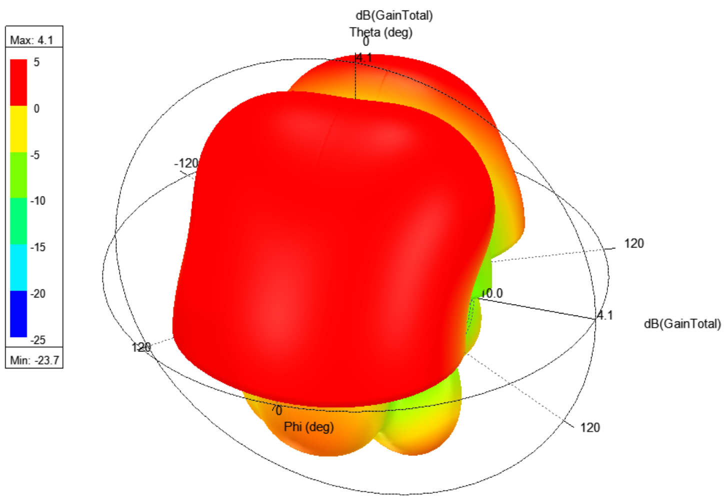
For case 2, when D1 is in ON state and D2 is in OFF state, the S11 plot of the CRA has three bands for which the primary band has the central frequency at about 6.7GHz as shown in Fig.3.6(i). On plotting the 2D and 3D radiation plots at this centralized frequency, Fig.3.6(ii) and (iii), the CRA radiation pattern is unidirectional with 2 fused lobes and are slightly oriented towards right side. The CRA here has displays frequency, radiation and rotational reconfigurable properties.


S11[dB]
0
-5
-10
-15
-20
0
2
4
6
8
10
Frequency[GHz]

(i)


Phi = 0 degree
Phi = 90 degree
0
30
60
90
120
150
180
210
240
270
300
330
5
0
-5
-10
-15
-20
-25
-20
-15
-10
-5
0
5

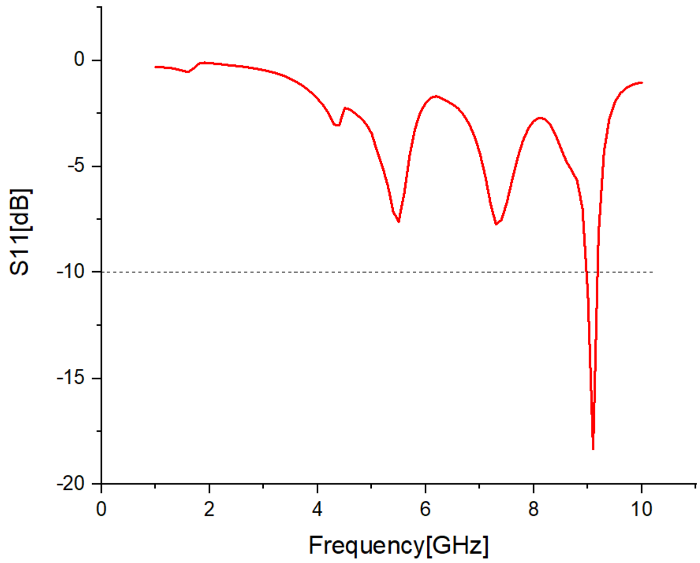
(ii)


dB(GainTotal)
Theta (deg)
Max: 4.1
5
0
-5
-10
-15
-20
-25
Min: -23.7
-120
120
120
dB(GainTotal)
120
Phi (deg)

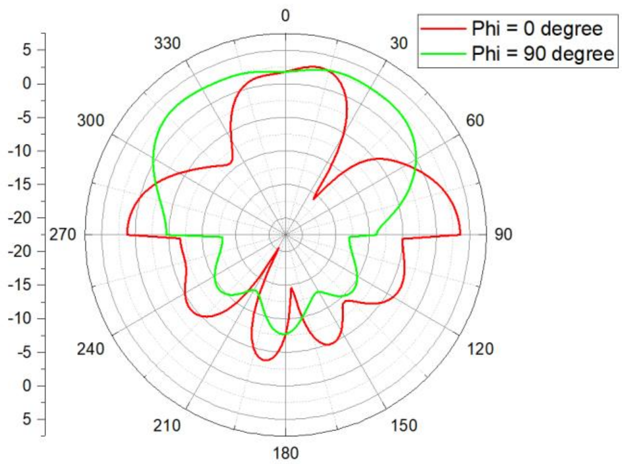
(iii)

Fig.3.6. Plots for case 2: (i) S11 plot, (ii) 2D plot and (iii) 3D plot

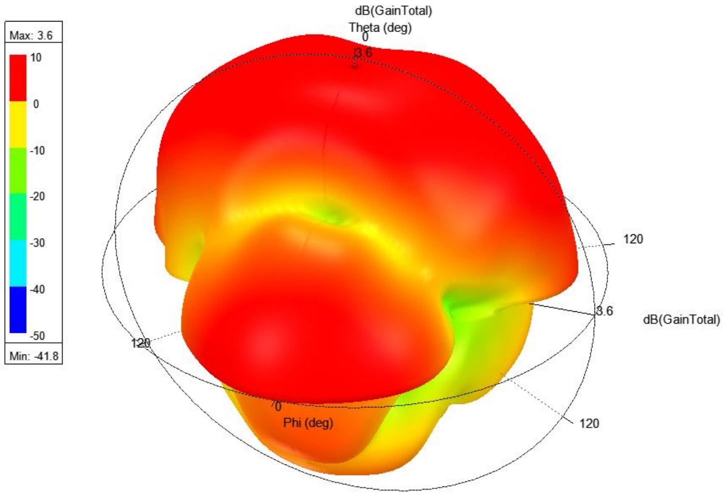
For case 3, when D1 is in OFF state and D2 is in ON state and for case 4, when both D1 and D2 are in OFF state, the results are very similar except for the fact that case 3 provides higher gain as compared to case 4. The plots of the CRA in both cases 3 and 4 are displayed in Fig.3.7 and Fig.3.8 respectively. It is observed that in both cases, there is only one band in S11 plot which is centralized around 9.1GHz frequency and the radiation patterns for the cases are omnidirectional and multilobed distorted.




