DESIGN AND ANALYSIS OF FREQUENCY RECONFIGURABLE MICROSTRIP ANTENNAS

A THESIS

SUBMITTED IN PARTIAL FULFILLMENT OF THE

REQUIREMENTS FOR THE DEGREE OF

MASTER OF TECHNOLOGY

IN

COMMUNICATION AND NETWORKS

BY

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Department of Electronics and Communication Engineering

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Rourkela-769008

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UNDER THE GUIDANCE OF

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May 2015

DEPARTMENT OF ELECTRONICS AND COMMUNICATION ENGINEERING

NATIONAL INSTITUTE OF TECHNOLOGY, ROURKELA

ROURKELA- 769008, ODISHA, INDIA

CERTIFICATE

This is to certify that the work in this thesis entitled "**DESIGN AND ANALYSIS OF FREQUENCY RECONFIGURABLE MICROSTRIP ANTENNA"** by Mr. **NISHANT KUMAR** is a record of an original research work carried out by his during 2014-2015 under my supervision and guidance in partial fulfilment of the requirement for the award of the degree of Master of Technology in Electronics and Communication Engineering (Communication and Networks), National Institute of Technology, Rourkela. Neither this thesis nor any part of it, to the best of my knowledge, has been submitted for any degree or diploma elsewhere.

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ROURKELA- 769008, ODISHA, INDIA

Declaration

I certify that

a) The work comprised in the thesis is original and is done by myself under the supervision of my supervisor.

b) The work has not been submitted to any other institute for any degree or diploma.

c) I have followed the guidelines provided by the Institute in writing the thesis.

d) Whenever I have used materials (data, theoretical analysis, and text) from other sources, I have given due credit to them in the text of the thesis and giving their details in the references.

e) Whenever I have quoted written materials from other sources, I have put them under quotation marks and given due credit to the sources by citing them and giving required details in the reference

Nishant Kumar

213EC5246

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Nishant Kumar

Abstract

The goal of this thesis is to design and analyse the frequency reconfigurable microstrip patch antenna which are mainly the combination of filters and antennas called filtering antennas (filtennas). The increasing demand for high data rate and new wireless communication has led to the development of multifunctional devices including antennas and radio frequency (RF) front ends. The novel solution is to design antennas which has multiband, multimode, low profile, low cost and easy to integrate with portable devices. In this thesis three different frequency reconfigurable microstrip patch antenna has been proposed for cognitive radio system. The design and simulation of the proposed antennas are done in CST (computer simulation technology) microwave simulation software. The first design is single port frequency agile antenna for overlay cognitive radio. When all the PIN diodes are in ON state, it is UWB and used to sense the entire spectrum and by selectively changing the PIN diode states five different reconfigurable cases occurs which is used for communication. The reflection coefficient curve of UWB antenna shows bandwidth from 3.1 GHz to 9.8 GHz and reconfigurable antenna resonate at 6.7 GHz, 5.33 Hz, 5.73 GHz, 7.04 GHz, 6.33 GHz and 9.45 GHz. The second antenna proposed is dual port microstrip patch for cognitive radio system. This design is used for overlay cognitive radio in which one antenna is for sensing and other for communication. Sensing and communication can be done simultaneously and tuning in reconfigurable antenna can be done continuously. UWB antenna bandwidth is from 3.4 GHz to 13.2 GHz and the reconfigurable antenna is dual and triple band resonating frequency according to the biasing of varactor. The radiation pattern obtained in both cases are almost omnidirectional which is good for mobile application and sensing antenna. The third design is proposed for underlay cognitive radio system in which UWB antenna is used which radiate at very low power. The UWB antenna resonates from 2.8 GHz to 13.4 GHz. The filter is then added to this antenna as notch reconfigurable and this can be used to communicate over long distance without interference with primary used. The notches depends on states of PIN diodes, the frequency which are rejected are 5 GHz, 5.7 GHz, 6.45 GHz, 7.5 GHz, 9 GHz. The fourth proposed design is planar inverted F antenna (PIFA) for mobile devices. Currently cellular phones are using more than one services, so many antennas are needed. In the proposed design two varactor diodes has been used for tuning of operating frequency so that one antenna can replace many antennas for different wireless services like WIFI, WIMAX, GPS,WLAN , WiBro etc. .The simulated refection coefficient of this antenna shows dual band and triple band from 2 GHz to 5.5 GHz at different varactor diode biasing states.

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Chapter 1
Introduction

Recently multifunctional antennas with controllable features like frequency tuning, pattern reconfigurabilty, polarisation reconfigurabilty, or hybrid antenna received much attention as it can fulfil demand for low profile antennas for different services in just single terminal. A single wireless devices can work for many wireless services such as GPS, GSM, WLAN, Bluetooth, etc. To make these devices low profile and more functional reconfigurable antennas are needed. The intentional redistribution of the currents or electromagnetic fields of antennas aperture can be used to change the impedance or radiation properties to introduce reconfigurabilty in the antennas.

A microstrip antennas provides much needed demand of low profile, light weight and also can be easily integrated with ICs and switching elements. It can be produced in large amount by printed circuit technology and thus integrated in mobile phones and other wireless applications like satellite communications, spacecraft, radars, wireless phones and wireless computer networks for large scale production. The techniques that can be used for reconfigurabilty in antennas are many such as by using active switches based on micro electro mechanical systems(MEMS)[1],PIN diodes[2]-[3], varactor diodes or using a mechanical movement of different patches by using stepper motors, bending of one or more of its parts or even using a photo- conductive switches. Another way to achieve controllable antenna features is to bias different antenna parts at different times, appropriately feed antenna array and reconfigure feeding networks.

1.1 Reconfigurable Antennas Classifications and Categories:

Antenna with reconfigurable feature can be of large variety and different shapes and sizes, but these can be mainly grouped in four categories based on their functionality as:

- A frequency reconfigurable antenna[8 - 12]
- A pattern reconfigurable antenna[13]
- A reconfigurable polarization antenna[14]

- A hybrid antenna(combination of above stated categories)[15]

In the first category frequency reconfigurable antenna the frequency tuning can be done by controlling switching circuits or manually changing the configuration of the antenna. The return loss curve shows the shifting of resonating frequency. These kind of antenna can be used in wireless devices working at different wireless services with different frequency of operation, it can also be used in future advance technology like cognitive radio. Cognitive radio is software controlled dynamic band sharing technology to accommodate large traffic and demand of higher data rate. In case of pattern reconfigurable antenna the radiation parameters changes in terms of shape, direction or gain. [13] In third case polarisation of the antenna can be reconfigured using switches, the antenna can show circular, linear or elliptical polarisation. These kind of antenna is necessary to reduce multipath contributions and hence employing high gain antennas [14]. The last kind employ combination of above mentioned types, called hybrid antennas for example frequency reconfigurable antenna with pattern diversity. [15]

Reconfigurable antennas can further be categorised in 6 main groups based on switching elements and their present configuration techniques:

- Antennas using switches (like PIN diodes)[3,7]
- capacitors or varactor diode based antennas[16]
- physical angular altered antenna
- antenna having different biasing networks
- antenna arrays
- reconfigurable feeding network based antenna

1.2 Reconfigurable Antennas Functional Mechanism:

Varies types of Reconfiguration of antenna can be achieved based on these simple mechanism

1) In order to achieve frequency reconfiguration the surface current distribution has to be altered by using varies types of switches. [9,10]
2) To achieve pattern reconfiguration in the antenna the radiating edges, slots or the feeding network has to be altered accordingly. [13]
3) To achieve polarisation reconfiguration in the antenna the surface structure of the antenna or the feeding network has to be altered accordingly. [14]
4) To achieve hybrid reconfiguration above principles has to be done accordingly[15]

1.3 Motivation:

In modern day wireless devices multiple antennas are required to make sure that it can be used for multiple communication services, this not only make the system bulky but power loss is also more. In frequency reconfigurable antenna a single antenna can replace them making system low profile and handheld devices more light weight and energy efficient. Combining wideband and narrowband functionality makes the antenna more useful in multimode operation and reduce size and increases flexibility of operation for users. This also introduces pre-filtering of the communication signals so that interference level can be reduced at the receiver end, giving them extra advantage over fixed non – reconfigurable transceivers. Recently cognitive radio system has attracted attention of communication researchers as it can deal with limited bandwidth availability and ever increasing demand of wireless services, to accommodate large number of users and increase data rate, this technology uses dynamic sharing scheme of the bandwidth. Antenna designers on the other hand plays very important role in making this technology work efficiently

Researchers are using frequency reconfigurable antenna for software defined radio technology so that a single antenna can be used for sensing the band and communicating in the particular band after locating free band, this can be done by filtering out other signals and making communication interference free. Three frequency reconfigurable antenna for cognitive radio application has been proposed here using PIN diodes and varactor diodes. A PIFA (planar inverted F antenna) is also proposed for cellular devices which can be used for GSM, DCS, PCS, UMTS, Bluetooth, and wireless local-area network (LAN).

1.4 Objective of the Work

This topic of this thesis is in the area of increasing the functionality of the antenna and making communication system more interference resistant. Beside this, work has also been done in making antenna for cognitive radio application. Antenna for cognitive radio has two major roles, one is to sense the entire UWB (ultra wide-band) frequency range i.e. from 3.1 GHz to 10.6 GHz as defined by FCC. [17] After sensing we need to reconfigure the antenna to communicate in particular frequency by filtering out the other undesired signals. Reconfiguration in the microstrip antenna is done by using PIN diode in first design and varactor diode in second design. The design is notch reconfigurable antenna for underlay cognitive radio system, this is done by adding filter in feed network. Fourth design is based on PIFA technology, which is used in mobile phones as it more compact and light weight.

Design and analysis of these antennas are done in CST Microwave studio software, it is a full-wave electromagnetic simulation tool. First three designs works in UWB range and fourth one is in commercial wireless services range, i.e. in GSM, PCS, UMTS, Bluetooth, and wireless local-area network (LAN), DCS band. First basic design formulas are used to make antenna and then optimized in CST tool for better impedance matching and gain. Antenna parameters are varied and studied to study the effect of these on antenna performance.

1.5 Literature Review on frequency reconfigurable antennas

In this topic varies previously presented antennas are analysed and compared. Reconfigurable antennas firstly introduced in 1998 [1], in which the functionality of the antenna can be altered by changing their configuration upon request. In this paper a new technique is proposed by the author Elliott R. Brown in which RF MEMS **(**radio frequency microelectromechanical system**)** are used as switching element for reconfigurable antenna. RF MEMS has greater performance joint with ultra-low-power dissipation and large-scale integration. Reconfigurable Antenna Challenges for Future Radio Systems [2] presented by Hall P S, Gardner P and et-al shows antenna design and analysis for software defined radio .In this paper cognitive radio system is defined in detail and possible antenna designs are studied, the first design wideband and Omni-directional, feeding a receiver capable of both coarse and fine spectrum sensing over a broad bandwidth. The second antenna is directional and is frequency reconfigurable to select a particular band. Vivaldi Antenna with Integrated Switchable Band Pass Resonator [3] is proposed by M. R. Hamid, Peter Gardner in which a single pair of ring slot resonators is located in the Vivaldi to realize frequency reconfiguration. The proposed antenna is capable of switching six different narrow pass bands within a wide operating band of 1–3 GHz , to achieve this PIN diodes are used with biasing network. The ring slot is placed above circular slot stub and then switches are added, with varies cases of ON OFF condition of the switches different operating frequencies are obtained. A Novel Band-pass Defected Microstrip Structure (DMS) Filter for Planar Circuits [6] is the filter proposed by M. Kazero oni and et-al which shows model of band-pass filter that The BPF has a bandwidth more than 39%and can be used in feeding network of microstrip planar antennas to filter out undesired signals. To achieve reconfigurability switches are added after detailed analysis and optimization.

Similar approach can be seen in the paper Analysis and circuit modelling method for defected microstrip structure in planar transmission lines by Girdhari Chaudhary, Phirun Kim and et-al. in this paper detail analysis and comparison has been done between varies filters and proposed G slot filter for microwave applications. Two port frequency reconfigurable antenna for cognitive radios [7] proposed by F. Ghanem, P.S. Hall and J.R. Kelly, in which simultaneous sensing and communication can be achieved as two different antennas are used for sensing and communication. The decoupling is shown here is below -10 dB as required, otherwise interference will be more. A Reconfigurable Triple-Notch-Band Antenna Integrated with Defected Microstrip Structure Band-Stop Filter for Ultra-Wideband Cognitive Radio Applications [11] proposed by Yigsng Li and et-al where underlay cognitive radio system can use this type of antenna . Defected microstrip structure (DMS) band stop filter (BSF) embedded in the microstrip feed line is used for filtering a particular band of frequency and reconfiguration is done by using PIN diodes. PIFA-Based Tunable Internal Antenna for Personal Communication Handsets [18] proposed by Viet-Anh Nguyen, Rashid-Ahmad Bhatti, and Seong-Ook Park is a very good candidate for cellular phones where the device having different antennas for varies communication services can be replaced by a single antenna. The design uses a varactor diode for smooth and continuous frequency tuning.

1.6 Outline of the Thesis

Chapter 1 of the thesis contains the overall introduction to the reconfigurable microstrip antenna with their advantages and applications and this chapter also contains motivation, objective, literature survey and concludes with outline of this thesis.

Chapter 2: this chapter deals with basic parameters and characteristics of antenna that will be used in further chapters. Brief discussions on impedance, bandwidth, radiation pattern, polarization, gain, efficiency, directivity are given.

Chapter 3: in this chapter microstrip patch antenna theory is discussed. The general design process of rectangular patch antenna is given with equations. The advantages and disadvantages are given. Different feeding techniques including microstrip, coaxial probe, aperture coupling, proximity coupled is discussed. The fringing field effect in microstrip and how radiation occurs is discussed.

Chapter 4: In this chapter deals with the theory of frequency reconfigurable antenna and cognitive radio system in detail. Different types of techniques used for reconfigurability is like RFMEMs, PIN diodes, varactor diodes, optical switches, physical switch , smart materials.

Chapter 5: in this chapter three frequency reconfigurable antenna design and simulation is discussed. First design is single port frequency reconfigurable, which is used for cognitive radio, second antenna is dual port for same application. The third design is notch reconfigurable for underlay cognitive radio. The simulation results like reflection coefficient, radiation pattern, gain, efficiency, surface current distribution etc. are discussed and studied.

Chapter 6: in this chapter small tunable and reconfigurable planar inverted F antenna is discussed for 4G cellular phone. Two varactor diodes are used to tune the operating frequency. This antenna can be used for wireless services like WLAN, GPS, PCS, CDMA, WIFI, and WIMAX. The return los curve, radiation pattern, gain and efficiency are discussed and studied.

Chapter 7: Contains the conclusion and future work of the thesis and future work.

Chapter 2

Microstrip Patch Antenna

This chapter contains brief introduction to microstrip patch antenna and its advantages and disadvantages. A brief theory of PIFA antenna with its major applications has also been added. After this some feed techniques has been discussed .at last detailed analysis and working principals is discussed.

2.1 Introduction

The demand for smaller antenna size in order to meet miniaturization in mobile devices has increased the need for microstrip antennas since its invention in 1953[25], [26].because of its extremely thin profile, light weight, mass production by print circuit technology and easily integrated with ICs it has have found main applications in military aircraft, missiles, rockets, and satellites. Due to high cost of substrate and fabrication cost and also communication system was not able to adopt this kind of antenna, it was not popular in commercial sector. But during last decade the development and manufacturing cost of the microstrip antenna has dropped significantly, due to reduction in the cost of substrate material and manufacturing process, also the newly developed CAD tools for simulation and analysis. Much significant progress has been reported in the design of compact microstrip antennas with broadband, dual-frequency, dual polarized, circular polarized .reconfigurability in this types of antenna has attracted much attention of the researches as switches can be easily implemented and fabricated without much difference in measurement between fabricated and simulated antennas. There are some disadvantages of microstrip antenna like High quality factor, Narrow bandwidth, Spurious feed radiation and Low efficiency.

2.2 Basics of microstrip antenna design

In its simplest form microstrip antenna is designed by placing radiating patch on top of dielectric substrate and ground plane below it as shown in figure 2.1

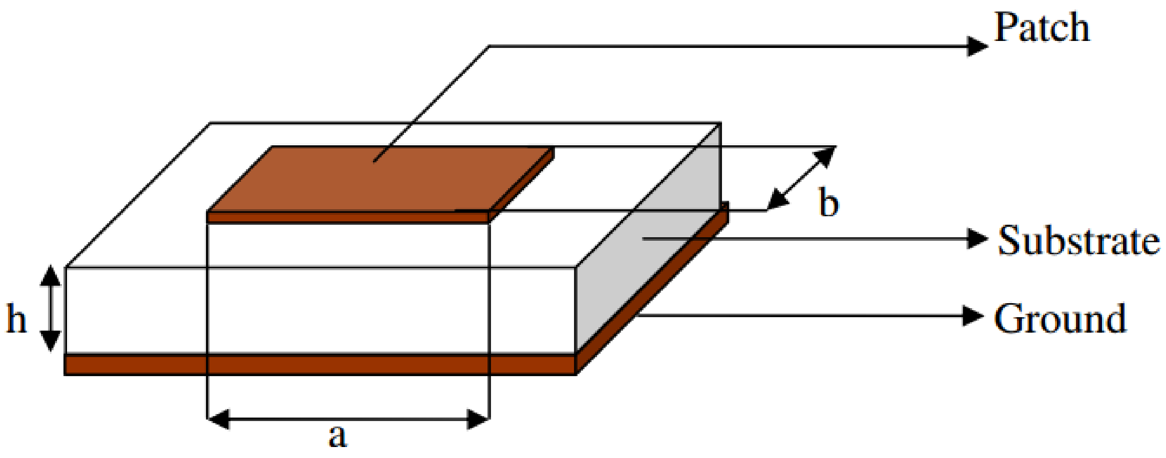


Fig 2.1 Basic rectangular microstrip patch antenna design

The radiation by the antenna is primarily because of the fringing fields between the patch edge and the ground plane. A quasi-TEM mode is generated as the radiating electromagnetic fields are both in the substrate and in free space. In the above figure 'a' shows length and 'b' shows width of the patch and substrate height is given by 'h'. The fundamental resonant mode is TM10 when 'a' is greater than b and TM01 is the secondary. If dimension of 'a' is less than b than it is wise versa [25].

The transmission line model is the simplest model to describe working of the microstrip antenna [24]. It is sufficiently accurate in calculating the input impedances for simple geometries but it is difficult to get impedance bandwidth and radiation pattern especially when substrate is very thin. The cavity model is more complex as compared to transmission line model but more accurate [25].in this model patch and the ground is assumed as electrical plates and edges of dielectric substrate is surrounded by magnetic walls. The substrate that are used for designing microstrip antenna usually have dielectric constant in the range of $2.2 \leq \xi_r \leq 12$. Better efficiency and larger bandwidth is provided by substrate which are thicker and having lower dielectric constant.

2.3 Feed mechanisms

There are many feed mechanism of microstrip antenna, these determines the complexity of the microstrip antenna design. The most popular way to classify them as given below

2.3.1Directly connected to patch:

Microstrip line, coaxial probe are the common example of this kind of feeding, the radiating patch is directly connected to electrical source. In case of microstrip line feed the edge of radiating patch is directly connected to a conducting strip. To provide the right impedance match between the patch and the feed line sometimes inset feed is used instead of direct connection as shown in the figure 2.2. The advantage of this kind of feeding technique is simple to match, easy to fabricate and simple to model. But as the substrate thickness increases surface waves and spurious feed radiation increases which effects the bandwidth of the antenna.

In coaxial –line feeding the inner conductor of coaxial cable is connected to the patch while the outer conductor is connected to ground plane. Its main advantage is low spurious radiation and easy to fabricate and match but on the other hand it is difficult to model and has narrow bandwidth.it is shown in figure 2.3

2.3.2Coupled to the patch:

Aperture coupling and proximity are most widely used feeding technique in this type of feeding mechanism. Electromagnetic field coupling is used to couple between feed and radiating patch. In case of aperture coupling ground plane separates two substrates of which the bottom one has the feed line whose energy is coupled to the patch through a slot on the ground plane, see figure 2.4.This feeding mechanism is most difficult to fabricate and it also has narrow bandwidth. This technique has some advantages like it is easier to model and has moderate spurious radiation.

Proximity coupled feed consist of two substrate between them a feed line is sandwiched. The top substrate has radiating patch and bottom has ground plane, in this the coupling is primarily capacitive in nature, see figure 2.5.Among all the feeding techniques discussed it has the largest bandwidth and has low spurious radiation but it is more difficult to fabricate.

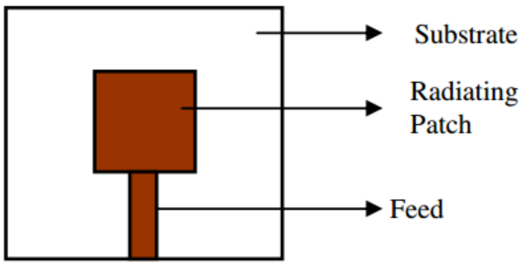


Fig 2.2 antenna with microstrip feed

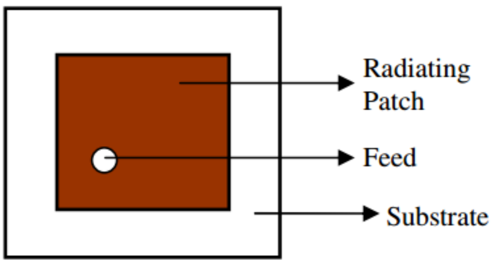


fig 2.3 coaxial probe feed

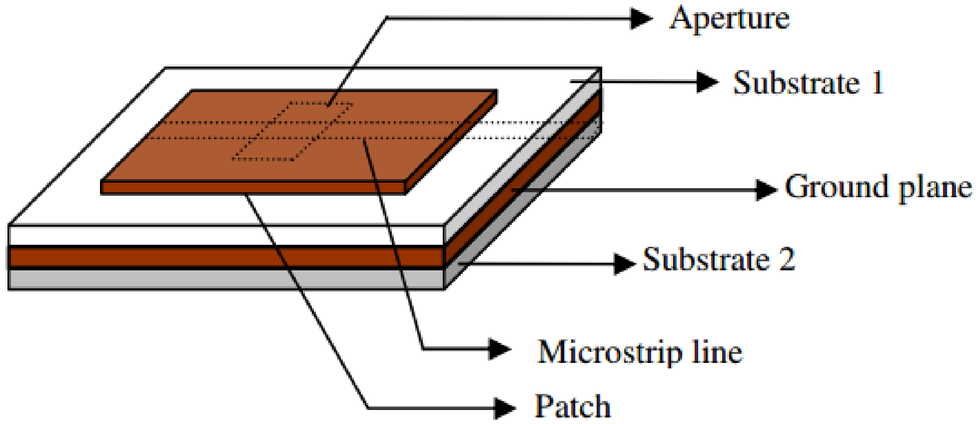


Fig 2.4 antenna with aperture coupling

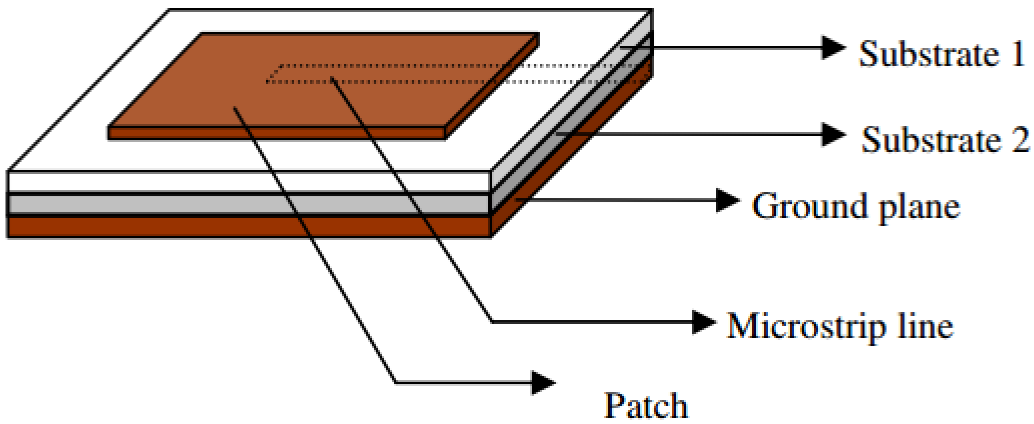


Fig 2.5 proximity coupled antenna configuration [25]

2.4 Rectangular Microstrip Antenna

Rectangular patch antenna is the most widely used and very easy to implement and analyse using transmission line model and cavity models. The figure 2.6 shows schematic diagram of general rectangular patch, here designer has two degree of freedom, one is the length and other is width of the radiating patch.

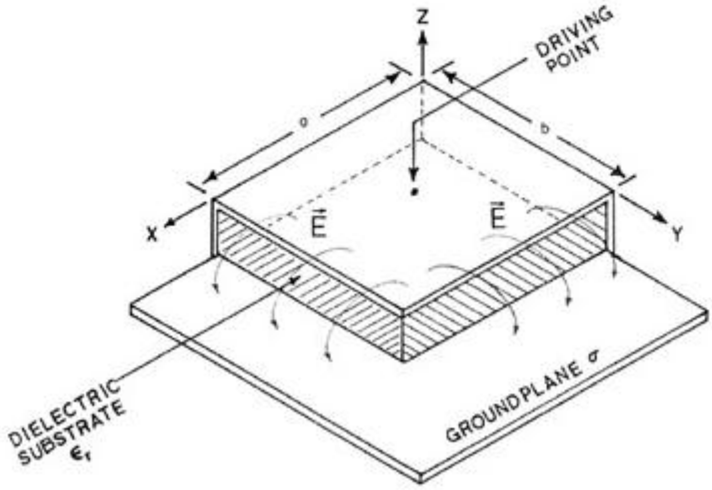


Fig 2.6 rectangular patch antenna [25]

In the figure 2.6 'a' is the length and b is the width of the patch and the patch is feed by coaxial probe feed. Method of analysis can be transmission line or cavity model. The transmission line model is the easiest of all but not so accurate, microstrip antenna in this model is treated as part of transmission line. The field at the edges of the patch undergo fringing as it is truncated, the amount of fringing is the function of the height and the length or breadth of the patch this is shown figure 2.7. Generally L/h ratio is >> 1, the fringing fields are less but it should be taken into account as it influences resonating frequency of the antenna. From the figure 2.7 it can be seen that most of the electric fields resides in the substrate and some part is in air. Effective dielectric constant ξ_{reff} is introduced because the fields are not only in substrate but also in air that is to account for fringing and the wave propagation in the line. This is written mathematically by equation 2.1

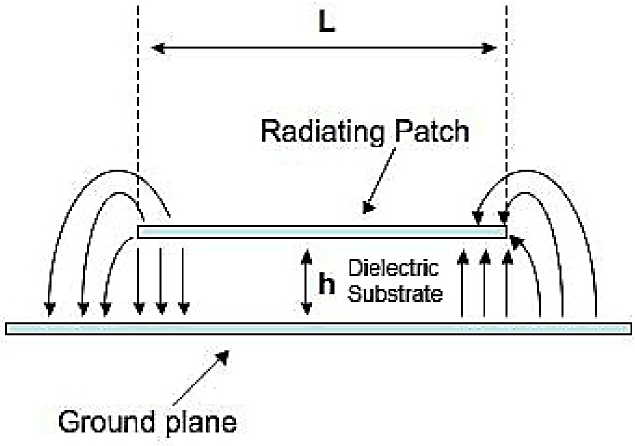


Fig 2.7 Fringing Field Effect

$$W/h >> 1 \tag{2.1}$$

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

The actual length of rectangular patch is more than the physical length. It is due to Due to the fringing field coming out from the radiating slots. The extended length on each side of the antenna ΔL is the function of the effective dielectric constant and width-to-height ratio, W/h. The approximate relation for extended distance is given below

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

The actual physical length of the patch due to extension length is not equal to λ/2 so extension of the length has to be taken in consideration as given in equation 2.3

$$L = L_{eff} - 2\Delta L \tag{2.3}$$

The L_{eff} as dominant mode TM_{010} the length of patch is equal to λ/2 is given by

$$L_{eff} = c/f_r \tag{2.4}$$

$$= \frac{c_0}{2f_r\sqrt{\varepsilon_{reff}}}$$

Where f_r is resonating frequency for which antenna is designed and c_0 is the speed of light in vacuum.

Width of the patch can be calculated by this formula for the dominant mode TM_{010} as there is no fringing fields along the width so no need to take effective dielectric constant.

$$w = \frac{c_0}{2f_r}(\frac{\varepsilon_r+1}{2})^{-1/2} \tag{2.5}$$

The antenna resonates at the frequency given by equation 2.6 for the dominant mode TM_{010}

$$f_r = \frac{c_0}{2L\sqrt{\varepsilon_{reff}}} \tag{2.6}$$

The antenna will radiate at the frequency given in equation 2.7 when considering ε_{reff} and L_{eff}

$$f_r = \frac{c_0}{2(L+2\Delta L)\sqrt{\varepsilon_{reff}}} \tag{2.7}$$

To find the point along the patch dimension where the input impedance is equal to that of feedline is very important for the perfect impedance matching. In the figure 2.8 a recessed microstrip–line feed is shown to show the technique for impedance matching at a particular resonant frequency. For inset feed the input resistance is given approximately by equation 2.8 using modal expansion analysis.

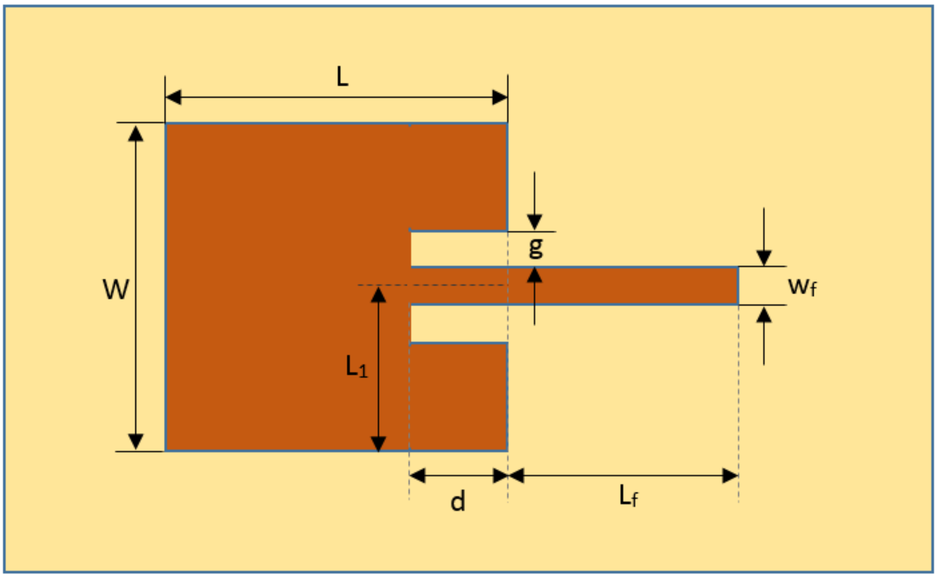


Fig 2.8 recessed microstrip – line feed

$$R_{in(y=d)} = \frac{1}{2(G_e \pm G_{12})} \cos^2\left(\frac{\pi}{L}d\right) \tag{2.8}$$

$$= R_{in(y=0)} \cos^2\left(\frac{\pi}{L}d\right)$$

2.5 Application

A microstrip antennas provides much needed demand of low profile, light weight and also can be easily integrated with ICs and switching elements. It can be produced in large amount by printed circuit technology and thus integrated in mobile phones and other wireless applications like satellite communications, spacecraft, radars, wireless phones and wireless computer networks for large scale production. Some of the major applications of microstrip antennas are:

- Mobile Communication: - Antennas used in mobile applications should be low profile, light weight and energy efficient. Due to large number research going on this field, its disadvantages like low bandwidth are minimized. It can be integrated in handheld gadgets or pocket size equipment, cellular phones, UHF pagers

- Satellite Communication: - microstrip antenna used in satellite communication should give circular polarization. This antenna can be reconfigured easily by dual feed network and other techniques.
- Global Positioning System: - for this application an omnidirectional microstrip antenna with wide beam and low gain can be easily design with dual frequency operation in L-band which is used for GPS.
- Direct Broadcast Satellite System: - for the television services a high gain (~33db) antenna should be used. An array of microstrip antenna with circular polarization can be used.
- In Radar Applications: - An array of microstrip antenna with desired gain and desired beam width can be used for Radar application such as Manpack radar, Marine radar etc.
- Application in Medical Science: - for treating the malignant tumors microwave energy, Microstrip patch antenna is the only candidate which fulfils the requirement of being light weight and adaptable to the surface being treated.

Chapter 3

Frequency Reconfigurable microstrip patch antenna and its application in cognitive radio

In this chapter frequency reconfigurable antenna is discussed in detail with its applications in modern day communication system especially in cognitive radio system. A frequency agile antenna is the type of antenna in which the operating frequency is controlled and keeping the radiation patterns unchanged .this can be achieved by using different types of switches like PIN diodes, varactor diodes, RF MEMS(radio frequency microelectromechanical-systems).these are mostly used in modern day mobile devices that are using varies communication services like GSM(Global System for Mobile Communications), WLAN(wireless local area network), WIFI, and GPS (Global Positioning System)by a single antenna system. Currently for different communication systems different antennas are used that not only increases size and weight of the devices but the versatility also i.e. if any new band is allocated by any service like 4G or LTE (Long-Term Evolution) then cellular phone manufacturers has to develop new devices for it. Further in multi antenna system the communication is more vulnerable to interference. The frequency reconfigurable antenna can have multiband operating frequency or narrowband which can be selected dynamically, this would have better efficiency than multiband or wideband. This antenna can also be used to dynamically control the wideband to narrowband reconfigurability which is primarily investigated for cognitive radio system. The narrowband selectable reconfigurable antenna also fulfils the need for extra filters in RF front end of communication system, it also reduces interference ant receivers.

3.1 classification of frequency reconfigurable techniques

Frequency control in an antenna can be achieved by controlling current distribution in the patch and the ground. In literature many types of defected microstrip structure (DMS) [27] and defected ground structure (DGS) [28] has been reported which are used to get desired output of resonating frequencies. The current distribution in the patch can be changed and thus resonance frequency by using active switches based on micro electro mechanical systems (MEMS) and PIN diodes [2]-[3] or using a mechanical movement of different patches by using stepper motors or even using a photo- conductive switches. Integration of electronic switches in microstrip patch antennas is very easy by soldering, so researchers are been continuously working in this field to design new multifunctional antennas. Beside ease of fabrication there are numerous issues that limits its usage like non-linearity, interference, losses, negative effect of DC biasing circuit and size by the biasing circuit. Table 3.1 shows advantages and disadvantages of tunable switching components used in reconfigurable antennas.

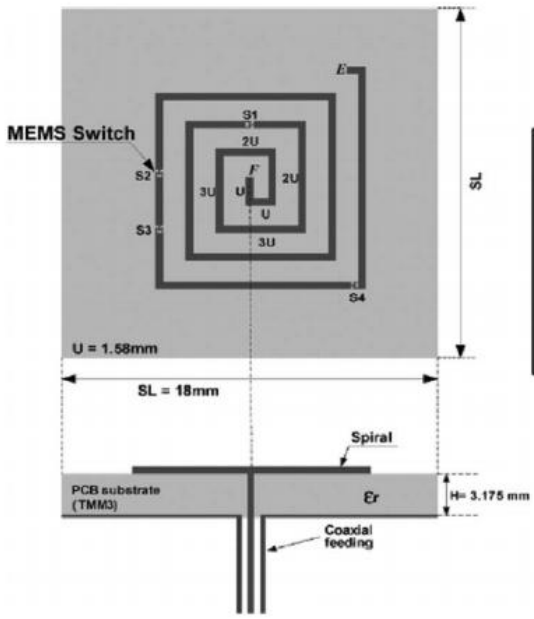
Table 3.1 comparison of different tunable components

Tunable component	**Advantages**	**Disadvantages**
RF MEMS	Insertion loss is less, very high linearity, good isolation, low power loss and consumes no DC power used.	High control voltage is needed (50-100 V) poor reliability, switching speed is slow, discrete tuning, limited lifecycle.
PIN diodes	Driving voltage needed is less, tuning speed and power handling capabilities is high, very low cost, and very reliable as no rotating part.	In its ON state needs high DC bias voltage and consumes large amount of energy, on linear characteristics, poor quality factor and discrete tuning.
Varactor	It gives continuous tuning, and consumes less energy than others.	Highly nonlinear and have low dynamic range and require complex circuitry.
Optical switches	More reliable , linear characteristics , no biasing circuits	Lossy behavior, complex activation mechanism
Physical technique	Does not require bias circuits which eliminates interference , losses and radiation pattern distortion	Slow response, cost, power requirements, size, complex integration,
Smart materials	Size as it has high relative permittivity and permeability	Low efficiency

A frequency reconfigurable antenna can be classified into varies category based on switching network used given below

3.1.1 RF-MEMS Based Reconfigurable Antennas

RF MEMS are new revolution in microelectronics, it is similar to VLSI circuits as it works in a very low power and functions as transducers or sensors in a very small size replacing large circuits. This device works on the principal of mechanical movements to short circuit or open circuit in the surface of antenna structure and redistributing surface current path. Magnetostatic, electrostatic, piezoelectric, or thermal designs are used for the force applied to do mechanical movement.in figure 3.2 [22] an antenna design with fabricated model is shown, where RF MEMS switches has been embedded in the rectangular spiral antenna design. The antenna and switches are fabricated using same substrate, the antenna is fabricated in printed circuit board (PCB) substrate with dielectric constant of 3.27 and feed at its centre by coaxial probe. There are 4 switches connecting 5 spiral arms of the antenna which are increased in steps by this the radiation beam direction of the antenna is altered according to the switch being ON or OFF.



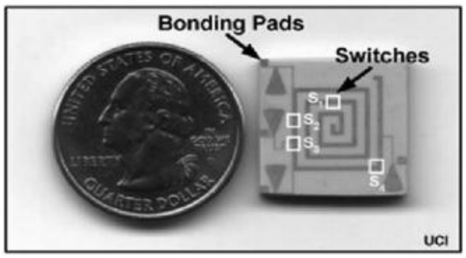
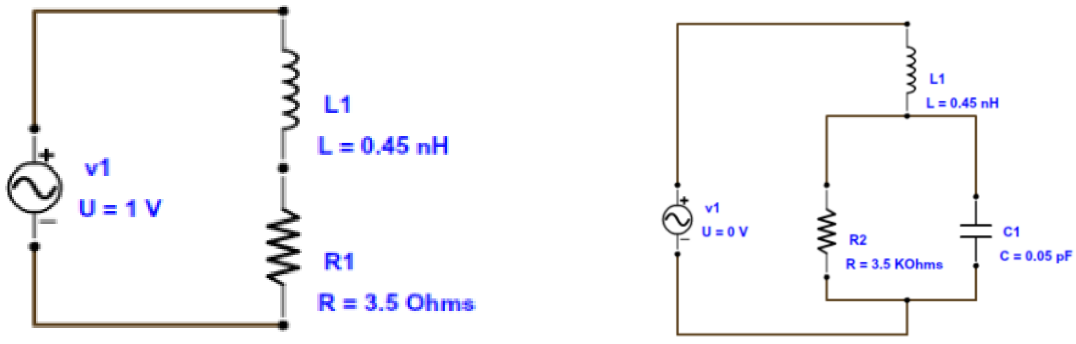


Fig 3.1 (left) reconfigurable antenna based on RFMEMS and (right) fabricated prototype [22]

3.1.2 PIN Diodes Based Reconfigurable Antennas

PIN diodes are very easy to utilize for switching purpose in antenna design as its biasing circuitry is not so complex. When a PIN diode is forward biased it is in ON state, it allows the flow of current and when it is reverse biased it is in OFF state and current flow is restricted. Figure 3.3 shows forward and reverse biased equivalent circuit model for PIN diodes.



(a) (b)

Fig: 3.2 Equivalent circuit of PIN diode in (a) forward bias and (b) reverse bias

PIN diodes as a switching element are of very low cost and easily embedded on the antenna surface. Figure 3.4 [23] shows a frequency reconfigurable antenna used for cognitive radio application where two radiating patches are used with double C slot. The feed of the antenna has two switches attached that controls the operating frequency from wideband to narrowband, two chip capacitors are also used to block DC current. When switch 1 is ON and switch 2 is OFF, dual band is obtained at WLAN band of 5 and 5.7 GHz. When switch 1 is OFF and switch 2 is ON then it operates at 5.6 GHz and 6.2 GHz. The current path becomes longer when both switches are ON and thus gives wideband from 4.9 GHz to 7 GHz.