(i)



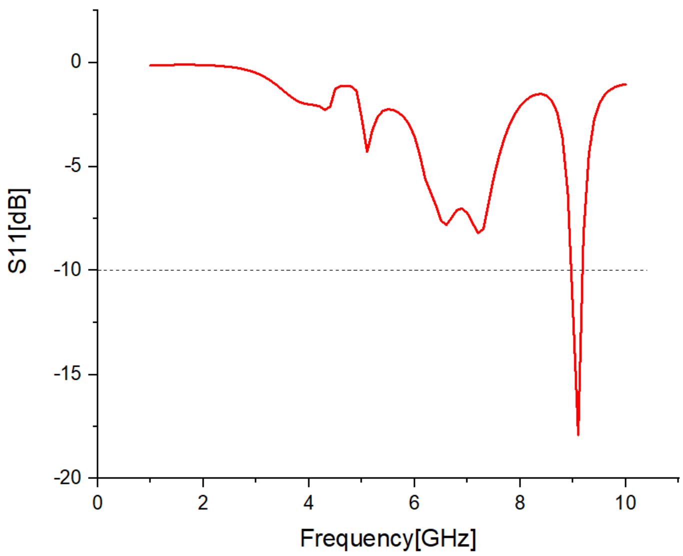

(ii)



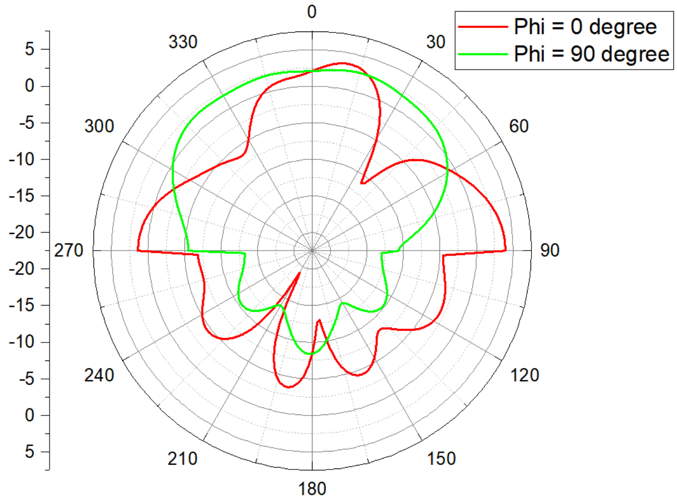

(iii)

Fig.7. Plots for case 3: (i) S11 plot, (ii) 2D plot and (iii) 3D plot

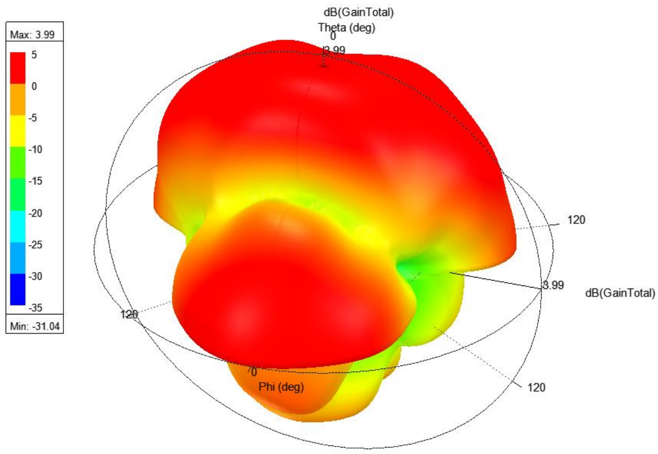
It is observed on changing the biasing across D1 and D2 that when we change the state from case 1 to case 2, there is a reconfiguration of frequency and radition pattern. On changing state from case 2 to case 3, reconfiguration of frequency bandwidth and polarization is observed. Whereas, on shifting the state from case 3 to case 4, reconfiguration of antenna gain occurs. Each change in state results in different functionality reconfiguration for the proposed CRA.




(i)




(ii)




(iii)

Fig.3.8. Plots for case 4: (i) S11 plot, (ii) 2D plot and (iii) 3D plot

Table 3.2. below provides the comparison between the proposed Fox-face CRA and prior existing works.

TABLE 3.2 COMPARISON WITH PRIOR EXISTING WORKS

| **Reference** | **Type of Reconfiguration** | **Number of diodes used** |
|---|---|---|
| [3] | Frequency | 7 |
| [4] | Polarization | 2 |
| [5] | Polarization | 4 |
| [6] | Bandwidth | 4 |
| [7] | Compound | 7 |
| This work | Compound | 2 |

## 3.5 CONCLUSION

This paper presents a multi-band Compound Reconfigurable Antenna (CRA) that has a compact structure and is designed with only two PIN diodes. The cases depicted in the paper for this Fox-face CRA shows that because of the effective bandwidths being at around 5.5GHz, 6.7GHz and 9.1GHz, the design finds its application in the fields of 5G services (5.5GHz)[8]–[10], digital high-capacity fixed point-to-point links (6.7GHz)[8], [11] and satellite and military applications (9.1GHz)[12]. This may be relevant in MIMO utility wherein spectral performance may be increased via way of means of making use of pattern and polarization reconfigurability. For cognitive radio systems too this proposed antenna can be utilized where a frequency reconfigurable antenna is needed after sensing the idle band in the wide frequency spectrum[13].

# CHAPTER 4

# PAPER 2

The title of the first published paper is “Bandwidth Reconfigurable Wideband Antenna with comparison between PIN diodes and Vanadium Dioxide switches”. A wideband microstrip patch antenna design is proposed in this paper having resonant frequency at around 5GHz and capability of bandwidth reconfiguration. The proposed design is a compact bidirectional wideband antenna having wideband starting frequency at around 5GHz and keeping the design simple, provides a high reconfigurability of bandwidth from 0.8GHz to 3.63GHz as the states of the antenna are switched. In this design only two PIN diodes are used to achieve bandwidth reconfiguration and the same design is also tested by replacing the PIN diodes with Vanadium dioxide(VO2) switches to check their compatibility with the designed antenna and see if same results could be achieved with the same.

## 4.1 Introduction

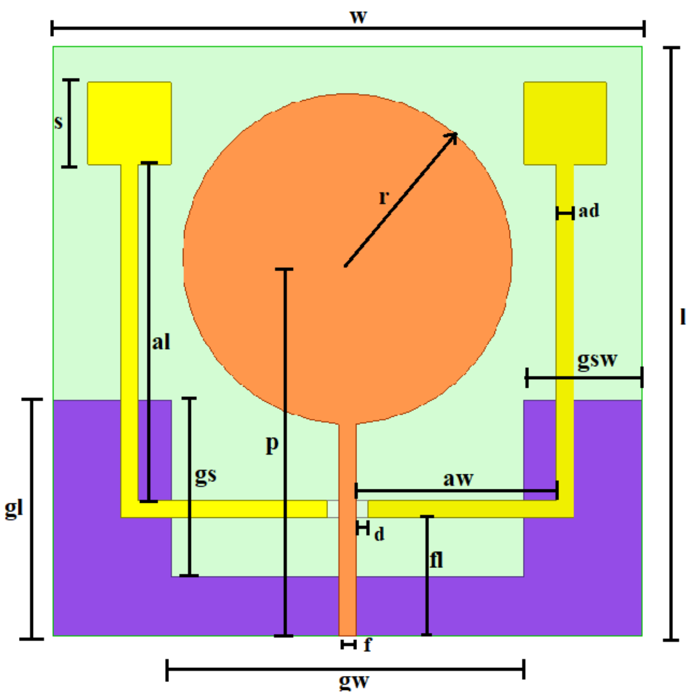
Microstrip patch antennas are getting large number of applications in various fields for the advantages they offer such as small size, light weight and volume, low manufacturing cost etc. But some disadvantages that are of high concern are also encountered such as lower gain and bandwidth with the usage of microstrip patch antennas[1]. Researches have made efforts to tackle these shortcomings and designed antennas to both increase the gain and the bandwidth at the resonant frequencies for the patch antenna. The design proposed here offers a wideband at the resonant frequency of