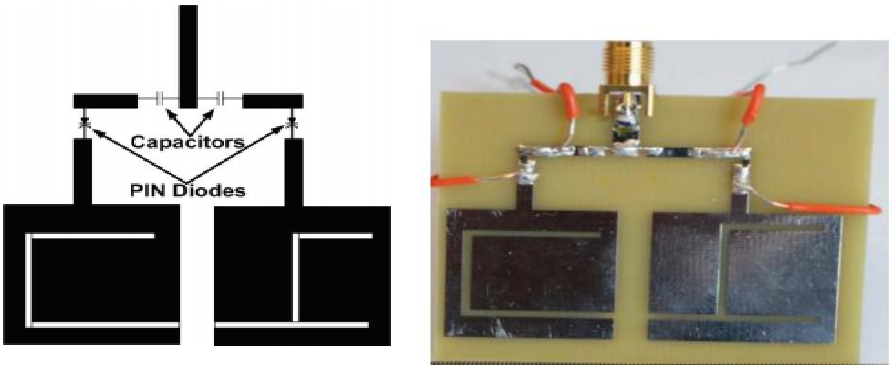


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Fig 3.3 frequency reconfigurable antenna using PIN diode and its fabricated prototype [23]

3.1.3 Antennas based on varactor diodes

Varactor diodes are also known as varicaps and its small junction capacitance varies by applied DC bias voltage as given in equation 3.1.it has continuous tuning ability and has wide applications in RF and microwave applications. Usually silicon or gallium arsenide semiconductors are used to make varactor diodes.an equivalent circuit for varactor in reverse bias condition is shown in figure 3.5.

$$C_j(V) = \frac{C_0}{(1 - \frac{V}{V_0})^{\gamma}} \tag{3.1}$$

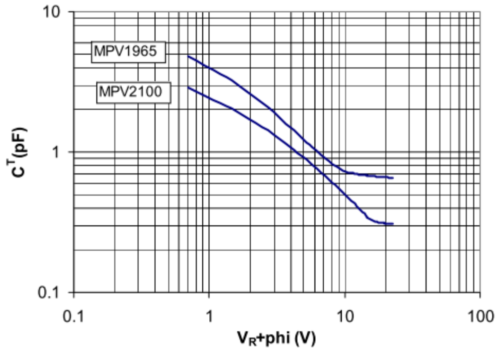


Fig 3.4 Capacitance vs reverse bias voltage of varactor

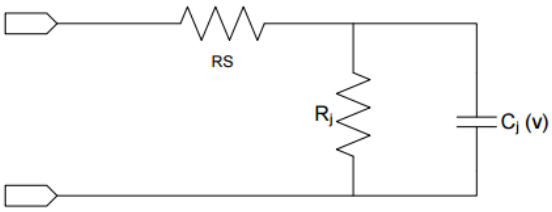


Fig 3.5 Equivalent circuit of varactor

3.1.4 Optically reconfigurable antenna

An optically reconfigurable antennas uses lasers which incident on semiconductor materials like silicon, gallium arsenide. The photoconductive switch works on the principal of electron transfer from valence band to conduction band which makes it ON from OFF state. Laser light with appropriate wavelength is used to make the switch ON or OFF. Its main advantage is linear characteristics and no need of external biasing circuit, this compensates its disadvantage of lossy feature and need of laser light for activation. Most important issue for utilizing it is activation mechanism in antenna structure. Three different activation techniques for optically reconfigurable antenna are as follows.

1) *Using non-integrated optical fibre:*

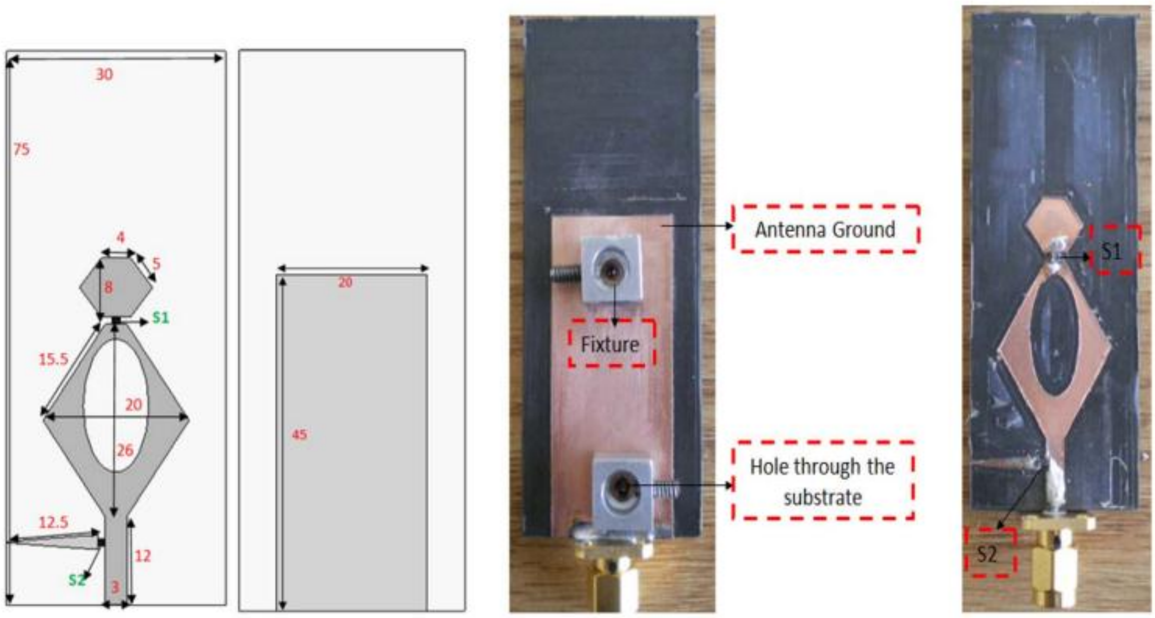
   This is easiest type of activation mechanism but make the antenna bulky. The configuration of this kind of technique consist of slots or gaps in the radiating patch than placing silicon dices over it. Silver loaded epoxy are used to hold them ,than two external 980 nm lasers operating at 200 mW are focused over them to get ON or OFF condition.

2) *Using integrated optical fibre:*

   This techniques works on the same principal as explained above but are fixed on antenna structure itself by drill and plastic fixture. It has advantage that external circuitry which increases size of antenna is not required.

3) *Using integrated laser diode :*

   The antenna structure having integrated laser diode make it less bulky and eliminates the use of fibre cables for delivery of light. It's easier integration with antenna makes it very good candidate for optically reconfigurable antenna design. The required amount of power generated with the help of current drivers. In figure 3.7 author has designed optically reconfigurable antenna for cognitive radio using laser diodes. [24] Laser diodes are integrated in the ground and holes are created to allow the light to pass through.



(a) (b) (c)

Fig 3.6 (a) optically reconfigurable antenna (b) laser diode fabricated with copper fixture (c) front view of the antenna.

Table 3.2 shows electrical properties of different types of switches and compares these properties among PIN diodes, RF MEMs and optical switches

Table 3.2 electrical properties of different switching components

Electrical properties	**RF MEMs**	**PIN diodes**	**Optical switches(si)**
Voltage(V)	20-100	3-5	1.8-1.9
Current(mA)	0	3-20	0-87
Power consumption	0.05-0.1	5-100	0-50
Switching speed	1-200 µsec	1-100 nsec	3-9 µsec
Isolation(1- 10 GHz)	Very high	High	High
Loss(1 - 10 GHz)[dB]	0.05-0.2	0.3-1.2	0.5-1.5

3.1.5 Physically reconfigurable antennas

By physical alteration of the radiating structure of the antenna, reconfigurability ca be achieved. Its main advantage is that it does not require biasing circuit and power loss is less. It has some disadvantages like antenna size increases, the tuning speed is very less, and that is why it cannot be used in cognitive radio system. The modification of antenna structure can be controlled by using stepper motors.

3.1.6 Smart materials based reconfigurable antenna

Materials for example liquid crystals or ferrites are used in making substrate which can change its characteristics. These substrates are used to make reconfigurable antennas, the substrate usually changes its relative electric permittivity or magnetic permeability using different voltage (liquid crystals) or static electric or magnetic fields (ferrites). When liquid crystals are biased by DC source, the molecules are parallel to the fringing fields and thus gives electrostatic field in the substrate, on the other hand molecules are perpendicular when biasing is not provided.

3.2 cognitive radio system

As the communication industry is growing the users and the need for higher data rate is also increasing. The limited spectrum band and current band allocation techniques are not able to fulfil this need. The current band sharing scheme assigns particular band to a communication service which are not dynamic and a licensed user can only use the band allocated to them. Software defined radio is future technology which will solve this problem by dynamic sharing of spectrum, as the unlicensed users(secondary users) can access the licensed band of primary user in opportunistic way without having any interference with them. Spectrum underlay and spectrum overlay are the two techniques that can be used for dynamic sharing of spectrum. In underlay cognitive radio (CR) system the secondary user uses spectrum of primary user under the noise floor, so the transmission power used by secondary user is restricted(less than -42 dBm/MHz in the 3.1–10.6 GHz band). In overlay cognitive system the secondary user searches unused band of primary user for communication without interference.

The users in CR system must follow some requirements in order to communicate without interference and have good quality of services

- Spectrum sensing :– determine the part of spectrum of licensed user which is not been used and is available
- Spectrum decision :– select best vacant channel
- Spectrum sharing :- Manage access to this channel with other users
- Spectrum mobility: - when licensed user need that channel then vacate it.

To fulfil the above requirements cognitive radio has to be reconfigurable, self-organised and software defined and cognitive. Cognitive capability means the system has to sense the entire channel and find out the best available channel which is not being used by the primary user. Reconfigurable capability enables the system to dynamically change its operating frequency and adapt its modulation process and transmit power. Self-organised means the system has the ability of good connection management and mobility, it also ensures security to the spectrum sharing. Figure 3.8 shows the cognitive radio system operation.

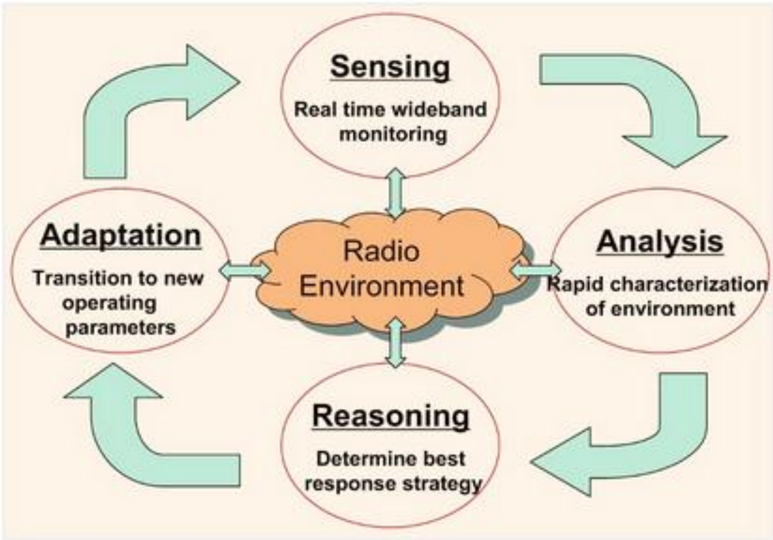


Fig 3.7 cognitive radio system

Two dynamic spectrum access techniques are discussed below

3.2.1 Underlay System

In underlay cognitive radio system both primary and secondary users access the band simultaneously. Secondary user in this approach transmit the signal in very low power i.e. less than -42 dBm/MHz[4] which are spread over large bandwidth, ultra wideband range (3.1 GHz to 10.6 GHz). Power restriction make sure there is very little interference and very short frequency signals insures the high data rate in a short range. This approach does not need spectrum sensing and searching for holes and thus can do communication process while the primary user is using the spectrum. In this technique the UWB spread spectrum technique is used, for this UWB notch reconfigurable antenna is used.[2] The antenna has notches which can be changed according to the need when primary user is using particular band and we have to avoid interference between primary and secondary users. Figure 3.9 shows underlay technique.

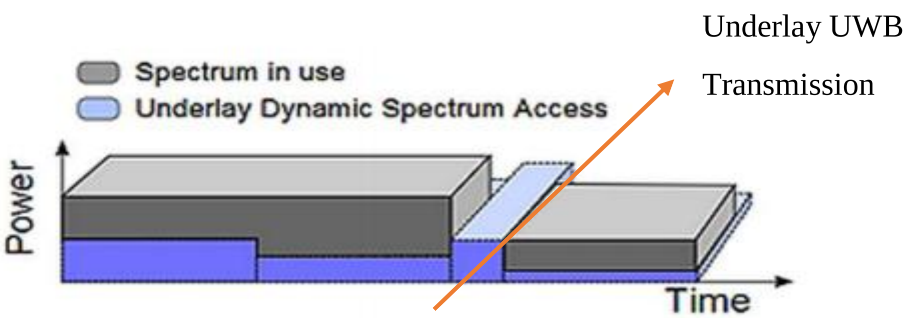


Fig 3.8 underlay cognitive radio spectrum sharing approach

3.2.2Overlay System

In overlay cognitive radio system secondary user has to use a UWB antenna to sense the entire spectrum and choose the unused band where it can transmit or receive communication signals. In this process the unlicensed user has to manage its band requirements and see when and where to transmit its communication signal rather than restrict power of transmission.[4] Most important thing is this is to use better filter techniques so that the signals used should not interfere with licensed user, and also the dynamic management system should sense the channel every defined time to see if that spectrum is being demanded by licensed user. If that spectrum is demanded by licensed user than the secondary user has to sense again the channel and change its operating frequency to new white space (hole) and this process continuous. Overlay approach uses two different ways: The selfish approach, and selfless approach. In selfish approach the secondary user uses all its power to send signal to secondary user. The secondary user has the information about primary user message and this information is used to cancel the interference between primary and secondary transmission. In selfless approach the secondary user divide its power in two ways one to transmit its own message and other to transmit primary user signal. Figure 3. 10 shows overlay cognitive radio system approach in which secondary user uses the spectrum in opportunistic way. [2]

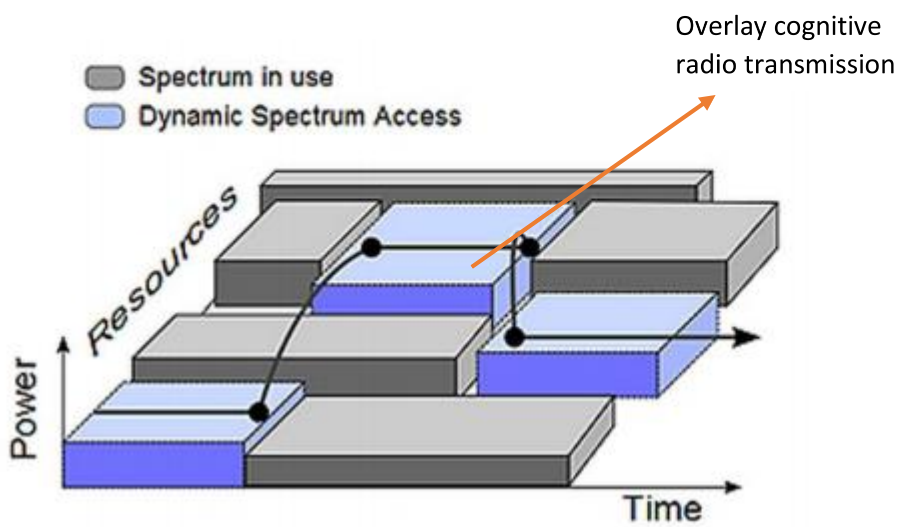


Fig 3.9 overlay cognitive radio system spectrum sharing scheme

3.3 Spectrum sharing and allocation using reconfigurable antennas

In opportunistic spectrum access (OSA) model CR system has to scan and spectrum and spot holes where it can transmit its signal. There are two main ways in which spectrum sensing and communication can be done

- Continuous sensing of the channel and parallel communication process. This approach needs two antenna one is UWB antenna with omnidirectional pattern for sensing and other is reconfigurable narrowband by which communication can take place. It is shown in figure 3.10
- Sensing and communication process is done simultaneously. In this approach single antenna is used which is both wideband omnidirectional for sensing the entire spectrum and narrowband for transmission of communication signals. Figure 3.11 shows single antenna system for CR system.

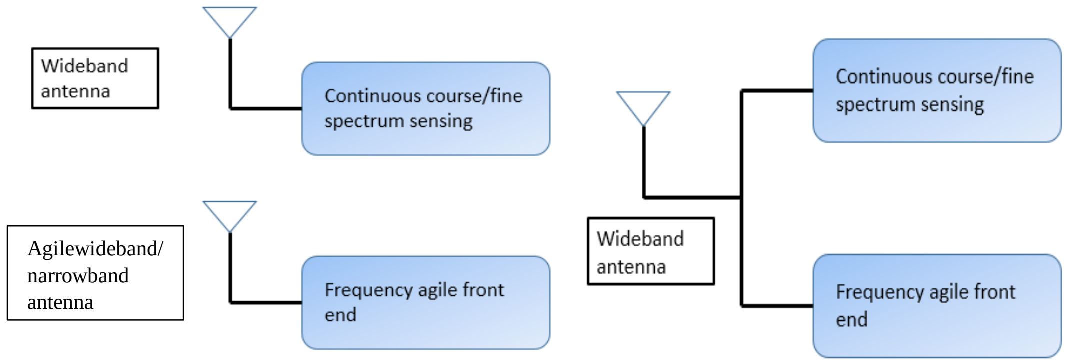


Fig 3.10 parallel sensing and communication process in CR system [2]

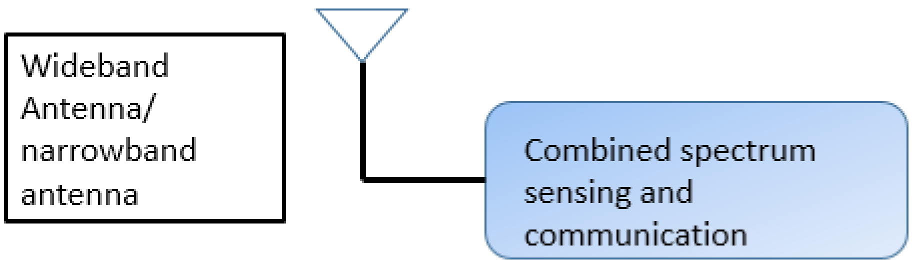


Fig 3.11 combined spectrum sharing approach for CR system [2]

Chapter 4

Frequency Reconfigurable Microstrip Antenna for Cognitive Radio System

In the last chapter cognitive radio system and frequency reconfigurable antennas has been discussed in details. In this chapter antenna requirements for software defined radio is discussed. The recent developments in cognitive radio system has encouraged new challenges in reconfigurable antenna design which can dynamically change the operating frequency keeping radiation pattern and gain to be same. At different resonant mode of structure, keeping gain constant is one of the foremost challenge.one of the potential solution for this problem is to integrate a reconfigurable filter in the feed network of the antenna. This will not modify structure of the radiating patch thus surface current distribution is not altered, so pattern and gain will not be affected much. This type of antennas with filter embedded in it are called filtennas. In this chapter three frequency reconfigurable antennas with embedded bandpass filters on first two designs and bandstop filter in third design are shown. First two antennas are used designed for overlay cognitive radio in which sensing and communication antennas are required, third design is designed for underlay cognitive radio in which a notch reconfigurable antenna is required.

4.1) UWB antennas

For underlay cognitive radio system and sensing of the spectrum ultra wideband antenna is required. This kind of antenna radiate short pulses of low power over short range. It is used in medical applications, GPRs, PC peripherals, radar-imaging technology. UWB antenna can be defined by its fractional bandwidth as given by Defence Advanced Research Projects Agency (DARPA) Federal Communications Commission (FCC) as given below [17]

$$\text{BW} = 2\frac{f_h - h_l}{f_h + h_l} \geq \begin{cases} 0.25 & DARPA \\ 0.2 & FCC \end{cases} \quad (4.1)$$

Designing UWB microstrip antenna is a challenging process as patch antenna is generally narrowband. But in general we can follow steps given below to design UWB antenna

- Selection of structure is critical, shape of radiating patch should be selected properly. Smoother flow of current in round shape and circular patch leads to wideband characteristics.
- Ground plane should be properly designed as it plays major role in bandwidth enhancement. Partial ground plane and properly placing slots in ground plane are used to design UWB antenna.

- Impedance matching between feed and radiating patch can be achieved by tampered connection, inset feed, or placing slits below the ground plane. The impedance matching generally is optimized by using computer simulation tools like CST.

- Fractal antenna design leads to wideband and multiband characteristics.as they are self-repetitive and the increase in electrical length without changing the overall physical size of the antenna gives UWB characteristics.

4.2 Single-port antennas for overlay Cognitive radio

Antennas designed for overlay CR system are capable of sensing the channel and choosing narrow band for communication as shown in figure 4.1

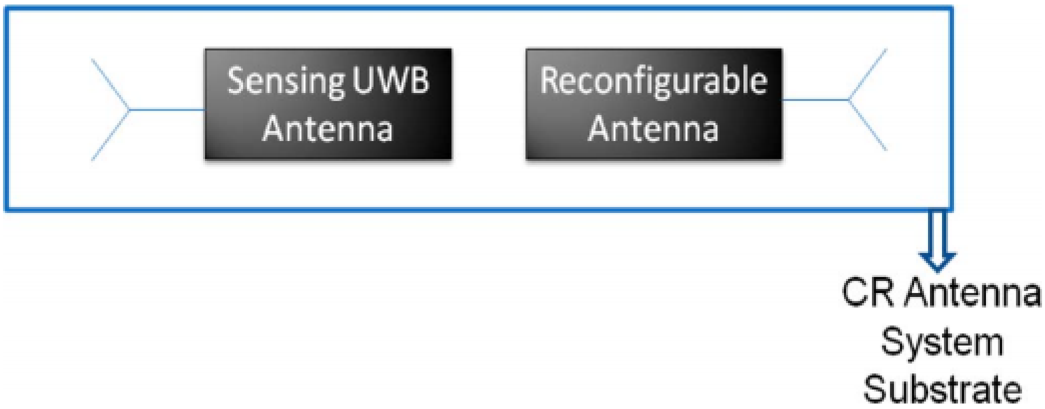
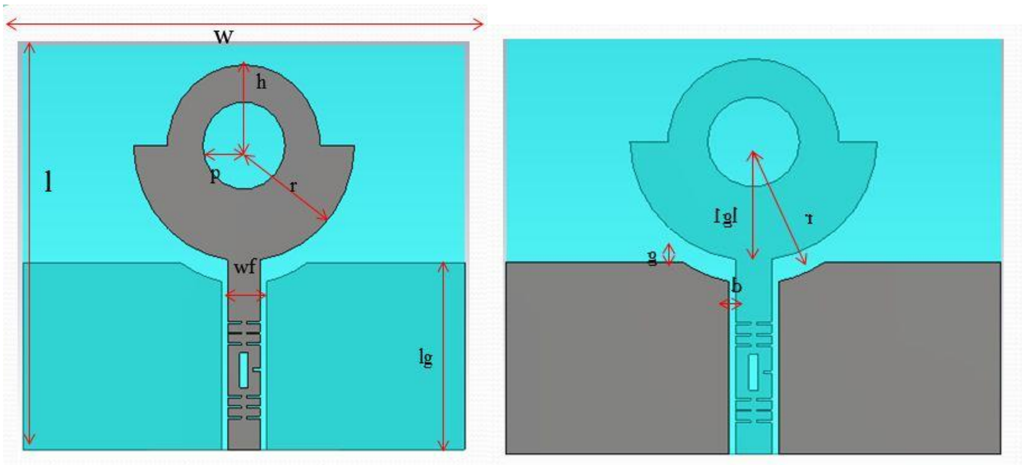


Fig 4.1 antenna system for overlay cognitive radio system

The antenna designer for cognitive radio system should consider some key points such as the operation of sensing and communication antenna should not affect each other, the sensing antenna should be omnidirectional to get signal from every directions. The reconfigurable antenna should have omnidirectional or reconfigurable radiation pattern to cancel out other signals. Last point is to make the antenna system as small as possible to fit in mobile devices. Instead of using two antennas for sensing and communication the antenna proposed here uses single antenna for both purposes, it not only reduces size but also eliminates degraded radiation pattern and coupling between two ports. Single-port antenna design is more challenging.

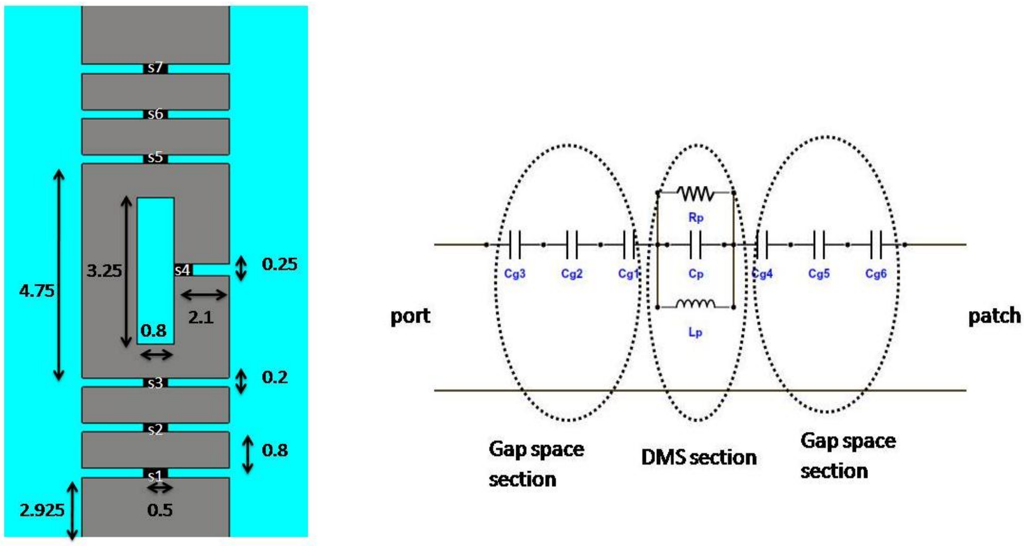
4.2.1 Proposed Antenna Geometry

The proposed antenna geometry is shown in figure 4.2 (a) front view (b) rear view .two semicircular patches are used as radiating elements . the substarte used is FR4-epoxy with dielectric constant of 4.3, height 1.6 mm and loss tangent 0.0018.Table 4.1 shows the values of the parameters used in designing the antenna.For the purpose of achieving frequency reconfigurability, three pairs of gaps are symmetrically placed around the T-slot, using DMS bandpass structure[6] and seven electronic switches are placed across the slots as shown in fig. 4.4(a)and 4.4(b) shows the equivalent circuit of the DMS bandpass filter.



(a) (b)

Fig 4.2 A reconfigurable UWB/NB antenna (a) front view (b) rear view



(a) (b)

Fig 4.3 Bandpass DMS configuration (a) closer view of the filter (b) related Equivalent circuit

According to [6] the capacitance Cp in pF, the inductance Lp in nH and the resistance Rp in ohm of the equivalent circuit of a bandstop DMS filter as shown in Fig. 4.4 is given below:

$$C_p = \frac{fc}{200\pi(f_0^2 - f_c^2)} \tag{4.2}$$

After we extract capacitance, the inductance of equivalent circuit is extracted,

$$L_p = \frac{1}{4\pi^2 f_0^2 C} \tag{4.3}$$

Where fc is the resonant frequency and f_0 is the 3-dB cutoff frequency. For simplicity we ignore the frequency dependence of Rp and use a constant value for Rp obtained for $\omega = \omega_0$. Using,

$$R_p = 2z_0 \frac{1 - S_{21}(\omega_0)}{S_{21}(\omega_0)} \tag{4.4}$$

Where S_{21} is the transmission coefficient that can be obtained by using port 2 in place of the patch of the antenna. In the case of a bandpass DMS configuration, the equivalent inductance and coupling capacitance form a series resonance circuit. The design approach for the proposed antenna is shown in figure 4.5

4.2.2 Simulation Results and Discussions

The antenna proposed is a single port frequency agile for CR system. It has a radiating ring shaped patch and microstrip feedline which is having T slot which basically acts as a bandstop filter and parallel slots which acts as a capacitors making overall bandpass filter. The antenna having embedded filter are also known as filtennas. Six switching cases are considered, as indicated in Table 4.2. Case 0 corresponds to all the switches being ON. In this case, the effect of the filter is canceled, bringing back the UWB response of the antenna. The reflection coefficient curve is shown in fig 4.5 which shows UWB band covering from 3GHz to 10 GHz. The frequency characteristics of the filter depend on the dimensions of the slots, and on the switching state. The computed reflection coefficient plots for the six switching cases are given in Fig. 4.7.

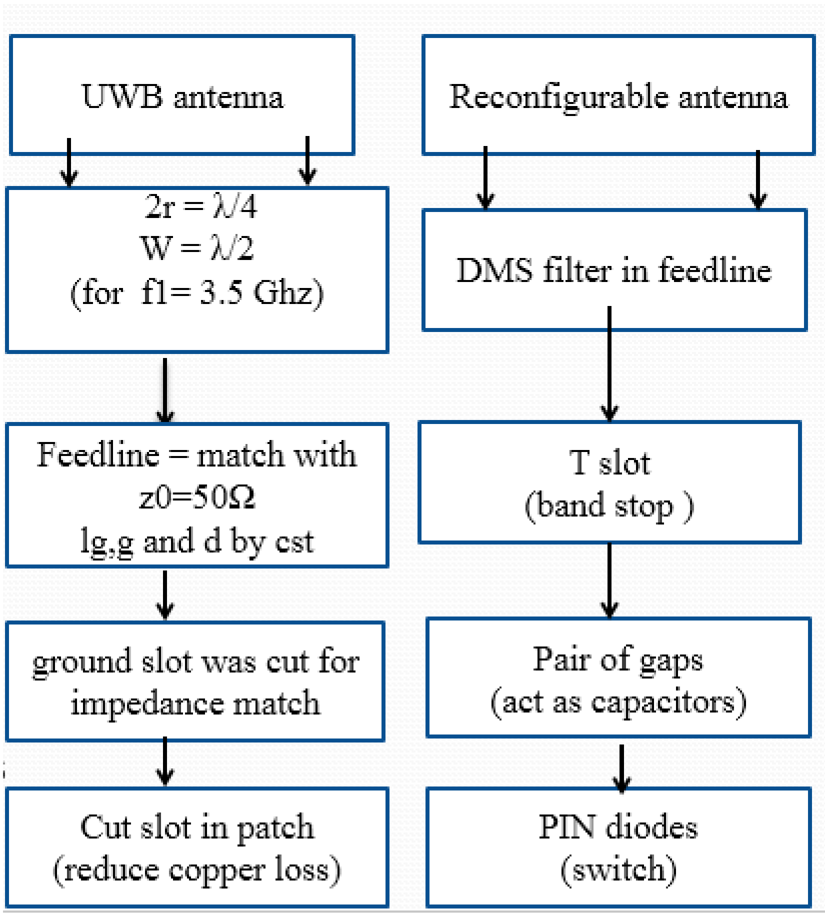


Fig 4.4 design steps for proposed antenna

Table 4.1 values of the parameters of proposed design

NAMES	VALUES	DESCRIPTION
l	38	Length of the substrate
w	44	Width of the substrate
lg	17.6	Length of the feedline
h	6.83	Radius of smaller patch
g	0.6	Gap between feed and ground
d	0.8	Gap between patch and ground
wf	3.2	Width of feedline
r	10.5	Radius of larger patch
p	3.5	Radius of slot in patch

The proposed antenna can be used as a front end system for cognitive radio system. When all the PIN diodes are in ON state i.e. case 0, the antenna works for sensing the entire spectrum to get vacant bands in the spectrum. Whereas in other cases as shown table 4.2,we selectively OFF the PIN diodes to operate in required band to communicate Further resonances can be obtained by including more gaps around the T-slot and appropriately choosing their locations and widths as shown in the Table4.1 .By controlling the switches the resonant frequency can be varied from 5.33GHz to 10 GHz, the parameters for designing this antenna are given in table4.1.It must be noted that the switches used here is simulated in CST by using equivalent circuit model in forward and reverse biased condition as shown in fig 4.7

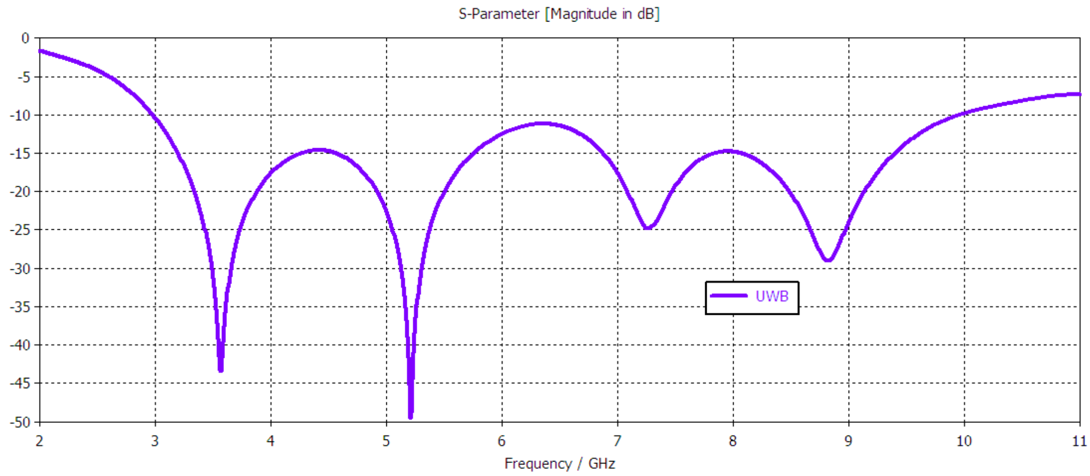


Fig 4.5 Simulated reflection coefficient curve for UWB case of the antenna

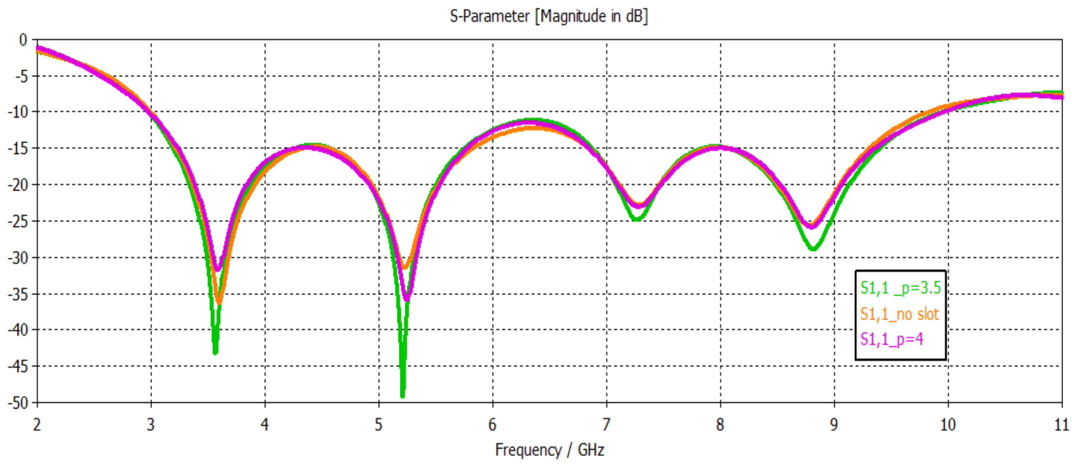


Fig 4.6 simulated s11 vs frequency curve varying slot in the patch.

Figure 4.6 shows three return loss curve for different conditions of slot radius on the radiating patch. When slot radius is 3.5 mm s11 is deepest however for no slot and slot of radius 4 mm and 3.5 mm are almost same. Slot has been cut from patch to reduce copper loss without affecting gain and radiation pattern. Reflection coefficient (dB) demonstrations that when all PIN diodes are ON, S11 is below -10 dB in frequency band 3.0 GHz to 10GHz, this circumstance is used to check the spectrum to find holes /unused frequency bands. The simulated result is shown in fig 4.6 and 4.7 which shows the agreement for all cases as in Table 4.2. For case 1 switches 3, 4 and 6 is in off state that gives operating band from 6.33 GHz to 7.07 GHz, likewise other cases gives different operating bands. Figure 4.7 shows reflection coefficient curve for communication antenna, different states can be achieved by varying the PIN diodes states.

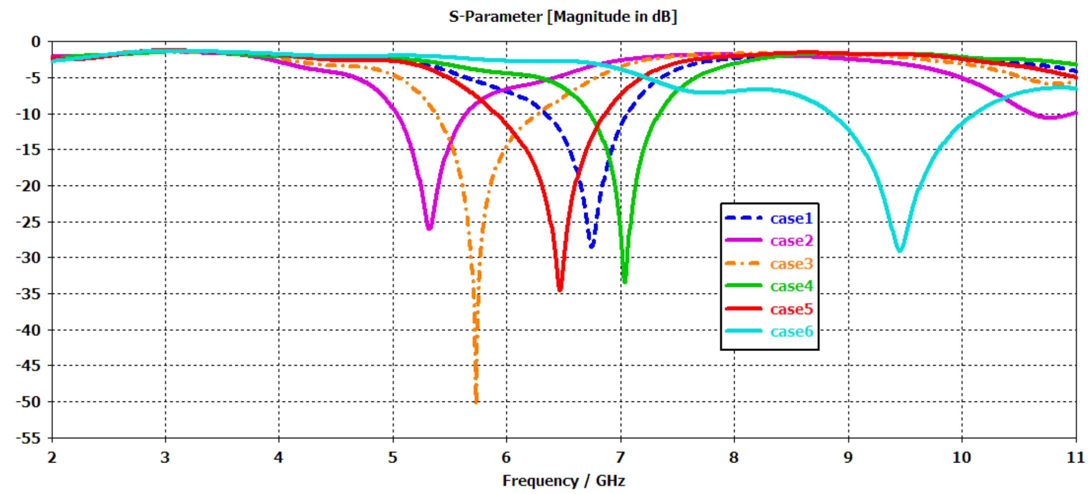


Fig 4.7 simulated return loss curve for communication antenna

Table 4.2 simulated bandwidth for each case

CASE	SWITCHES IN OFF	BANDWIDTH IN GHz (%)
0	None	from 3.1 GHz to 10 GHz
1	S3,s4,s7	6.33-7.07(10.7%)
2	S1,s4,s7	5-5.6(12.3%)
3	S2,s4,s7	5.37-6.28(13.9%)
4	S3,s4,s5	5.9-6.86(14.3%)
5	S3,s6	8.83-10.15(12%)

The gain (dBi) and efficiency for UWB antenna in each of the 6 cases with resonating frequency at 6.734 GHz it is 4.75 dBi this means antenna placed at far field would receive 4.75 dB higher power than the antenna would receive from an isotropic antenna with same input power. Thus gain is comparison of proposed antenna with isotropic one. ,at 5.33 GHz 3.491 dBi, at 5.762 GHz 3.869 dBi, at 7.04 GHz 4.687 dBi, at 6.338 GHz 4.33 dBi, at 9.45 GHz 4.33 dBi efficiency for different respective frequency is shown in table 4.3. efficiency is given is percentage ,it can be shown in decibel or number from 0 to 1 for example an efficiency of 0.5 or 50% is -3 dB

Table 4.3 realized gain and efficiency of the proposed UWB antenna

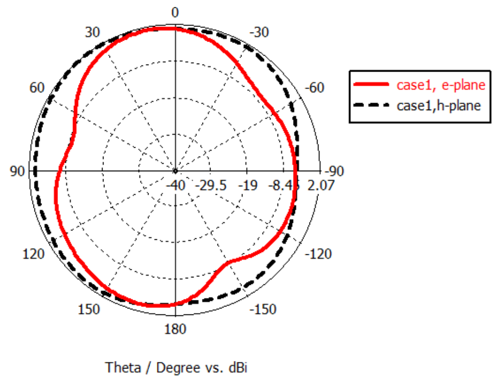
CASE	Resonant frequency (GHz)	GAIN(dBi)	EFFICIENCY (%)
1	6.734	4.75	90
2	5.33	3.491	97
3	5.762	3.869	90
4	7.04	4.687	90
5	6.338	4.33	91
6	9.45	4.33	82

The gain and efficiency in case of reconfigurable antenna is given in table 4.4 more than 60% efficiency is good for microstrip antenna. For the proposed antenna more than 80% in case of UWB antenna and due to filtering mechanism some losses occur and it is more than 70% in case of reconfigurable antenna.