5GHz. It is not much feasible to design a specific antenna for performing a specific task so researches have made efforts to make these microstrip antennas as reconfigurable[2], making it possible for us to reconfigure the frequency range[3], radiation pattern[14], polarization[4][15], gain and bandwidth[16][17] of the antenna that we have. To make an antenna reconfigurable, switching mechanism is included in the design of the antenna for making the antenna switch its states and give different outcomes in different cases, thus achieving reconfigurability. The need for increasing or decreasing the bandwidth can occur anytime when different tasks and loads at hand have different bandwidth requirement. Most reconfigurable antennas that we encounter offer frequency reconfiguration[3] or radiation pattern reconfiguration[14]. Not much work, as per authors' knowledge has been done in the field of bandwidth reconfiguration, and that too especially at around 5GHz frequency, which is a frequency range of importance in today's times for a better and higher speed Wi-Fi service[8]–[10]. The bandwidth reconfigurable antennas research works [16][17] that are available usually have a very complex structure and adds up into the difficulty in fabricating the device. Common practice to make microstrip antenna reconfigurable is to either use a PIN diode or a varactor diode, which both require a biasing circuitry so that the states of the diodes in use can be changed for achieving different working states for the antenna and thus, achieving reconfiguration. But this methodology adds up into the complexity in fabrication of the antenna. The antenna design proposed in this paper presents a simpler design for a bandwidth reconfigurable antenna at around 5GHz frequency range using only two PIN diodes. The design is also tested for replacing the PIN diodes with VO2 switches[18], which are thin film temperature based switches on which not much work based on authors' knowledge has been published[18]–[21]. VO2 switches provide the advantage over diode based switches in reducing the complexity of the structure, by not restricting the antenna reconfiguration on biasing circuitry such as stubs, capacitors and inductors that are needed to be soldered to the antenna design, touching the radiating surfaces[18]. The methods that could be used for VO2 switches tuning are conductive heating, Joule heating, using photothermal techniques, voltage biasing, and ultrafast optical excitation [18], providing the advantage of flexibility in design based on the tuning mechanism that we utilize.

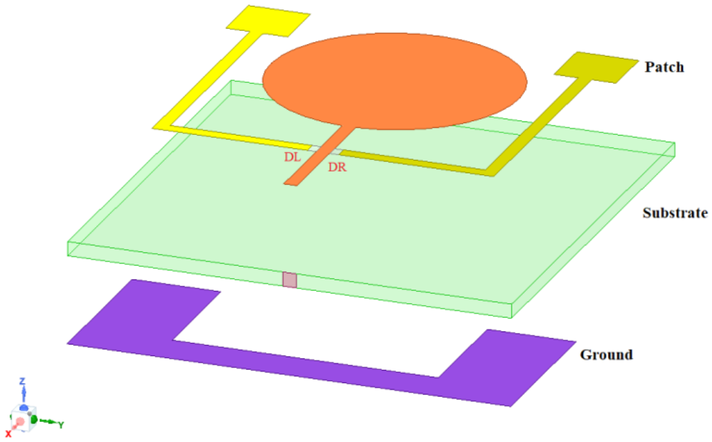
## 4.2 ANTENNA DESIGN

### 4.2.1 BASIC VISUALIZATION

The designing of the proposed structure of the bandwidth reconfigurable antenna is done using the Ansys HFSS software. As seen in Fig.4.1. the antenna is designed by mounting an FR-4 epoxy substrate of dielectric constant of 4.4 over a metallic ground plane. The ground plane does not cover the entire back of the substrate material and it is slotted too. Over the substrate at front, a circular patch structure made up of metal is imposed, along with two side rectangular reflecting patches. Using the line feed feeding technique, strips of metal are imposed and fused with these patch structures on the substrate as seen in Fig.4.1. At the junction of the strips connecting the side patches to the central feed line, at both sides separation is done for connecting the PIN diodes/switches there. By changing the biasing across these PIN diodes, DL and DR, the states of the antenna are changed to have bandwidth reconfiguration. The dimensions associated with the designing of this antenna structure are presented in Table 4.1.




(i)




(ii)

Fig.4.1. Design of the Bandwidth Reconfigurable Antenna displaying (i) top and (ii) 3D view.

### 4.2.2 CALCULATED PARAMETERS

For designing the structure of the basic antenna with circular patch, first the fixed values of substrate height h and the frequency of resonance i.e. 5GHz were considered for making calculations. Since substrate height h is very small with $h<0.05\lambda_0$, the formula for first dominant mode for circular patch can be applied as in [1]:

$$(F_{rc})_{110} = \frac{1.8412\upsilon_0}{2\pi a_e\sqrt{\varepsilon_r}} = \frac{8.791\times10^9}{(a_e\sqrt{\varepsilon_r})} \tag{4.1}$$

where $f_{rc}$ is resonant frequency traveling at speed of light, $v_0=c$; $a_e$ is the effective radius of patch and $\varepsilon_r$ is the dielectric constant. Based on this, we can further find the actual radius of circular patch required as:

$$a = \frac{F}{\left\{1+\left(\frac{2h}{\pi\varepsilon_r F}\right)\left[\ln\left(\frac{\pi F}{2h}\right)+1.7726\right]\right\}^{1/2}} \tag{4.2}$$

where,

$$F = \frac{8.791 \times 10^9}{(f_{rc}\sqrt{\varepsilon_r})} \quad (4.3)$$

The side patches, the positioning of connecting feed lines and the slot in the ground plane were made based on approximate effective wavelength value and multiple design changes and respective simulations of results. This made the antenna to continue to resonate at around the resonant frequency of 5GHz while serving the purpose of a bandwidth reconfigurable antenna.