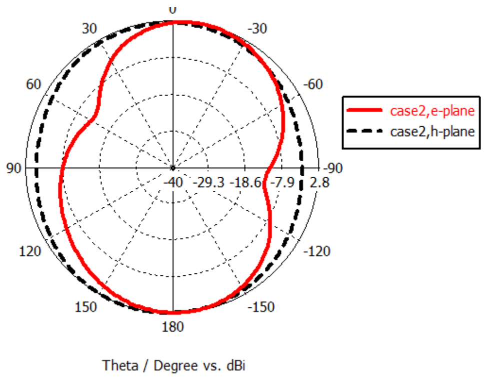
Table 4.4 realized gain and efficiency of the proposed reconfigurable antenna

CASE	Resonant frequency (GHz)	GAIN(dBi)	EFFICIENCY (%)
1	6.734	3.81	70
2	5.33	2.02	79
3	5.762	2.7	82
4	7.04	4.14	70
5	6.338	3.76	76
6	9.45	3.8	83

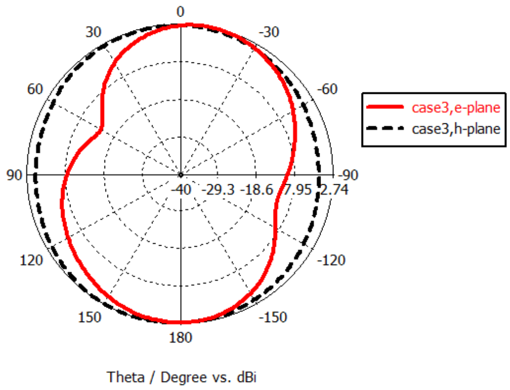
Figure 4.7 shows radiation pattern with principal E and H plane. It shows that antenna is almost omnidirectional in both planes which is good for mobile application and sensing of the channel.



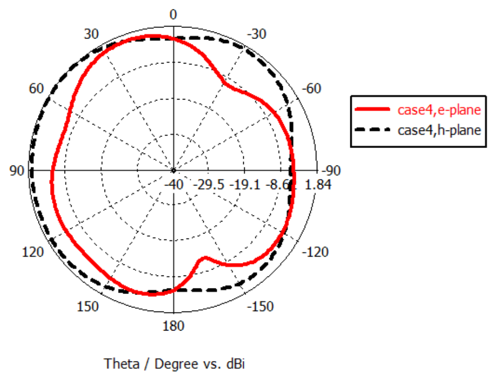
(a)



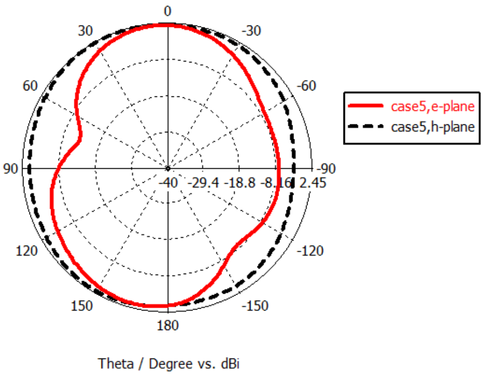
(b)



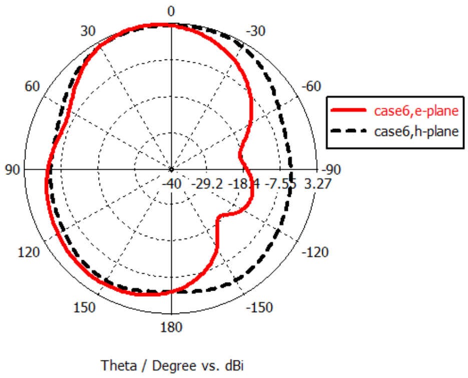
(c)



(d)



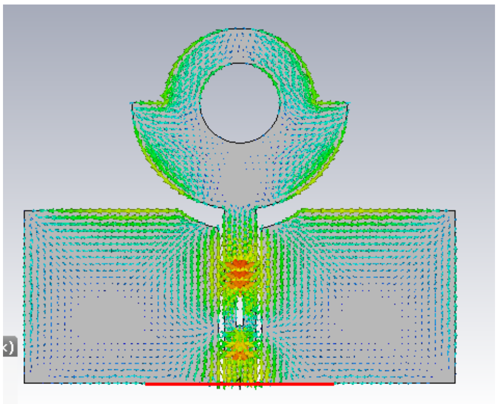
(e)

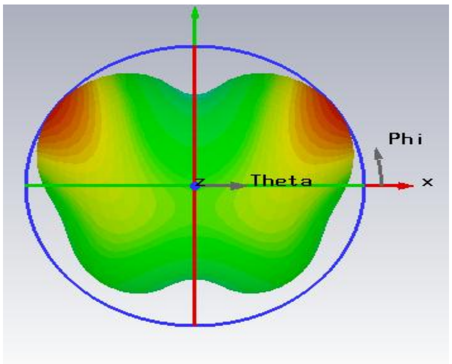


(f)

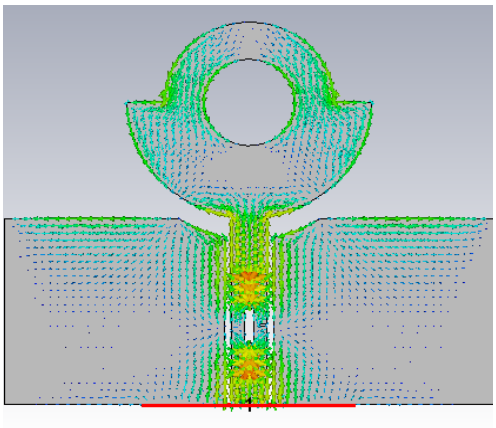
Fig 4.8 normalized E plane and H plane radiation pattern at frequencies (a) 6.7 GHz (b)5.32GHz (c)5.7GHz (d)7.04GHz (e)6.46GHz (f) 9.4 GHz

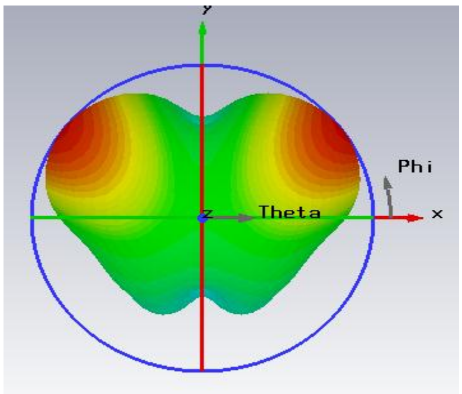
Figure 4.8 shows 3D radiation pattern and surface current distribution of the proposed design at three frequencies



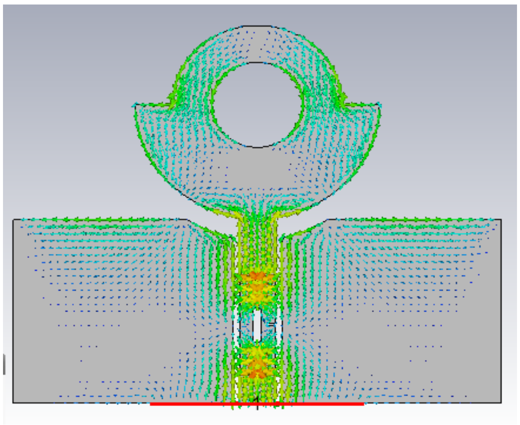


(a)





(b)



(c)

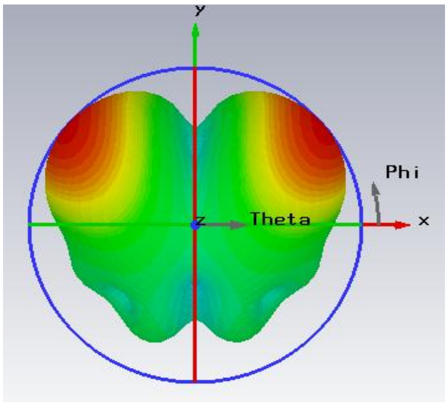


Fig 4.9 3D radiation pattern and surface current distribution at frequencies (a) 5.2 GHz (b) 6.5 GHz (c) 7.2 GHz.

4.3 dual-port antennas for overlay Cognitive radio

In the overlay cognitive radio system antenna are used for two purposes sensing and communication. In single port antenna sensing and communication cannot be done simultaneously, as to do one other has to be stopped, this may lead to failure of real time communication. Also it may induce interference to primary user. To resolve this problem dual port antenna is proposed, but it has some disadvantages like size and weight increases, coupling between two ports and interference between them [2]. One antenna is UWB and other is narrowband and reconfigurable, proposed design is having good isolation, the S12 vs frequency curve given fin figure 4.11 shows it is below -15 dB

4.3.1 Proposed Antenna Geometry

The proposed antenna geometry is shown in figure 4.9 (a) front view 4.9(b) rear view. It consist of two square patches with microstrip feedline. The substrate used in this design is FR4- epoxy with dielectric constant 4.3, thickness is 1.6 mm and loss tangent of 0.0018. The optimized parameters of the proposed design is given in table 4.5.the reconfiguration in the narrowband antenna is created by embedding G shaped filter with two parallel slots and a varactor for tuning in feedline.as the filter is in filter, it does not degrade radiation pattern or surface current distribution and thus gain and efficiency does not changes drastically. Varactor diode is used as a switch in the reconfigurable narrowband in this case for fine tuning that was not possible in case of other switches. The bandpass defected microstrip structure (DMS) filter is shown in figure 4.10 with its equivalent circuit.

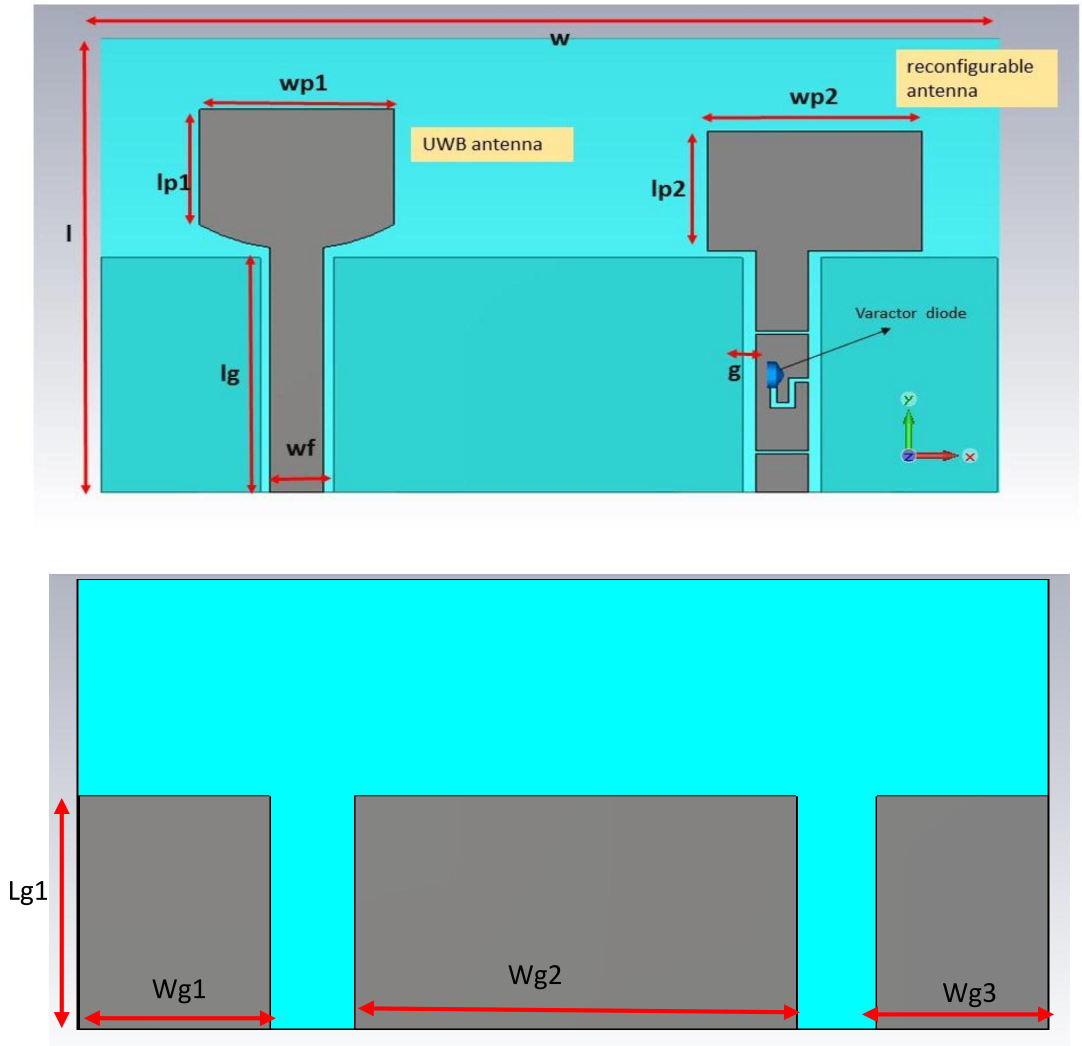


Fig 4.10 proposed antenna design2 (a) front view (b) rear view

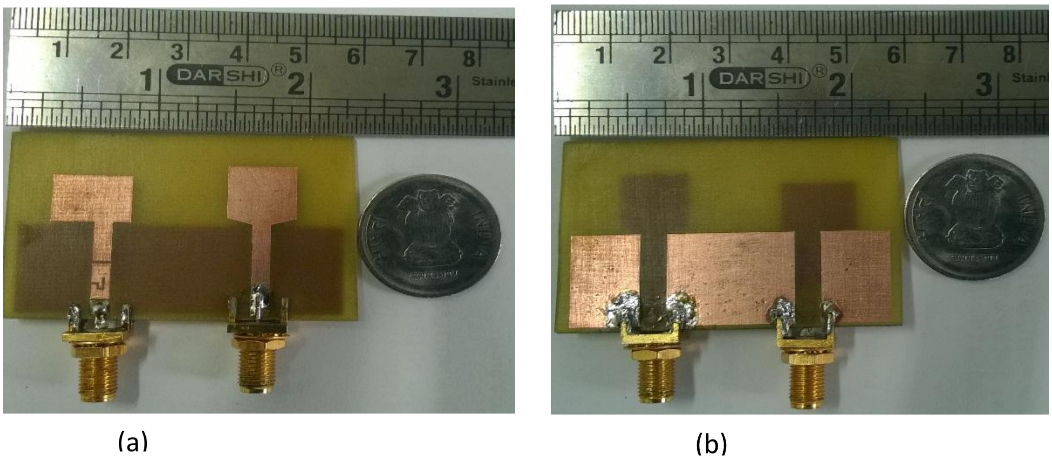
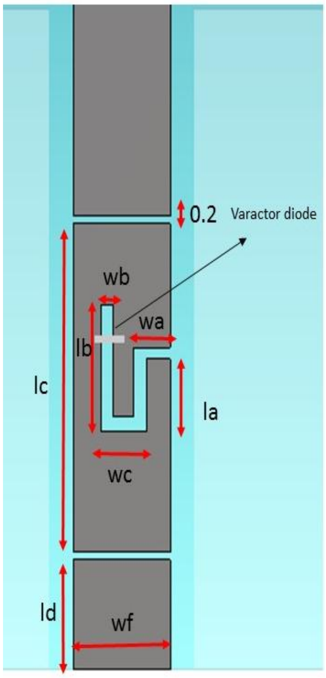
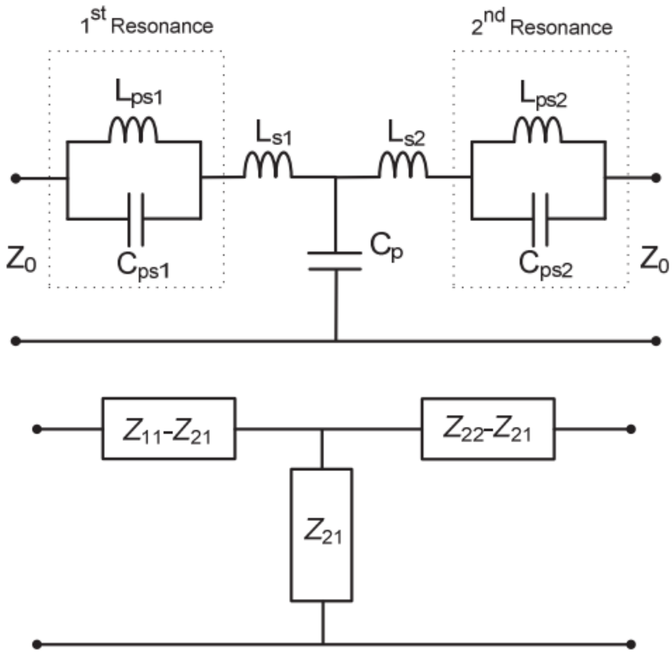


Fig 4.11 Fabricated antenna design (a) front view (b) rear view



(a)



(b)

Fig 4.12 (a) design of proposed DMS filter 2 (b) equivalent circuit diagram

G shaped bandstop filter is modelled by two LC resonator as shown in figure 4.10(b).The values of LC resonator can be extracted by EM simulation , the equation for Lpsi and Cpsi is given below, these values are derived from transmission parameters S21 of a port. [9]

$$C_{psi} = \frac{1}{4\pi Z_0 \Delta_{3dB\_f0i}} \quad for \ i = 1, 2 \tag{4.5}$$

$$L_{psi} = \frac{1}{(2\pi f_{0i})^2 C_{psi}} \quad for \ i = 1, 2 \tag{4.6}$$

Where,

Z_0 = characteristic impedance of the network port

f_{0i} = First and second resonant frequency.

C_{psi} = capacitance of the equivalent circuit

L_{psi} = inductance of the equivalent circuit

The remaining parameters are calculated by matching Z network as shown in figure 4.10 (b). [9]

$$C_p = -\frac{1}{2\pi f_T X_{21}} \tag{4.7}$$

$$L_{si} = -\frac{X_{ii} - X_{21}}{2\pi f_T} + \frac{L_{psi}}{(\frac{f_T}{f_{0i}})^2 - 1} \quad \text{for } i=1,2 \tag{4.8}$$

Table 4.5 optimized values of parameters for (a) UWB antenna (b) reconfigurable antenna (c) ground plane (d) filter network

Name	Values (mm)
R	10.5
W	55
L	34
Wp1	11.8
Lp1	10.5
Lg	17.6
Wf	3.2

(a) UWB antenna parameters

Name	Values (mm)
Lp2	9.42
Wp2	13.14
G	0.6
Lg	17.6

(b) Reconfigurable antenna parameters

Name	Values (mm)
Lg1	17.6
Wg1	12
Wg2	22
Wg3	12

(c) Ground plane parameters

Name	Values (mm)
La	3.14
Lb	4.6
Lc	6.95
Ld	2.925
Wa	0.8
Wb	0.4
Wc	0.8
Wf	3.2

(d) Feedline filter parameters

4.3.2 Simulation results and discussions

The proposed antenna is dual port, one antenna is giving UWB bandwidth from 3.4 GHz to 13.2 GHz .the reconfigurable antenna is giving dual band or triple band with different resonating frequencies according to the values of capacitance of varactor diode. Figure 4. 11 shows the UWB antenna reflection coefficient curve and isolation coefficient curve, i.e. is below -15 dB, that means if port 1 is given 1W power than port 2 will receive below 0.03 W power, thus a good isolation is between them and they will not interfere each other. Figure 4.12 shows return loss curve of reconfigurable antenna with dual and triple resonating frequency, one is around 4 GHz to 5 GHz, second is from 6 GHz to 10 GHz, and third is from 10GHz to 11 GHz.

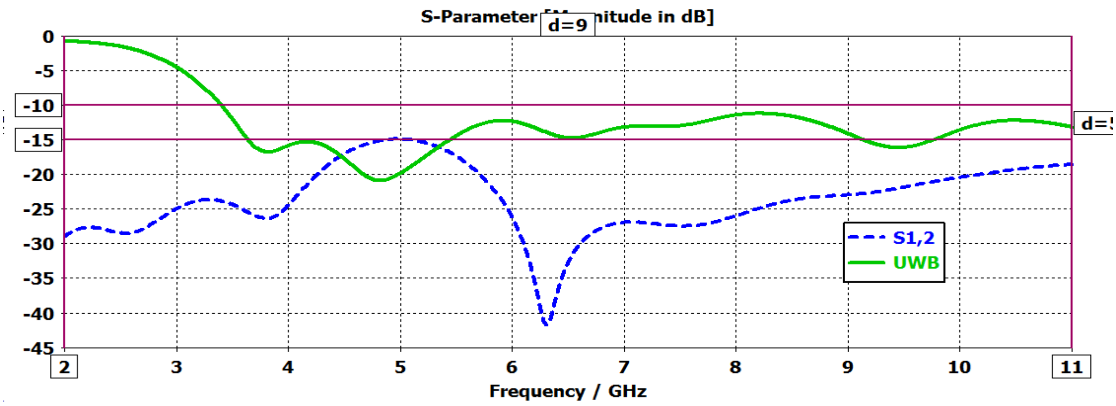


Fig 4.13 reflection coefficient and isolation coefficient curve for UWB antenna

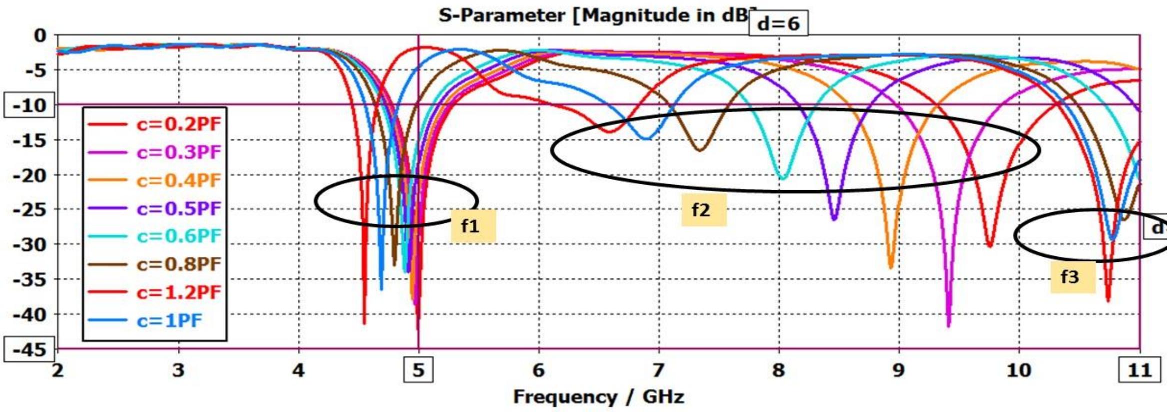


Fig 4.14 Reflection coefficient curve for reconfigurable antenna.

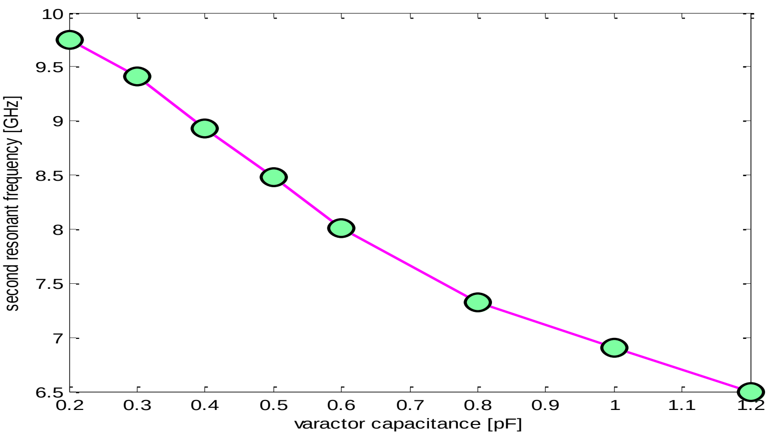
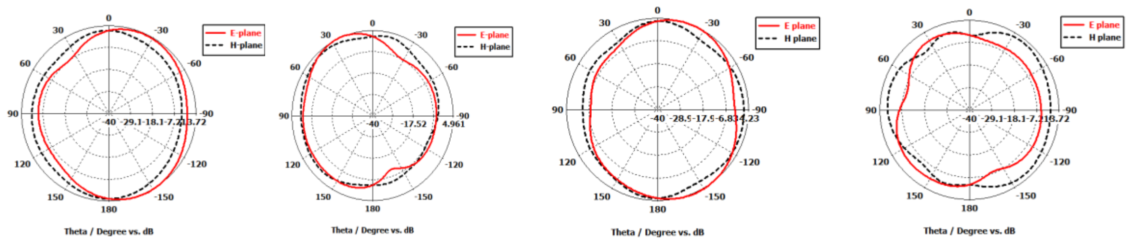


Fig 4.15 Variation of second resonating frequency Vs capacitance of varactor diode

Table 4.6 given below shows the resonating frequency, gain and efficiency of UWB and reconfigurable antenna at different bias voltages to the varactor. The radiation pattern of UWB and reconfigurable antenna for two frequencies 9.75 GHz and 6.5 GHz is shown below.



(a) (b) (c) (d)

Fig 4.16 UWB antenna polar radiation pattern at (a) 6.5 GHz (b) 9.75 GHz and polar radiation pattern of reconfigurable antenna at (c) 6.5 GHz and (d) 9.75 GHz.

Table 4.6 resonating frequency, gain and efficiency for different varactor capacitance

CASE	Varactor diode capacitance value (PF)	Resonating frequency		Gain (dB) and efficiency (%)			
		fr1(GHz)	fr2(GHz)	UWB		Reconfigurable(fr2)	
				Gain	Efficiency	Gain	efficiency
1	0.2	5	9.71	4.47	80	5.37	75
2	0.3	5	9.41	4.1	81	4.63	77
3	0.4	4.94	8.93	3.64	82	3.56	75
4	0.5	4.90	8.48	3.2	83	2.7	76
5	0.6	4.87	8.01	2.86	84	2.75	79
6	0.8	4.8	7.32	3.553	85	3.6	79
7	1	4.68	6.9	4.1	86	3.57	78
8	1.2	4.5	6.5	4.27	87	3.6	76

4.4 Antennas with reconfigurable band rejection

The UWB technology can be used in underlay cognitive radio system however it can be used in overlay CR system. These two system has a major difference in transmitting power, in case of underlay system very low transmitting power(below the noise floor of primary user) is used but the signal is spread over a large frequency range , this increases the data rate enormously but within a short distance communication. In case of overlay system high transmitting power can be used which is comparable to licensed user, which allows long distance communication. Conditions to implement UWB technology for long distance communication in overlay cognitive radio system.

- If the targeted licensed spectrum is completely free of signals of other system or the secondary user can adjust its band usage to give nulls in the bands used by licensed system.
- If this mode of operation is allowed by the regulation authorities like Federal Communications Commission (FCC).

The UWB system to operate in overlay CR network must be able to sense the entire spectrum then determine the band which are being used by primary user. After determining these bands it must induce notches in it to prevent interference with licensed user signals. The notch introduced by UWB antenna to prevent interference should be reconfigurable to introduce nulls wherever in the band primary user is transmitting signal. Several techniques can be used to design UWB antenna with notch. Split-ring resonators (SRRs) and the complementary split-ring resonators (CSRRs) are the most famous of them. The SRR comprises of two concentric metallic split rings printed on dielectric substrate. Apertures replaces the metal parts of the original structure and metal plates replaces the apertures, hence giving complimentary pair. Negative permeability is shown by SRRs at the resonance and negative permittivity is shown by CSRRs that leads to band rejection. Figure 4.16 shows topologies of SRRs and CSRRs with their equivalent circuit model

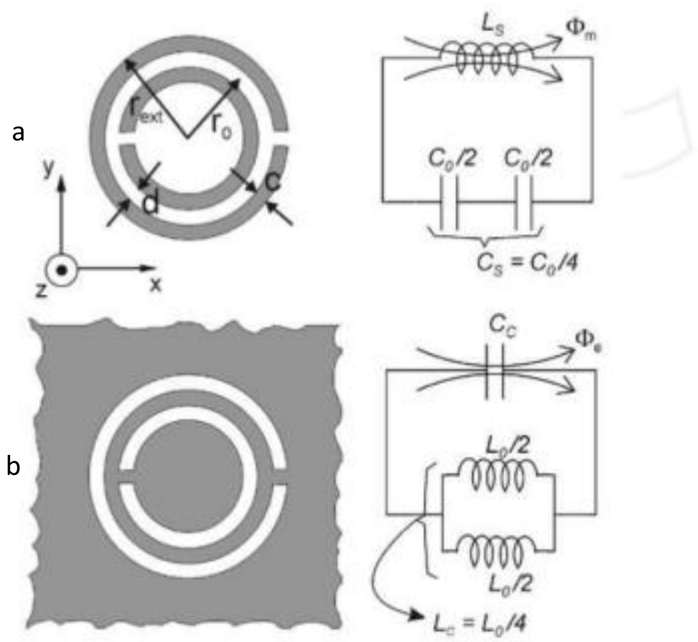


Fig 4.17 Topologies of (a) SRRs and (b) CSRRs with its equivalent circuit model.

4.4.1 Proposed Antenna Geometry

The front and back view of the proposed antenna is shown in figure 4.17. The substrate is FR4- epoxy with dielectric constant 4.3 and height 1.6 mm and loss tangent 0.0018. Partial ground plane and rectangular slot behind feedline increases the bandwidth of the antenna.

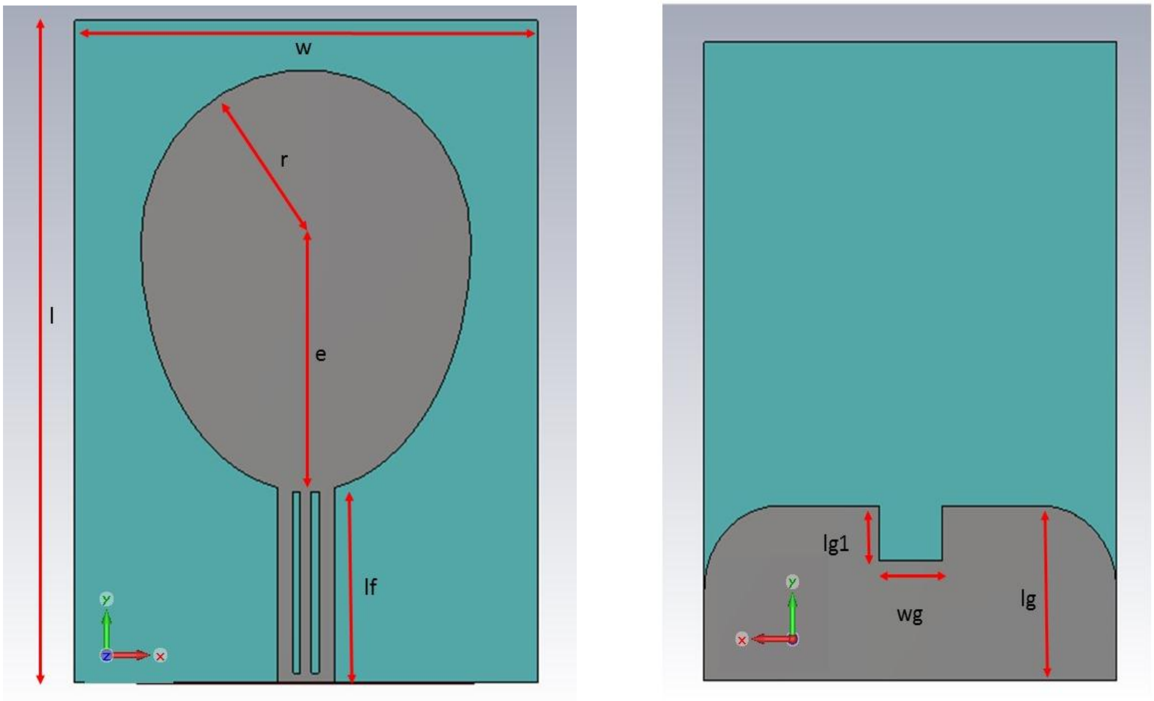


Fig 4.18 the proposed design3 (a) front view (b) rear view

The optimized values of design parameters are shown in table 4.7 and the filter network is show in figure 4.18.

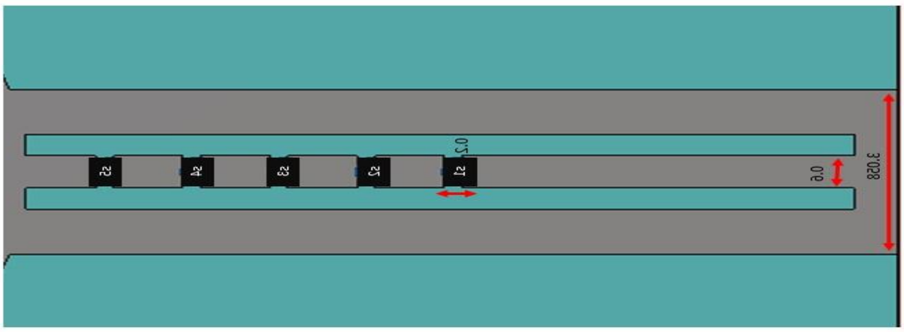


Fig 4.19 reconfigurable bandstop filter embedded in feedline

Table 4.7 optimized values of the antenna parameters

Name	**Values (mm)**
l	41.8
w	25.2
r	9
e	13
lg1	3
wg	4
lg	9.5
lf	10.2

4.4.2 Simulation Result

The reflection coefficient of UWB antenna when filter is disabled by switching ON all the PIN diodes. In the proposed design 5 PIN diodes are used to reconfigure band rejection of the antenna, the simulated return loss curve of reconfigurable antenna when PIN diode is selectively chose to give notch at 5 GHz, 5.7 GHz,6.45 GHz,7.5 GHz,9 GHz. The UWB antenna reflection coefficient shows the bandwidth from 2.8 GHz to 13.2 GHz which covers the UWB band defined by FCC (3.1 GHz to 10.6 GHz).

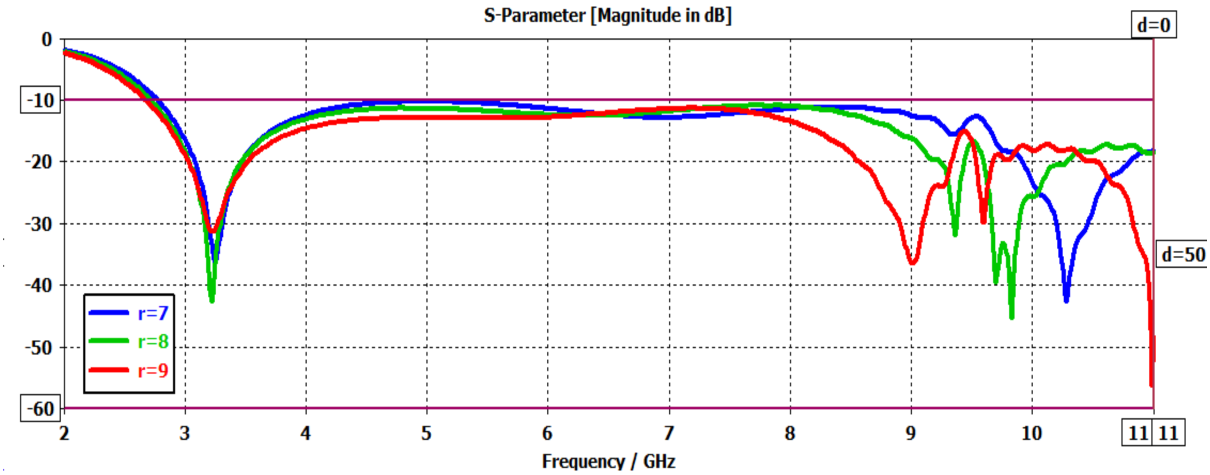


Fig 4.20 reflection coefficient of UWB antenna

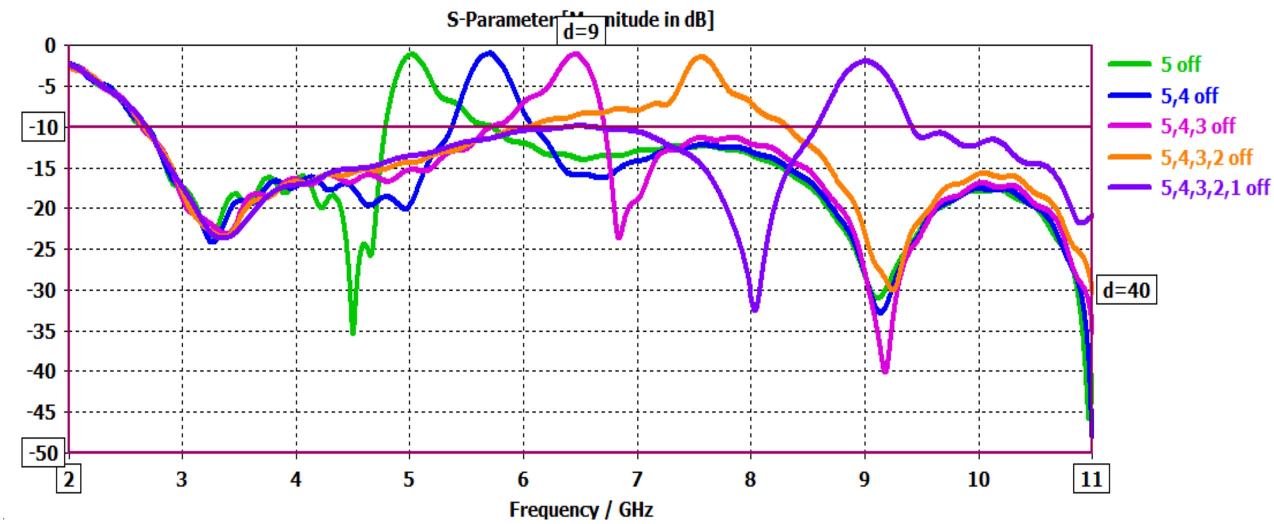


Fig 4.21 reflection coefficient curve for reconfigurable notch antenna

The voltage standing wave ratio (VSWR) shown below shows that at notch or frequency rejection narrowband the VSWR goes drastically high. For an antenna to radiate VSWR should be less than 2. Table 4.8 as given below states notch band, gain of UWB antenna gain at notch and gain at reconfigurable antenna which shows up to -11 dBi, i.e. The antenna at this frequency band will radiate nothing but reflected back.

Table 4.8 notch frequency, gain of UWB and reconfigurable antenna at different switching states of PIN diodes

Case	Switches in off state	Notch bands(GHz)	Gain rec.(dB)	Gain UWB(dB)
1	S5	5	-11.2	3.2
2	S5,s4	5.7	-11	3.7
3	S5,s4,s3	6.45	-5	4.2
4	S5,s4,s3,s2	7.5	-5.1	3.7
5	S5,S4,S3,S2,S1	9	-2.2	5.3

Realized gain of an antenna is comparative measure of antenna performance, for example for the first case of this antenna we are getting -11 dBi, it means at farfield we are getting 0.06 times the power that would be received by a lossless isotropic antenna. The realized gain Vs frequency plot is shown in figure 4.21.