Table 4.1. Design parameters measurement values

| Parameter | Value (in mm) | Parameter | Value (in mm) |
|---|---|---|---|
| w | 50 | gs | 15 |
| l | 50 | gsw | 10 |
| h | 1.6 | al | 28.5 |
| r | 14 | aw | 17 |
| s | 7 | ad | 1.5 |
| p | 32 | f | 1.5 |
| gl | 20 | fl | 10 |
| gw | 30 | d | 1 |

### 4.2.3 DESIGN CHANGES FOR TESTING VANADIUM DIOXIDE SWITCH AS ALTERNATIVE FOR PIN DIODES

The bandwidth reconfigurable antenna design proposed here is having a separation of 1mm at the junctions where the feed lines for the side patches and connecting to the central feed line for the circular main patch. This separation is done to connect the PIN diodes there as per our main design.

When we happen to test for having the $VO_2$ switch in place of the PIN diodes in the design we have to consider that $VO_2$ is a thermal based thin film that changes its solid state properties when the temperature is increased for over 68°c. In the design, the thickness of this layer is kept variable to check the thickness at which $VO_2$ layer can be utilized as a switch for replacing the PIN diodes in this structure to achieve similar results of making the antenna bandwidth reconfigurable. The equivalent circuit model and respective resistance, capacitance and inductance values of $VO_2$ switch are presented in [22] and are considered for the design as in Fig.4.3.

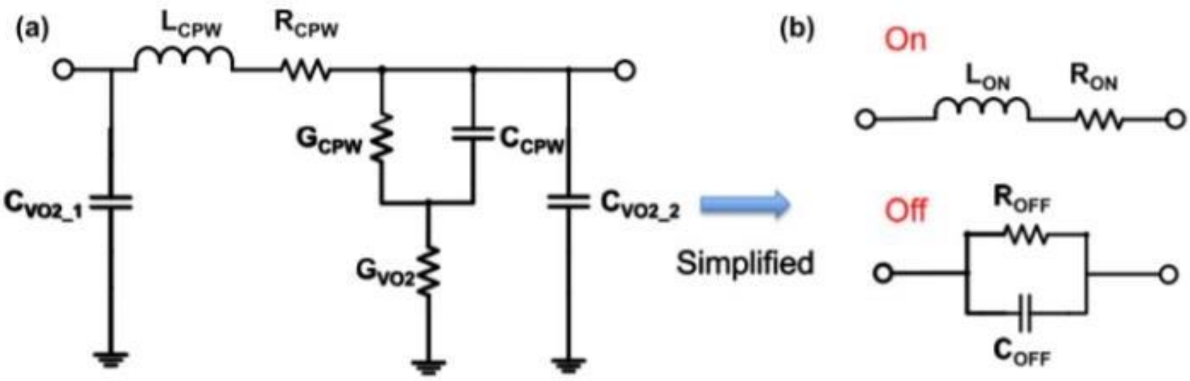



Fig.4.2. Equivalent circuit for VO2 switch, where RON = 1.2 Ω, LON = 80pH, ROFF = 480Ω and COFF = 7 fF.

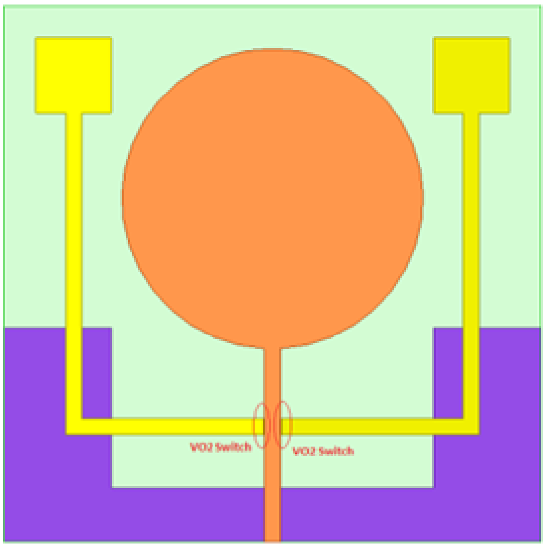



Fig.4.3. Placement of VO2 switches in place of PIN diodes at the junction of side patches feed lines with central feed line.

## 4.3 RESULTS

### 4.3.1 SELECTION OF PIN DIODE

The results for the S11 plots for the three different PIN diodes, operated for the case when both DL and DR are in ON state are presented in Fig.4.4. The objective for this stage of observation was to find the PIN diode that is best suited for being used in the design of the bandwidth reconfigurable antenna proposed here, by providing highest bandwidth result as compared to other PIN diodes and operating at resonant frequency of 5GHz. The plot shows that type MA4SPS402[23] PIN diode, which has equivalent forward resistance as R=5ohm and reverse capacitance as C=0.045pF is best suited and provides greater bandwidth than the other two PIN diodes models of which second model has equivalent forward resistance as R=5ohm and reverse capacitance as C=0.28pF and model third of type MADP-042505-13060[24] has equivalent forward resistance as R=0.83ohm and reverse capacitance as C=0.28pF.

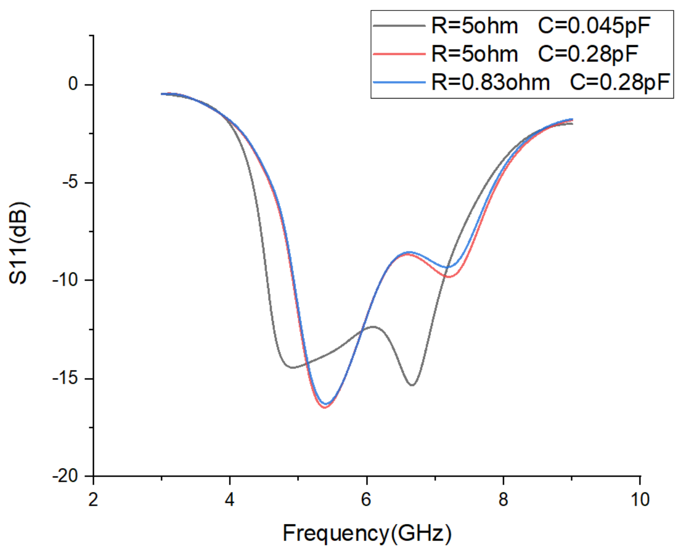



Fig.4.4. S11 plot comparison of the three PIN diode models for the case when DL=ON and DR=ON.

For the PIN diode model MA4SPS402 selected for the design, the equivalent circuit is represented in Fig.4.5.

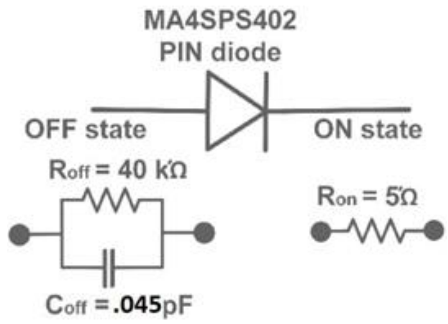



Fig.4.5. Equivalent circuit for MA4SPS402 PIN diode model.

### 4.3.2 BANDWIDTH RECONFIGURATION RESULTS

When the type MA4SPS402 PIN diode model is finalized for the design, the structure was then simulated and all four different operational cases for the antenna were observed to check for bandwidth reconfiguration. The Fig.4.6. below presents the S11 plots at the respective four cases, switching the PIN diodes at DL and DR as ON or OFF.

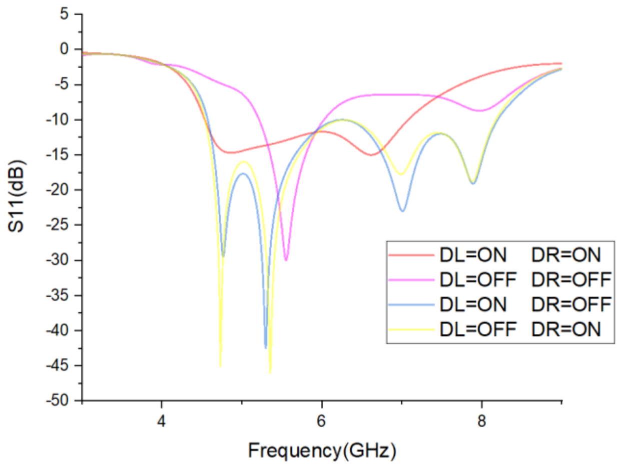
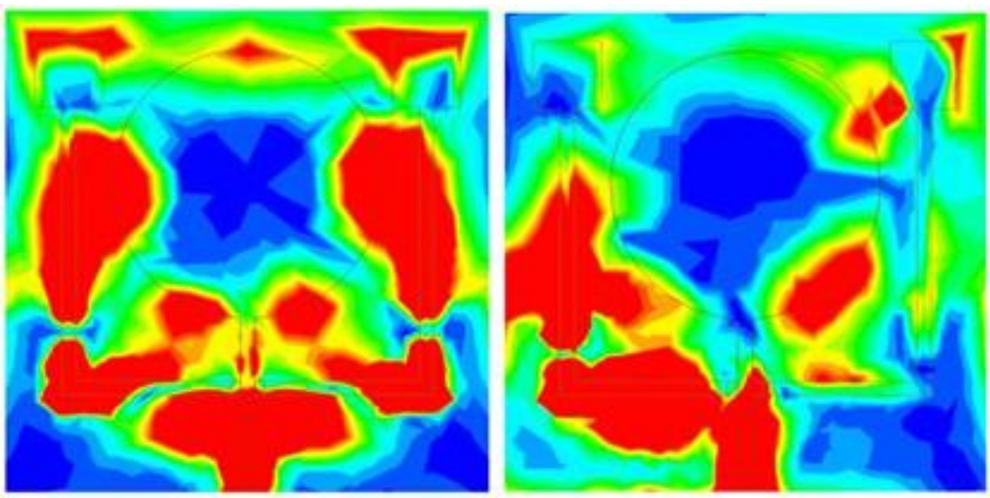
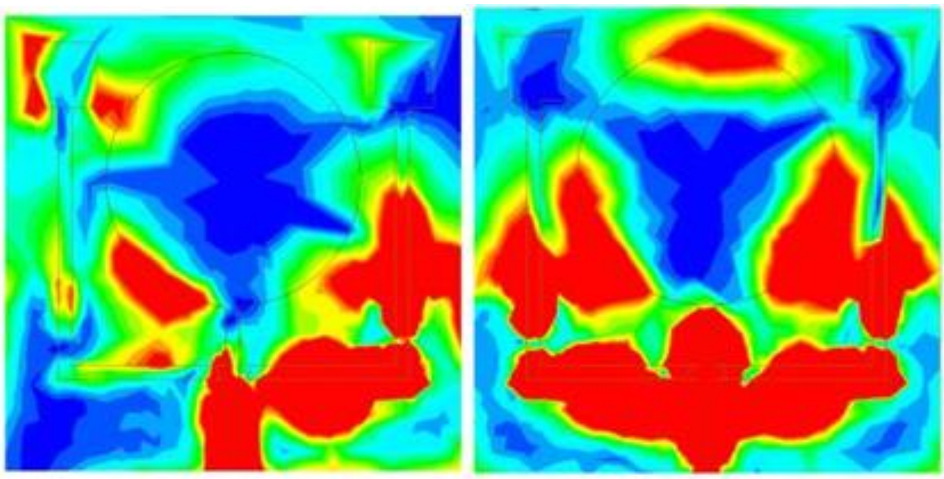



Fig.4.6. S11 plot of the bandwidth reconfigurable antenna using two PIN diodes on switching the PIN diodes DL and DR as ON or OFF.

The surface current for all the four different cases represents the working of the antenna in each case after feed was given as shown in Fig.4.7. The surface current is more towards area where the diode is switched ON. To find the radiation patterns, gain and polarization in all the four different states, gain plots for the design were simulated and the results are displayed in Fig.4.8. below. As evident from the gain patterns, the proposed design is a bidirectional antenna and the radiation patterns continue to have about symmetrical pattern and gain at the top and bottom side of the antenna about 5dB at 5GHz in all cases. Though when we switch either of DL or DR as ON and other as OFF, a lower gain side radiation lobe in opposite side of the side patch connected to feed line can be observed, which is due to the side patches acting as reflecting elements in the design. This is further evident from Fig.4.8.(iv) as when both DL and DR are switched OFF, the side patches are not connected to the feeding line and thus, somewhat distorting the shape of radiation pattern on both sides.

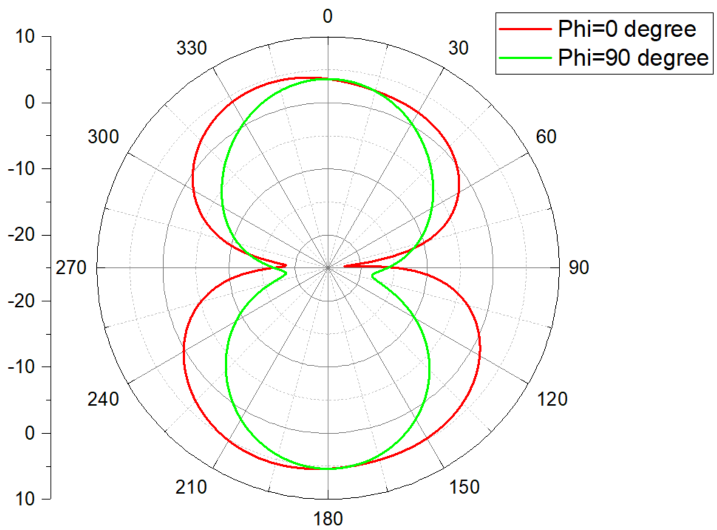


(i) (ii)