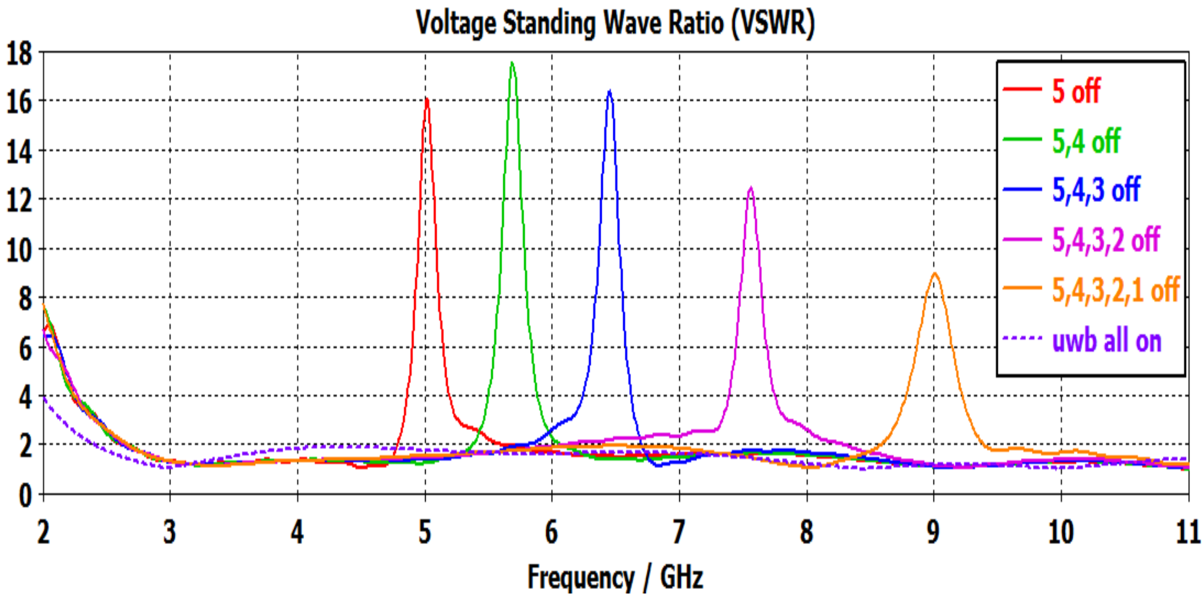


Fig 4.22 VSWR Vs frequency plot of reconfigurable antenna

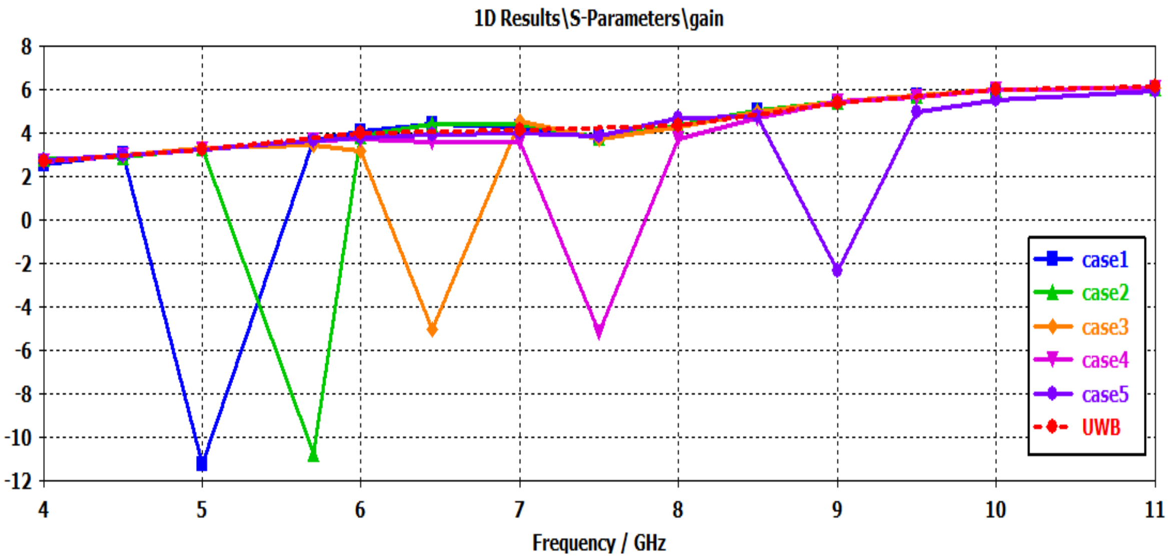
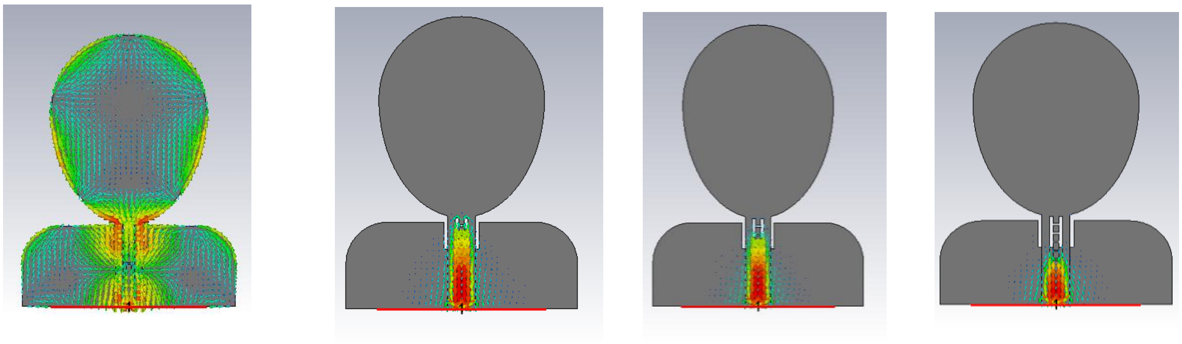


Fig 4.23 realized gain vs. frequency plot of proposed notch reconfigurable antenna

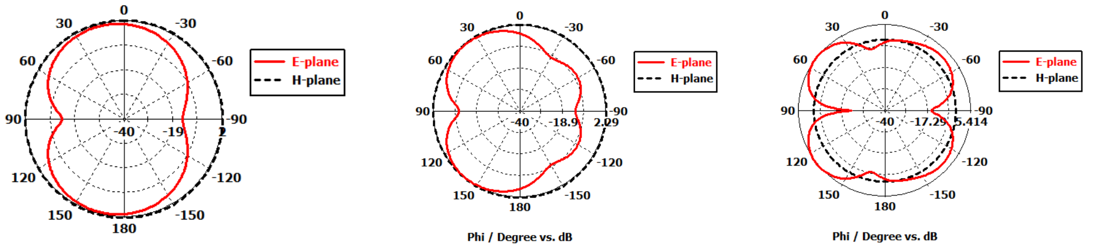
The surface current distribution of the antenna for different notch band according to the states of PIN diode is shown below, at band rejection the current does not reach radiating patch and is reflected from feedline to the port.



(a) (b) (c) (d)

Fig 4.24 surface current distribution at cases (a) UWB at 8.9 GHz (b) case2 at 5.7 GHz (c) case4at 7.5 GHz (d) case5 at 9 GHz

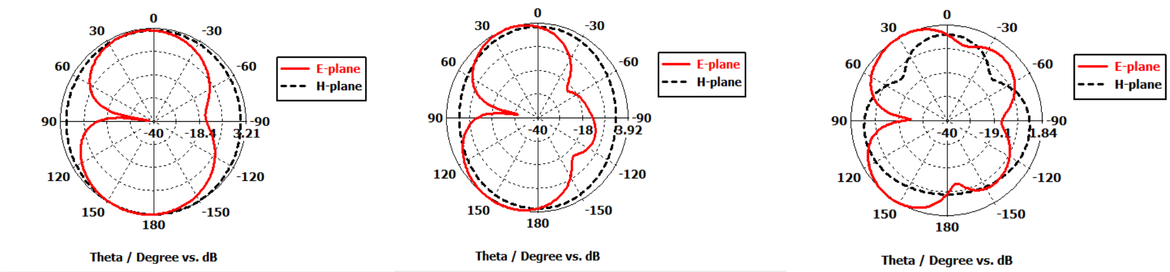
Normalized E plane and H plane radiation pattern for UWB and reconfigured at frequencies 5 GHz, 6.5 GHz and 9 GHz is shown below



(a) (b) (c)

Fig 4.25 E and H plane radiation pattern of UWB antenna at (a) 5 GHz, (b) 6.5 GHz

(c) 9 GHz



(a) (b) (c)

Fig 4.26 E and H plane radiation pattern of reconfigured antenna (a) 5 GHz (b) 6.5 GHz

(c) 9 GHz

Chapter 5

Small Tunable and Reconfigurable PIFA For 4G Handsets

In recent years demand of mobile devices with compact size and light weight has increased significantly. The major factor that limits the size of the devices are antennas. In recent years PIFA and microstrip patch antennas are becoming popular in the field of antenna design of small mobile devices like wireless local area networks (WLANs), cellular phone, wireless interconnects and mobile communication [20] .generally a PIFA antenna is designed of a rectangular planar patch section placed above ground plane and short circuited by a pin or plate. The PIFA antenna with feeding mechanism is shown in figure 5.1

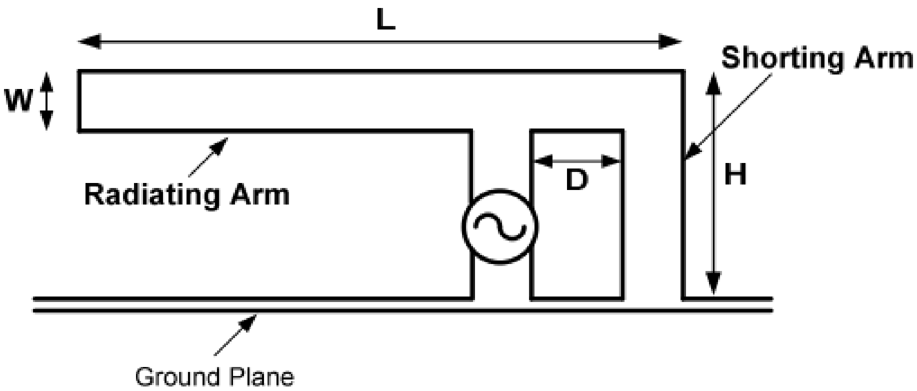


Fig 5.1 planar inverted F antenna general design

Input impedance of PIFA is typically complex and is function of frequency. Additional inductive impedance is added by shorting arm to the radiating arm. The resonating frequency is inversely proportional to the length of the PIFA and height of the shorting pin. This is shown by equation 5.1 [18]

$$f_r = \frac{c}{4(L+H)} \qquad (5.1)$$

Where

f_r = resonance frequency

C= speed of light

L = length of PIFA

H = height of shorting arm

Ground plane of PIFA plays an important role in radiation pattern, as like monopole ground plane of PIFA forms image of the radiating structure in main radiating arm. When the ground plane is at least λ/4 in length in the direction of dominant current distribution then antenna performs optimum. By changing its design parameters PIFA is able to control the imaginary component of its input impedance. The width of PIFA allows the length to change but resonating frequency must be kept constant, this can be utilized miniaturize the antenna. The figure shown below is antenna placed in Samsung galaxy S5, it has 6 antennas at different locations for different services like GPS, PCS, CDMA, WIFI/BT, WIMAX etc.to miniaturize the device antennas has to be replaced by tunable reconfigurable antenna which can give operating frequencies for above wireless services.[30]

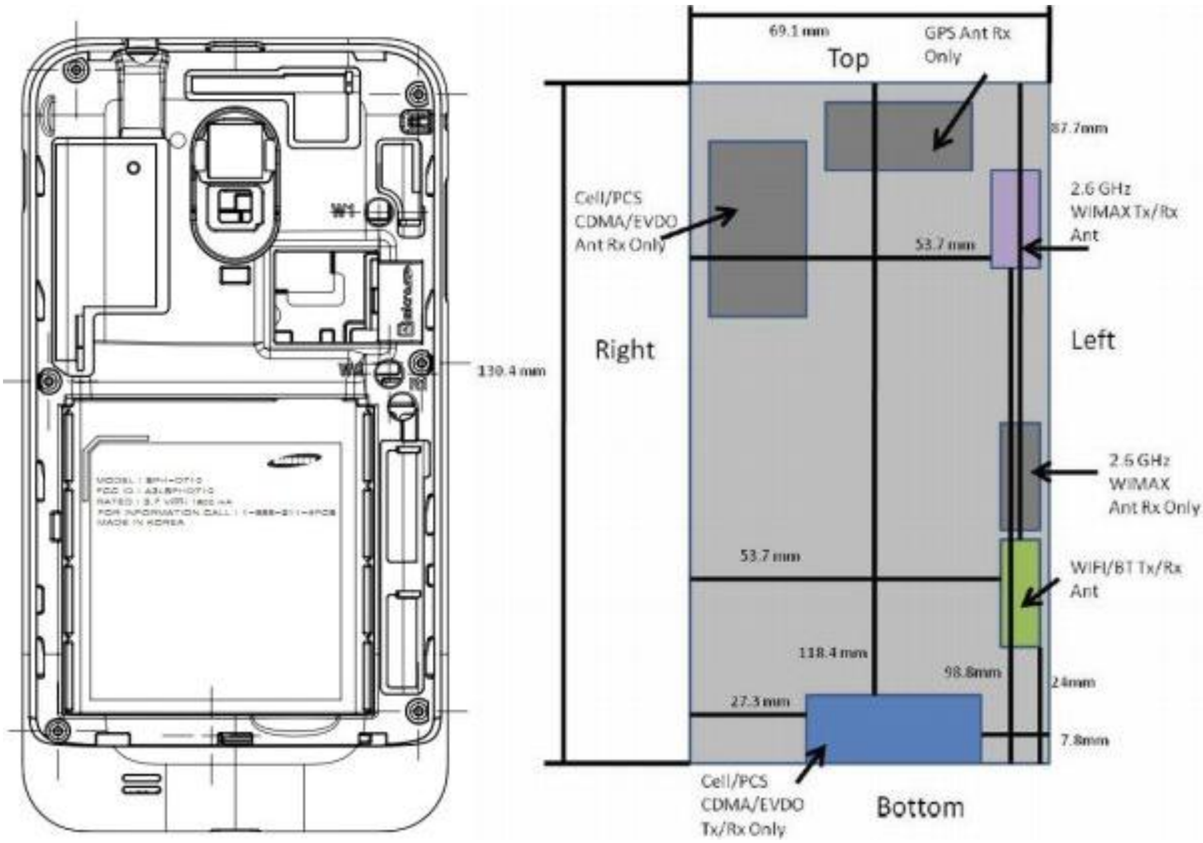
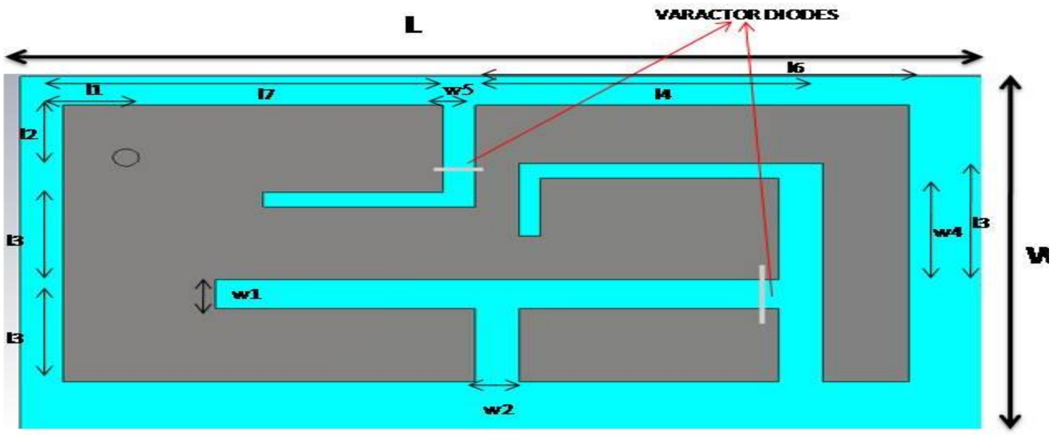


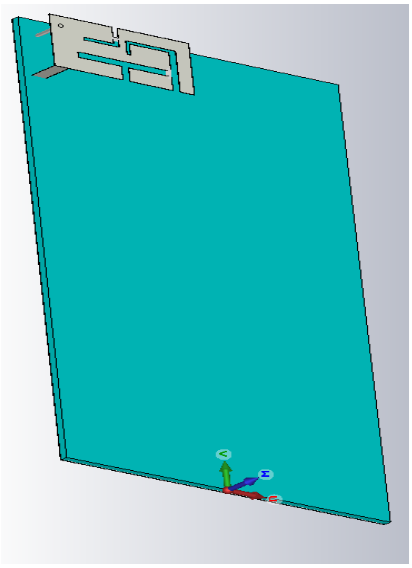
Figure 5.2 Antenna placed in Samsung galaxy S5 [30]

5.1 proposed Antenna Geometry

The geometry of the proposed antenna is shown in figure 5.1 (a) front view (b) rear view (c) PIFA antenna. The substrate used is FR4- epoxy, with dielectric constant of 4.3, height 1.6 mm and loss tangent 0.0018.PIFA is quarter wavelength antenna wherever microstrip is half wavelength antenna, this makes PIFA small in size and more useful for palm size devices like 4G handsets. Feeding is done by coaxial probe feed, optimization has been done in finding best position for probe feeding to get best results. Two varactor diodes are embedded on the radiating patch for tuning purpose, when one diode is fixed and other is varied we get dual band and triple band vice versa. There is air between substrate and radiating patch for better resonance, for practical situation air can be replaced by foam like material.



(a)



(b) (c)

Figure 5.3 design of proposed antenna (a) PIFA (b) front view (c) rear view

Table 5.1 shows the optimized values of design parameters used.

Names	**Values**
L	19.5
W	9.5
h1	1
h2	4
w1	1
w2	0.5
w3	2
w4	2
L1	1.45
L2	1.8
L3	2.5
L4	6.5
L5	6
L6	9
L7	9.75
W5	0.75

5.2 simulation results

The proposed antenna is simulated in CST microwave studio. Figure 5.3 shows the reflection coefficient curve when varactor 1 is fixed and varactor 2 is varying. Varactor diodes are shown in schematic design of PIFA, varactor 1 is above varactor 2. The S11 Vs frequency plot shows that we get dual band, in which one resonates at 2.5 GHz which does not vary and can be used for wireless services like GSM, PCS, WLAN etc. and other around 5 GHz which can be used for WIFI etc. When varactor 1 is varied and varactor 2 is fixed we get triple resonating band, first from 2.3 GHz to 2.6 GHz which can be used for GSM, PCS etc. second resonating band is from 2.5 GHz to 4.5 GHz which can be used for WIMAX, WLAN, WIFI, CDMA etc. third resonating band is at 5.5 GHz which is not varying with capacitance of varactor diode and which is used for WLAN, it is show in figure 5.4.table 5.1 gives bandwidth and resonating frequency by varying varactor 2. For simulation of this antenna lumped element is taken as capacitor and it is varied from 0.1 pF to 1.2 pF. Table 5.2 shows the resonating frequency and bandwidth when varactor 2 is varied and varactor 1 is fixed.

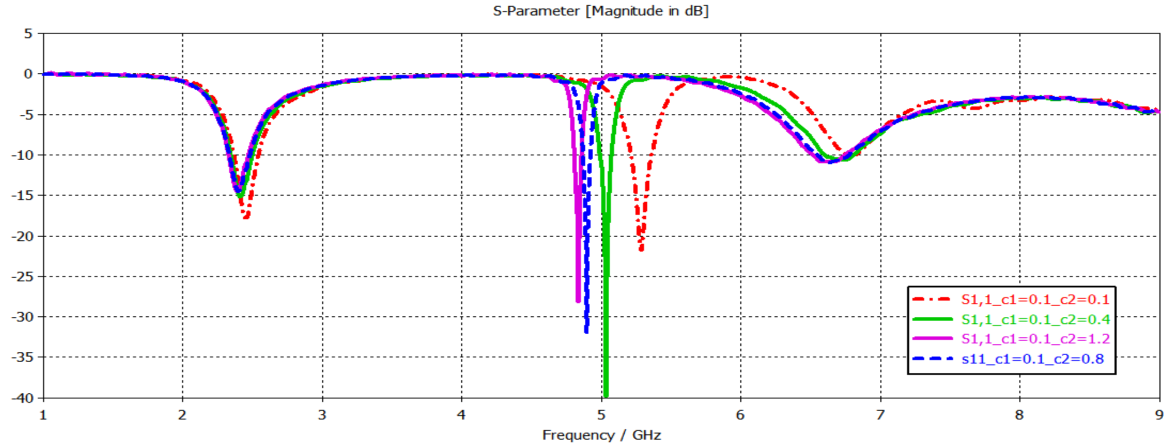


Figure 5.4 simulated reflection coefficient when varactor 1 is fixed and varactor 2 is varying

Table 5.2 Resonating frequency and bandwidth when varactor 2 is varied and 1 is fixed

CASE	**Capacitance(pF)**		**BANDWIDTH FOR RESONATING FREQUENCY BAND 2(f2)**	**RESONANT FREQUENCY (GHz)**
	Varactor diode 1	Varactor diode 2		
1	0.1	0.1	5.1 -5.4(2%)	5.3
2	0.1	0.4	5 -5.1 (2%)	5
3	0.1	0.8	4.9 – 5(2%)	4.92
4	0.1	1.2	4.8 - 4.9(2%)	4.83

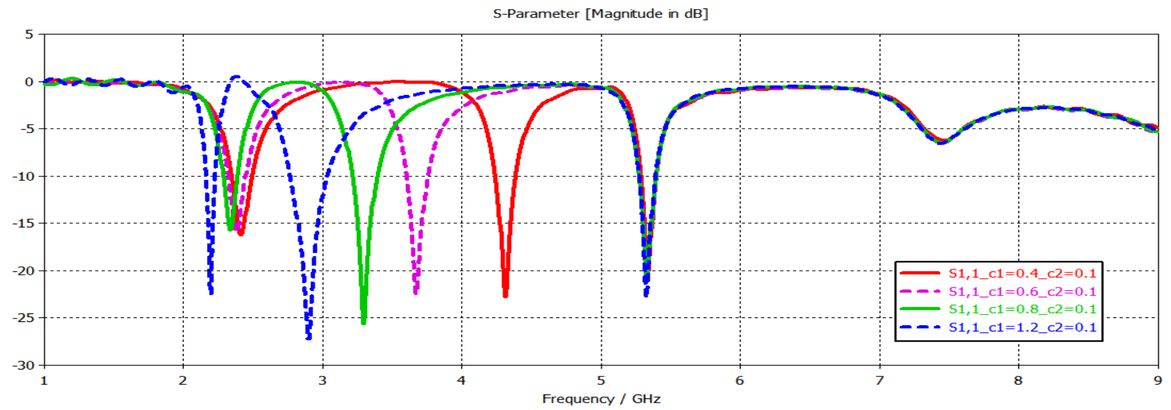


Figure 5.5 simulate S11 Vs frequency when varactor 1 is varied and varactor 2 is fixed

Table 5.3 resonant frequency and bandwidth when varactor 1 is varied and varactor 2 is fixed

CASE	**Capacitance(pF)**		**BANDWIDTH FOR RESONATING FREQUENCY BAND 2(f2)**	**RESONANT FREQUENCY (GHz)**
	Varactor diode 1	Varactor diode 2		
1	0.4	0.1	4.2 -4.43(5.3%)	4.3
2	0.6	0.1	3.6 -3.77 (4.6%)	3.67
3	0.8	0.1	3.2- 3.4(6%)	3.2
4	1.2	1.1	2.77 (9%)	2.9

The table given below depicts the gain and efficiency of the antenna for different operating frequency, gain for the case when varactor 2 is varied is above 2 dB and efficiency above 80%. And in the other case gain is above 2.5 dB and efficiency above 85% making it very good candidate for mobile applications.

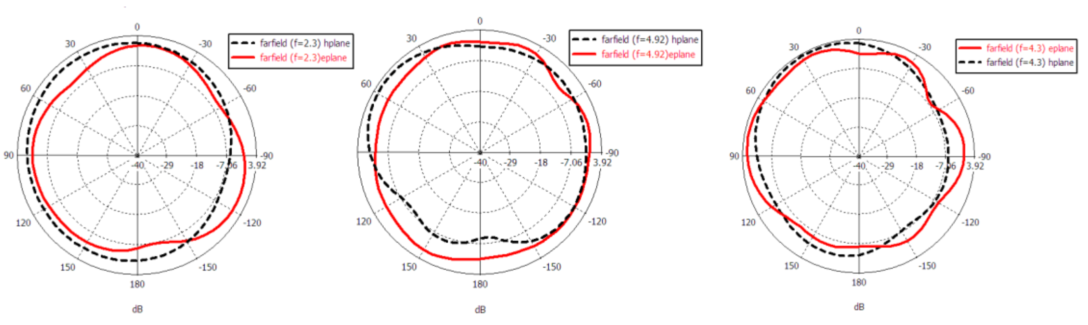
Table 5.4 resonant frequency, gain and efficiency when varactor 1 is fixed and varactor 2 varied

CASE	**Varactor diode capacitance value (PF)**		**Resonating frequency**		**Gain (dB) and efficiency (%)**			
			fr1(GHz)	fr2(GHz)	Band 1(f1)		Band2(f2)	
	Varactor 1 (pF)	Varactor 2 (pF)			Gain	Efficiency	Gain	efficiency
1	0.1	0.1	2.3	5.3	1.45	73	3.75	90
2	0.1	0.4	2.3	5	1.8	80	3.01	85
4	0.1	0.8	2.3	4.92	2.0	81	3.2	81
5	0.1	1.2	2.3	4.83	2.01	83	2.7	85

Table 5.5 resonant frequency, gain and efficiency varactor 2 is fixed and varactor 1 varied

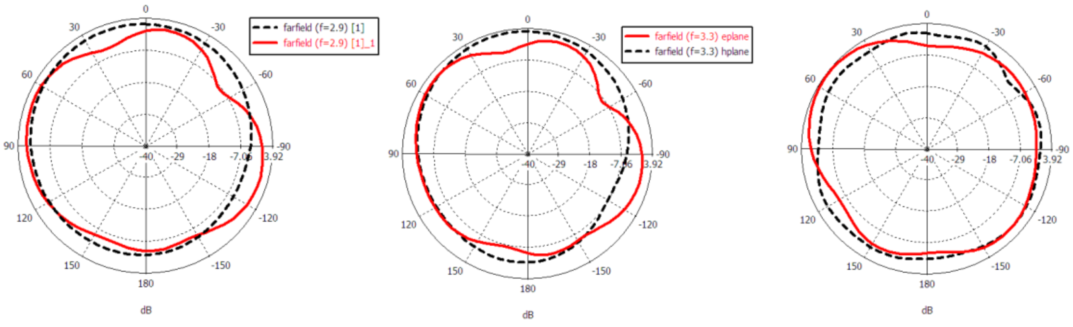
CASE	**Varactor diode capacitance value (PF)**		**Resonating frequency**			**Gain (dB) and efficiency (%)**					
	Varactor 1 (pF)	Varactor 2 (pF)	fr1(GHz)	fr2(GHz)	Fr3(GHz)	Band 1(f1)		Band 2(f2)		Band3(f3)	
						Gain	Efficiency	Gain	Efficiency	Gain	efficiency
1	0.4	0.1	2.3	4.3	5.3	2.5	78	3.3	92	3.0	84
2	0.6	0.1	2.3	3.67	5.3	2.5	94	3.6	95	3.3	87
4	0.8	0.1	2.3	3.3	5.3	2.1	82	3.1	92	3.4	88
5	1.2	0.1	2.4	2.9	5.3	2.1	80	2.8	90	3.5	92

The E plane and H plane radiation pattern of the proposed antenna is shown below, it depicts that the antenna is omnidirectional and can receive or transmit the signal in any direction which is must for a cellular phone. Radiation pattern shown below is shown for 3 resonating frequencies in each case of varactor capacitance when one is fixed and other is varied.



(a) (b) (c)

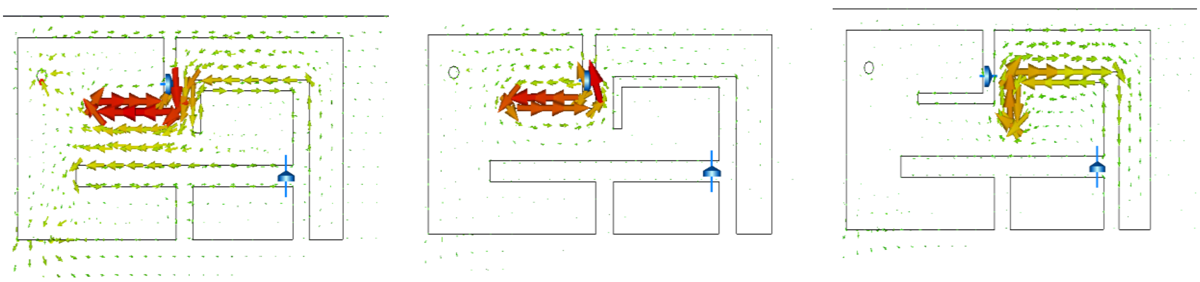
Figure 5.6 field pattern when varactor 2 is tuned to (a) 2.3 GHz (b) 4.83 GHz (c) 4.92 GHz



(a) (b) (c)

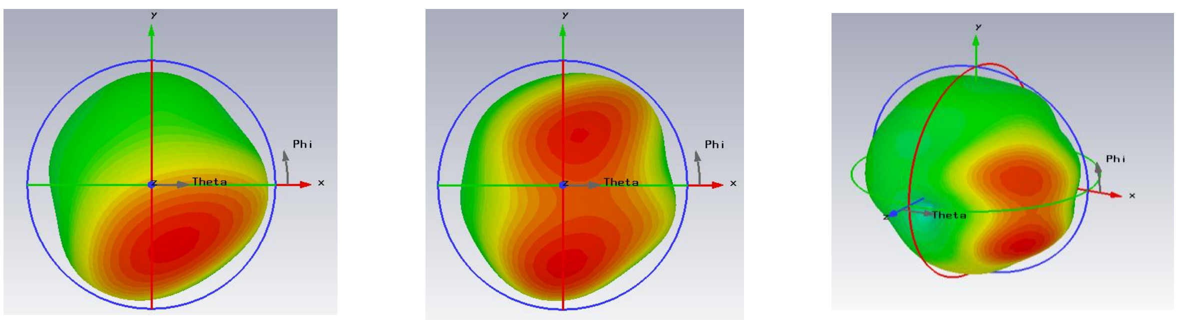
Figure 5.7 field pattern when varactor 1 is tuned to (a) 2.9 GHz (b) 3.3 GHz (c) 5.3 GHz

Simulated 3D far field radiation pattern and surface current distribution at some resonating frequencies is shown below. The surface current distribution depicts that which varactor is operative at that frequency and capacitance of varactor, the slots on the PIFA are cut such that current follow long path and short path according to varactor diode biasing status.



(a) (b) (c)

Figure 5.8 surface current distribution when varactor is tuned to (a) 2.4 GHz, (b) 6.5 GHz (c) 7.2 GHz



(a) (b) (c)

Figure 5.9 3D far field radiation pattern when varactor is tuned to (a) 2.4 GHz, (b) 6.5 GHz (c) 7.2 GHz

Chapter 6

Conclusion and Future Work

This thesis describes the frequency reconfigurable antenna and its application. Four different reconfigurable antennas are studied of which first three is designed for cognitive radio application and last is proposed for handheld devices like 4G cellular phone. First design is single port frequency reconfigurable microstrip patch antenna for overlay cognitive radio where single radiating patch is used as both sensing and communication. For reconfigurabilty PIN diodes are used on the feedline so that radiation pattern would not be distorted while changing the states of switches. According to the switching states there are 6 cases where one is UWB (ultra wideband) for sensing the entire spectrum and 5 other cases are for long distance communication operating at different frequencies. The bandpass filter used here comprises of T slot around which 6 parallel slots are cut and PIN diode is embedded. The second design is two port antenna for cognitive radio applications.one is used as sensing antenna which is UWB and other is frequency reconfigurable for communication. The filter used here is G slot with two parallel slots around, the varactor diode is embedded on the G slot for tuning of operating frequencies. Advantage of two port over single port is that simultaneous sensing and communication can be done but at the price of size. Third design is notch reconfigurable, designed for underlay cognitive radio.in this antenna filter is embedded in the feedline and PIN diode is embedded for reconfigurabilty. Bandstop filter used here rejects the spectrum where UWB signal is causing interference with the primary user. Fourth proposed design is planar inverted F antenna which are currently used in cellular phones and other handheld devices because of its small size. In this design two varactor diodes are used for frequency reconfigurabilty. This antenna is applicable to the wireless services like WLAN, GPS, PCS, CDMA, WIFI, and WIMAX. The simulated results gives good radiation pattern which is omnidirectional in E and H plane and gain and efficiency is also very good for practical applications.

New techniques such as graph model, neural networks can be used to optimize the antenna parameters and design procedure. Smart materials can be used for reconfigurabilty as it can decrease the size of the antenna. Hybrid antenna such as frequency with pattern reconfigurabilty for multiband and added interference rejection can also be designed for better functionality.

Publication

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REFERENCES

[1] Brown, E.R., "RF-MEMS switches for reconfigurable integrated circuits," *Microwave Theory and Techniques, IEEE Transactions on* , vol.46, no.11, pp.1868,1880, Nov 1998

[2] Hall, P.S.; Gardner, P.; Kelly, J.; Ebrahimi, E.; Hamid, M.R.; Ghanem, F.; Herraiz-Martínez, F.J.; Segovia-Vargas, D., "Reconfigurable antenna challenges for future radio systems," *Antennas and Propagation, 2009. EuCAP 2009. 3rd European Conference on* , vol., no., pp.949,955, 23-27 March 2009

[3] Hamid, M.R.; Gardner, P.; Hall, P.S.; Ghanem, F., "Vivaldi Antenna With Integrated Switchable Band Pass Resonator," *Antennas and Propagation, IEEE Transactions on* , vol.59, no.11, pp.4008,4015, Nov. 2011

[4] Mohammed Al-Husseini , Karim Y. Kabalan , Ali El-Hajj and Christos G. Christodoulou, "Advancement in Microstrip Antennas with Recent Applications Chapter 14 "Edited by Ahmed Kishk, ISBN 978-953-51-1019-4, 394 pages, Publisher: Intec,

[5] Al-Husseini, M.; Ramadan, A.; Zamudio, M.E.; Christodoulou, C.G.; El-Hajj, A.; Kabalan, K.Y., "A UWB antenna combined with a reconfigurable bandpass filter for cognitive radio applications," *Antennas and Propagation in Wireless Communications (APWC), 2011 IEEE-APS Topical Conference on* , vol., no., pp.902,904, 12-16 Sept. 2011

[6] Kazerooni M, Cheldavi A, Kamarei M (2009),"A Novel Bandpass Defected Microstrip Structure (DMS) Filter for Planar Circuits." *Proceedings of the 2009 Progress in Electromagnetics Research Symposium (PIERS 2009)*. Moscow, Russia. 1821 Aug 2009. pp.12141217.

[7] Ghanem, F.; Hall, P.S.; Kelly, J.R., "Two port frequency reconfigurable antenna for cognitive radios," *Electronics Letters* , vol.45, no.11, pp.534,536, May 21 2009

[8] Ebrahimi, E.; Kelly, J.R.; Hall, P.S., "Integrated Wide-Narrowband Antenna for Multi-Standard Radio," *Antennas and Propagation, IEEE Transactions on* , vol.59, no.7, pp.2628,2635, July 2011

[9] Chaudhary, G.; Phirun Kim; Yongchae Jeong; Jongsik Lim; Jaehoon Lee, "Analysis and circuit modeling method for defected microstrip structure in planar transmission lines," *Microwave Conference Proceedings (APMC), 2011 Asia-Pacific* , vol., no., pp.999,1002, 5-8 Dec. 2011

[10] Nishamol, M.S.; Aanandan, C.K.; Mohanan, P.; Vasudevan, K., "Dual frequency reconfigurable microstrip antenna using varactor diodes," *General Assembly and Scientific Symposium, 2011 XXXth URSI* , vol., no., pp.1,4, 13-20 Aug. 2011

[11] Yingsong Li,Wenxing Li,andQiubo Ye," A Reconfigurable Triple-Notch-Band Antenna Integrated with Defected Microstrip Structure Band-Stop Filter for Ultra-Wideband Cognitive Radio Applications," *International Journal of Antennas and Propagation* ,Volume 2013, Article ID 472645,13 pages

[12] Chang Yong Rhee; Jea Hak Kim; Woo Jae Jung; Taejoon Park; Byungje Lee; Chang Won Jung, "Frequency-Reconfigurable Antenna for Broadband Airborne Applications," *Antennas and Wireless Propagation Letters, IEEE* , vol.13, no., pp.189,192, 2014

[13] Jian Ren; Xi Yang; Jiayuan Yin; Yingzeng Yin, "A Novel Antenna with Reconfigurable Patterns Using H-Shaped Structures," *Antennas and Wireless Propagation Letters, IEEE* , vol.14, no., pp.915,918, Dec. 2015

[14] Zi-Xian Yang; Hong-Chun Yang; Jing-Song Hong; Yang Li, "Bandwidth Enhancement of a Polarization-Reconfigurable Patch Antenna With Stair-Slots on the Ground," *Antennas and Wireless Propagation Letters, IEEE* , vol.13, no., pp.579,582, 2014

[15] Xiaotao Cai; Anguo Wang; Weigang Chen, "A circular disc-shaped antenna with frequency and pattern reconfigurable characteristics," *Microwave Conference Proceedings (CJMW), 2011 China-Japan Joint* , vol., no., pp.1,4, 20-22 April 2011

[16] AbuTarboush, H.F.; Nilavalan, R.; Cheung, S.W.; Nasr, K.M., "Compact Printed Multiband Antenna With Independent Setting Suitable for Fixed and Reconfigurable Wireless Communication Systems,"*Antennas and Propagation, IEEE Transactions on* , vol.60, no.8, pp.3867,3874, Aug. 2012

[17] FCC, Revision of Part 15 of the commission's rules regarding ultra wideband transmission systems, ET Docket 98-153, FCC 02-48, Feb. 14, 2002.

[18] Viet-Anh Nguyen; Bhatti, R.-A.; Seong-Ook Park, "A Simple PIFA-Based Tunable Internal Antenna for Personal Communication Handsets," *Antennas and Wireless Propagation Letters, IEEE* , vol.7, no., pp.130,133, 2008

[19] Elfergani, I.T.E.; Hussaini, Abubakar Sadiq; Abd-Alhameed, R.A.; Abusitta, M.M.; Rodriguez, Jonathan, "Modified Small PIFA Frequency Tunable Antenna," *Wireless Conference (EW), Proceedings of the 2013 19th European* , vol., no., pp.1,4, 16-18 April 2013

[20] Lin, C.H.; Li, Z.; Ito, K.; Takahashi, M.; Saito, K., "A small tunable and wearable planar inverted-F antenna (PIFA)," *Antennas and Propagation (EUCAP), 2012 6th European Conference on* , vol., no., pp.742,745, 26-30 March 2012

[21] Balcells, J.; Damgaci, Y.; Cetiner, B.A.; Romeu, J.; Jofre, L., "Polarization reconfigurable MEMS-CPW antenna for mm-wave applications," *Antennas and Propagation (EuCAP), 2010 Proceedings of the Fourth European Conference on* , vol., no., pp.1,5, 12-16 April 2010

[22] Chang Won Jung; Ming-Jer Lee; Li, G.P.; De Flaviis, F., "Reconfigurable scan-beam single-arm spiral antenna integrated with RF-MEMS switches," *Antennas and Propagation, IEEE Transactions on* , vol.54, no.2, pp.455,463, Feb. 2006

[23] Abu Tarboush, H.F.; Khan, S.; Nilavalan, R.; Al-Raweshidy, H.S.; Budimir, D., "Reconfigurable wideband patch antenna for cognitive radio," *Antennas & Propagation Conference, 2009. LAPC 2009. Loughborough* , vol., no., pp.141,144, 16-17 Nov. 2009

[24] Constantine A. Balanis "Antenna Theory Analysis and Design" John Wiley & sons. Inc, 2nd edition 2009

[25] Ramesh Garg,Prakash bhartia,inder bahl and apisak ittipiboon, "Microstrip Antenna Design Handbook".Artech house, Inc., 2005

[26] Juyal, P.; Shafai, L., "Radiation pattern shaping of higher order broadside modes of circular microstrip radiator using impedance surfaces," *Antenna Technology and Applied Electromagnetics (ANTEM), 2014 16th International Symposium on* , vol., no., pp.1,3, 13-16 July 2014

[27] Can Ding ; Guo, Y.J. ; Pei-Yuan Qin ; Bird "A Defected Microstrip Structure (DMS)-Based Phase Shifter and Its Application to Beamforming Antennas", *Antennas and Propagation, IEEE Transactions* (Volume:62 , Issue: 2), Feb. 2014, Page(s):641 – 651

[28] Can Ding; Guo, Y.J.; Pei-Yuan Qin; Bird, T.S.; Yintang Yang, "A Defected Microstrip Structure (DMS)-Based Phase Shifter and Its Application to Beamforming Antennas," *Antennas and Propagation, IEEE Transactions on* , vol.62, no.2, pp.641,651, Feb. 2014

[29] Tawk, Y.; Costantine, J.; Avery, K.; Christodoulou, C.G., "Implementation of a Cognitive Radio Front-End Using Rotatable Controlled Reconfigurable Antennas," *Antennas and Propagation, IEEE Transactions on* , vol.59, no.5, pp.1773,1778, May 2011

[30] Shou-Hui Zheng; Xiong-Ying Liu; Tentzeris, M.M., "A novel optically controlled reconfigurable antenna for cognitive radio systems," *Antennas and Propagation Society International Symposium (APSURSI), 2014 IEEE* , vol., no., pp.1246,1247, 6-11 July 2014

[31] Wanuga, K.; Pfeil, D.; Gonzalez, D.; Dandekar, K., "A software defined testbed for reconfigurable antenna cognitive radio," *Cognitive Radio Oriented Wireless Networks and Communications (CROWNCOM), 2012 7th International ICST Conference on* , vol., no., pp.1,6, 18-20 June 2012

[32] Costantine, J.; Tawk, Y.; Woodland, J.; Flaum, N.; Christodoulou, C.G., "Reconfigurable antenna system with a movable ground plane for cognitive radio," *Microwaves, Antennas & Propagation, IET* , vol.8, no.11, pp.858,863, August 19 2014

[33] Abou Al-Alaa, M.; Elsadek, H.A.; Abdallah, E.A.; Hashish, E.A., "PIFA frequency reconfigurable antenna," *Antennas and Propagation Society International Symposium (APSURSI), 2014 IEEE* , vol., no., pp.1256,1257, 6-11 July 2014