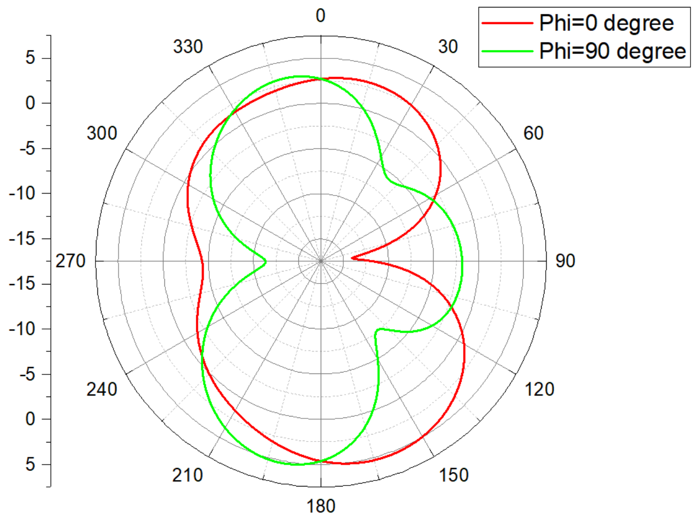


(iii) (iv)

Fig.4.7. Surface current of the bandwidth reconfigurable antenna using two PIN diodes on switching the PIN diodes DL and DR as ON or OFF: (i) DL=ON and DR=ON, (ii) DL=ON and DR=OFF, (iii) DL=OFF and DR=ON, (iv) DL=OFF and DR=OFF




(i)


Phi=0 degree
Phi=90 degree
0
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60
90
120
150
180
210
240
270
300
330
5
0
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-15
-15
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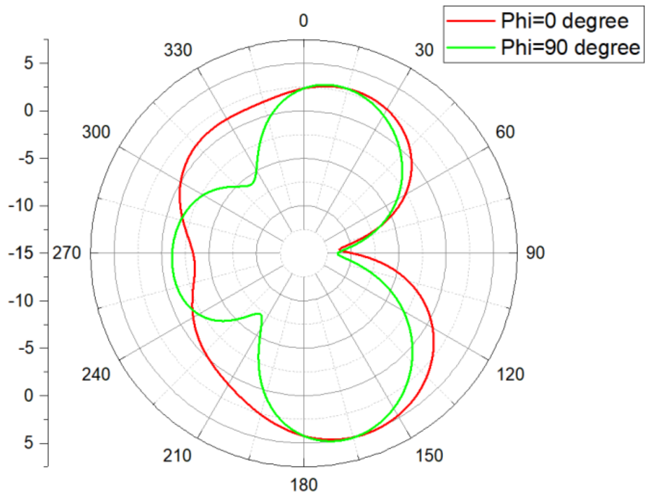
-5
0
5

(ii)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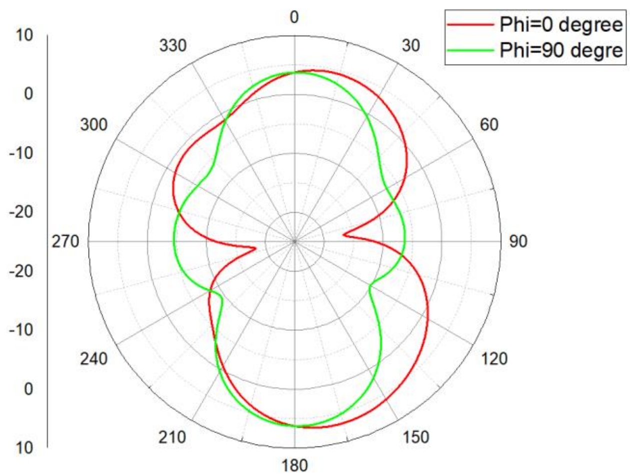
(iii)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(iv)

Fig.4.8. Gain plot of the bandwidth reconfigurable antenna using two PIN diodes on switching the PIN diodes DL and DR as ON or OFF: (i) DL=ON and DR=ON, (ii) DL=ON and DR=OFF, (iii) DL=OFF and DR=ON, (iv) DL=OFF and DR=OFF

### 4.3.3 VANADIUM DIOXIDE SWITCH

The results for the proposed design that are observed in Fig.4.7. and in Fig.4.8 are obtained when the design uses two type MA4SPS402 PIN diodes, placed at the separation of d=1mm at the junction of side feed lines connecting to the central feed line, but when we have to use vanadium dioxide switch in place of PIN diodes, the separation layer d is very thin and one of the states, i.e., when DL=OFF and DR=ON, for different thickness of vanadium dioxide layer, S11 plot was observed to see for the similar results as observed in same case for a PIN diode.

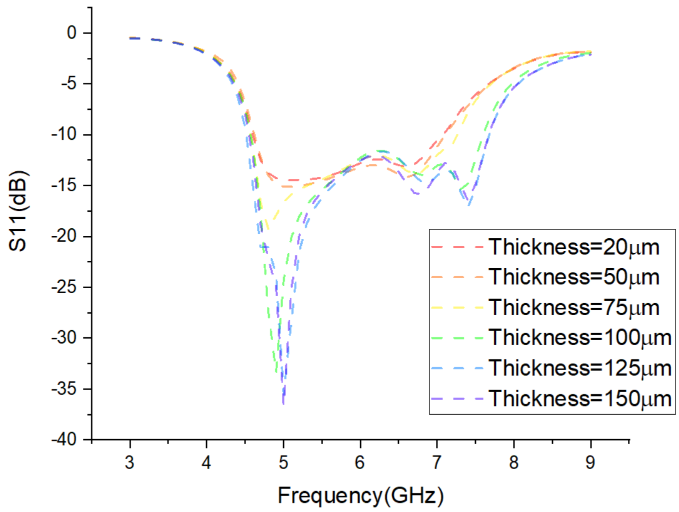


Fig.4.9. S11 plot comparison of different thickness of vanadium dioxide switch for the case when DL=OFF and DR=ON.

It can be seen from the Fig.4.9. S11 plot for the case when DL=OFF and DR=ON, that at about thickness of layer 100µm, the bandwidth is comparable to the situation when PIN diodes were used. To test whether using 100µm thickness vanadium dioxide switch in place of PIN diodes could also make the design bandwidth reconfigurable, the S11 plot for all four cases at 100µm thickness were observed as seen in Fig.4.10.

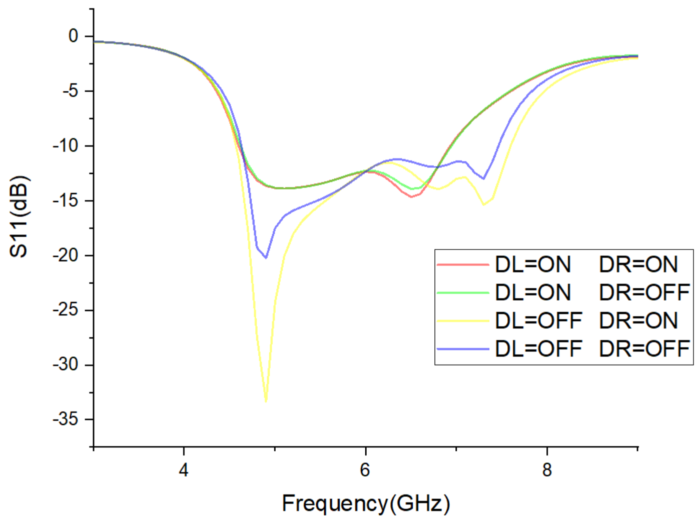


Fig.4.10. S11 plot of the bandwidth reconfigurable antenna using two 100µm vanadium dioxide switch on switching the states of DL and DR as ON or OFF.

## 4.4 RESULT ANALYSIS

### 4.4.1 SELECTION OF PIN DIODE

Based on the results observed in Fig.4.4, it was deduced that the type MA4SPS402 PIN diode was best suited for designing in the proposed structure. The observed results for each PIN diode model can be analyzed using Table 4.2 below.

Table 4.2. Bandwidth Reconfigurable antenna results on using three different PIN diode models for the case when both DL and DR are ON

| S.No | Diode Parameters | Bandwidth |
|---|---|---|
| 1 | R=5ohm C=0.045pF | 4.54 to 7.08=2.54GHz |
| 2 | R=5ohm C=0.28pF | 4.92 to 6.20=1.28GHz |
| 3 | R=0.83ohm C=0.28pF | 4.94 to 6.20=1.26GHz |

### 4.4.2 BANDWIDTH RECONFIGURATION RESULTS

When the type MA4SPS402 PIN diode was used for the design of the proposed antenna, at four different states, analyzed values of bandwidth and gain are represented in Table 4.3 below.

Table 4.3. Bandwidth Reconfigurable antenna results using two PIN diodes

| S.No | State of DL | State of DR | Bandwidth | Maximum gain at around 5GHz | Radiation Pattern |
|---|---|---|---|---|---|
| 1 | ON | ON | 4.54 to 7.08=2.54GHz | 5.7dB | Bidirectional, Symmetrical, No side bulge loss |

| | | | | | |
|---|---|---|---|---|---|
| 2 | ON | OFF | 4.57 to 8.20=3.63GHz | 5.5dB | Bidirectional, Symmetrical, Right leaning |
| 3 | OFF | ON | 4.54 to 8.17=3.63GHz | 5.5dB | Bidirectional, Symmetrical, Left leaning |
| 4 | OFF | OFF | 5.22 to 6.02=0.8GHz | 6.9dB | Bidirectional, Symmetrical, Both sides bulge |

### 4.4.3 VANADIUM DIOXIDE SWITCH

On observing the S11 plots at different states of the vanadium dioxide switch at 100μm thickness, the analyzed results are represented in Table 4.4.

Table 4.4. Bandwidth Reconfigurable antenna results using two Vanadium Dioxide switches

| S.No | State of DL | State of DR | Bandwidth |
|---|---|---|---|
| 1 | ON | ON | 4.61 to 6.93=2.32GHz |
| 2 | ON | OFF | 4.65 to 6.93=2.28GHz |
| 3 | OFF | ON | 4.54 to 7.68=3.14GHz |
| 4 | OFF | OFF | 4.68 to 7.43=2.75GHz |

It can be analyzed from the results that though the results of the VO2 switch at 100μm thickness might not be similar to that on using PIN diodes but still bandwidth reconfiguration results were obtained.

### 4.4.4. COMPARISON WITH PREVIOUS WORKS

Based on the comparison with previously published works related to the proposed design, comparison Table 4.5 is observed.

Table 4.5. Comparison with previous works

| **Reference** | **Number of switches used** | **Maximum Bandwidth** |
|---|---|---|
| [16] | 6 | 0.924GHz |
| [17] | 4 | 0.64GHz |
| [19] | 2 | 1GHz |
| This work | 2 | 3.63GHz |

## 4.5 CONCLUSION

This paper presents a bandwidth reconfigurable compact antenna, which has a resonant frequency at around 5GHz, a frequency range useful in Wi-Fi and 5G services[8]-[10]. The proposed design presented the antenna which has bidirectional radiation pattern and is less complex in design with the use of only two PIN diodes in its structure. Vanadium dioxide switch is only considered as a replacement for PIN diodes in designing to have shift from electrically tunable switches to temperature dependent tunable switches, which provide the added advantages of keeping antennas and microwave devices electrically decoupled, no longer restricting them to biasing network. Vanadium dioxide switches are also considered to maintain unaffected radiation pattern, useful for wideband tuning, low loss structures and reconfiguration[18].

# CHAPTER 5

# CONCLUSIONS AND FUTURE DIRECTIONS

## 5.1 CONCLUSIONS

In this chapter, we summarize the key findings and conclusions from our study on the proposed unique designs for compact C-band wireless application Antennas. The antenna designs were aimed at resolving the challenge of using a single antenna for a specific application. Through extensive analysis and evaluation, we have established the distinctive nature and performance of this antenna design.

The first design of Antenna namely Fox-face compound antenna provides the key benefits of being compact in size, using minimum number of switches i.e. 2 PIN diodes for achieving reconfiguration. Most antenna design works tat are being published, usually have a very complex approach and designing for achieving just a single type of reconfiguration like frequency, polarization, radiation pattern, gain etc. But this design provides the added advantage of achieving multiple forms of reconfiguration in just four of its switchable states. The presented antenna is multiband aswell and resonates at frequencies of significance in the mainly the C-band frequency range. The cases depicted in the paper for this Fox-face CRA show that because the effective bandwidths are at around 5.5 GHz, 6.7 GHz, and 9.1 GHz, the design finds its application in the fields of 5G services (5.5 GHz), digital high-capacity fixed point-to-point links (6.7 GHz), and satellite and military applications (9.1 GHz). This may be relevant in MIMO utility, wherein spectral performance may be increased by making use of pattern and polarisation reconfigurability. For cognitive radio systems too, this proposed antenna can be utilised where a frequency reconfigurable antenna is needed after sensing the idle band in the wide frequency spectrum.

The second design presented too finds its application for C-band wireless systems with the band focused to resonate at around 5GHz frequency. The design is simple and focuses on the challenge that not much work is available in the field of bandwidth reconfigurable antennas and that too centered around achieving wideband resonance at 5GHz frequency, which is a frequency of large-scale applications, the most common one includes Wifi 5G services. With only two PIN diodes used in its structure, the proposed design presented an antenna with a bidirectional radiation pattern that is simpler to construct. Vanadium dioxide switches are only considered as a replacement for PIN diodes in designing to shift from electrically tunable switches to temperature-dependent tunable switches, which provide the added advantage of keeping antennas and microwave devices electrically decoupled, no longer restricting them to biassing networks. Additionally, thought to maintain an unaltered radiation pattern, vanadium dioxide switches are useful for wideband tuning, low-loss structures, and reconfiguration.

## 5.2 FUTURE DIRECTIONS

There are four basic types of reconfiguration strategies based on the demand for the antenna's reconfiguration property: electrical, optical, mechanical, and material. The most popular of these reconfiguration approaches is electrical reconfiguration, which we used when utilising PIN diodes or varactor diodes. Not much resources and work are available for exploring the other methods of reconfiguration. There is lot of scope in exploring in that direction. The reconfiguration techniques are presented in Figure 5.1.

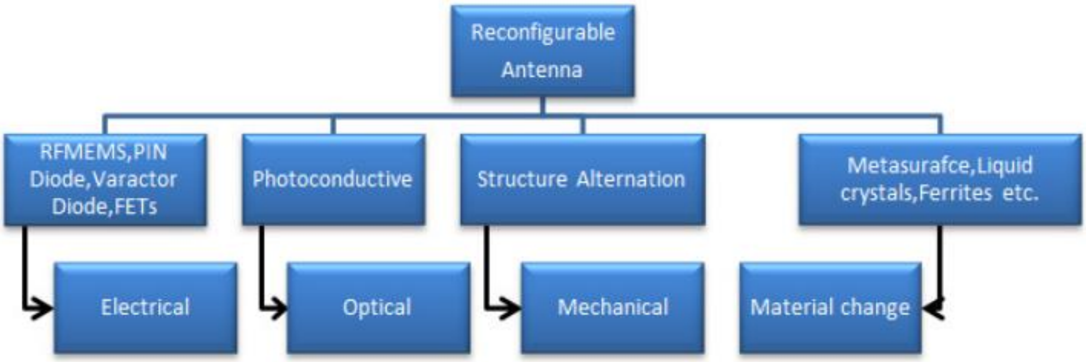


Fig.5.1 Antenna Reconfiguration Techniques

1. **Electrically reconfigurable antennas** can vary their radiating architecture or radiating edges to alter the distribution of surface current distributions. RF-MEMS, PIN diodes, varactor diodes, and FETs are examples of electronic switching components.Switches have been incorporated into the antenna design to assist designers in achieving the reconfigurable functionality required.

The electrical mechanism employs both discrete and continuous tuning strategies. These can be accomplished using P-i-n (PIN) diodes, varactor diodes, and field-effect transistors (FETs). To operate these electrical components, the antenna circuit requires a direct-current (DC) supply and biassing circuit. As a result, an electrically reconfigurable antenna requires a DC electrical supply and electronic switching components, which reduces the antenna's usefulness.

2. **Optically reconfigurable antennas** are a type of radiating component that may modify its radiation properties by using switches, such as optical activation of silicon switches of reactive elements. Metal wires that may obstruct the antenna's radiated qualities can be removed in the case of optically driven devices. Interference between the desired radiation pattern and the usage of additional metallic microstrip or wired biassing lines complicates the antenna when using DC-controlled microstrip antennas. These issues can be overcome by using an optically controlled reconfigurable antenna.

Optical switches can also be used to set the resonance frequency of an antenna. Because optical control outperforms electrical control, it is favoured over electrical switches. Even at high microwave frequencies, the optical signal isolates the controlling optical signal from the regulated microwave signal.

Optics-controlled devices switch at a rate ranging from 0.1 to 1 MHz. Using photoconductive switches, a single-band to dual-band frequency response reconfiguration will be possible.

3. In **Mechanically reconfigurable antennas**, altering the antenna's radiating structure physically is another way to change the configuration of an antenna. Antenna tuning is accomplished by altering the antenna's radiating components by changing its structure. The independence of this approach from biassing lines, switch mechanisms, or optical fiber/laser diode integration is critical. This strategy, however, is limited by the device's capacity to be physically adjusted.

4. **Material change reconfiguration** works implies that materials like as liquid crystals, dielectric fluids, ferrites, or metasurfaces can also be utilised to reconfigure antennas by adjusting the characteristics of the substrate.

The material changes when the relative electric permittivity or magnetic permeability changes. A liquid crystal, in actuality, is a nonlinear material whose dielectric constant can be changed by modifying the orientation of the liquid crystal molecules at different voltage levels. A static electric/magnetic field can change the relative permittivity/permeability of ferrites. The patch antenna in a metasurfaced antenna is placed on top of the metasurface, which is then rotated. This changes the equivalent relative permittivity of the structure, allowing the antenna's resonant frequency to be altered. To tune frequencies, materials having controllable electrical properties, such as liquid crystals, synthetic fluids, dielectric fluids, barium-strontium-titanate (BST), and yttrium iron garnet (YIG), can be utilised.

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# List of Publications

1. Presented Paper:
   - Title: " Fox-Face Compound Reconfigurable Antenna for Wireless Systems"
   - Conference: IEEE International Conference MAC 2023
   - Location: MNNIT, Prayagraj, Uttar Pradesh
   - Date: March 24-26, 2023

2. Paper to be Presented:
   - Title: " Bandwidth Reconfigurable Wideband Antenna with comparison between PIN diodes and Vanadium Dioxide switches"
   - Conference: IEEE International Conference WAMS 2023
   - Location: PDEU, Gandhinagar, Gujarat
   - Date: June 7-10, 2023

Our research work in the field of reconfigurable patch antenna design for C-band wireless applications has resulted in the following publications:

1. I had presented a paper titled " Fox-Face Compound Reconfigurable Antenna for Wireless Systems " at the IEEE International Conference MAC 2023, held in MNNIT, Prayagraj, Uttar Pradesh from March 24-26, 2023. The paper focuses on the design and performance of a Multiband co-axially fed CRA operating at four switchable states by changing the biasing across the 2 PIN diodes in its circuitry.

2. I have an upcoming paper presentation at the IEEE International Conference WAMS 2023, to be held in PDEU, Gandhinagar, Gujarat from June 7-10, 2023. The paper, titled " Bandwidth Reconfigurable Wideband Antenna with comparison between PIN diodes and Vanadium Dioxide switches," explores the design and characteristics of a bandwidth

reconfigurable antenna resonating at around 5GHz frequency and exploring an alternative switch namely the Vanadium Dioxide thermal switch.

These publications in the above-mentioned conferences were efforts to contribute to the advancement of antenna technology in the wireless systems, aiming to enhance the performance, functionality and applications of antennas used in various Wireless technologies.

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