A RECONFIGURABLE APERTURE COUPLED MICROSTRIP PATCH ANTENNA WITH BEAM STEERING CAPABILITY ON SILICON

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Department of Electrical Engineering

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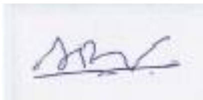

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This thesis entitled – A RECONFIGURABLE APERTURE COUPLED MICROSTRIP PATCH ANTENNA WITH BEAM STEERING CAPABILITY ON SILICON – by – Saddi Pradeep Reddy – is approved for the degree of Master of Technology from IIT Hyderabad.

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I would like to thank my parents for their support of all aspects of my life, but especially of my education.

Dedicated to

Family and friends.

.

Abstract

First reconfigurable antenna came into existence in early 1980s. Reconfigurable antennas provide various functions in operating frequency, polarization & radiation patterns since it can be used to avoid noise sources, improve system gain & security [1]. Reconfiguring the Frequency is the major issue & lot of recent work has been done on frequency reconfigurability A Barium Strontium Titanate (BST) based reconfigurable Aperture-coupled patch antenna on high resistivity silicon substrates with beam steering capability using PIN doides has been proposed in this paper. For low dielectric constant region in silicon substrate, Micromachined technique is used. Varying voltage across BST layer changes its permittivity thereby tunable frequency is achieved and switching p-i-n diodes will steer the beam. A Novel structure is proposed which gives high directivity (> 6 dB), Good gain (> 5 dB), low VSWR (<1.5), low control voltages (<80V) & 60° HPBWs & also The proposed reconfigurable aperture coupled microstrip patch antenna array with beam scanning capability has almost 40 degree scanning angle and BST based reconfiguring frequency is achieved with good gain and directivity

Contents

Chapter 1

Introduction

1.1 Introduction

First reconfigurable antenna came into existence in early 1980s [1]. Reconfigurable antennas provide various functions in operating frequency, polarization & radiation patterns since it can be used to avoid noise sources, improve system gain & security [1]. Reconfiguring the Frequency as well as Beam steering is the major issue in biomedical and radar applications & lot of recent work has been done on frequency reconfigurability [2].

Microstrip patch antenna is one of the best antenna for reconfigurability . Microstrip antennas are used for many reasons such as simplicity, conformality, small size, low profile & low manufacturing cost [3]. It has multiple applications in commercial sector of industry such as radars, telemetry, global positioning system, medical hyperthermia usage, bluetooth and satellites. Among all microstrip patch antennas, Aperture coupled microstrip patch antenna is the best for reconfiguring frequency since it has advantages over other types of microstrip antennas[4].

1.2 Aim and Motivation

The recent advent of Ferroelectric material components (BST) into microwave and Millimeter wave regimes has opened new and novel avenues of antenna technology development.

Modern communication and radar systems require reconfigurable antennas with Beam scanning capability for tracking the objects. People have worked on microstrip antennas on silicon substrates or reconfigurable microstrip antennas using MEMS devices on silicon substrates but this thesis shows a novel structure and implementation of antenna design which deals with reconfiguring the antenna using BST material and beam steering capabilityon silicon substrate.

1.3 Literature Survey

Originally implemented in 1950's [5] microstrip antennas have since been researched extensively. The inherent advantages like low profile, lightweight, and, low fabrication cost [36] along with ease of fabrication and integration with other microwave microstrip Devices, has lead to numerous industrial applications for microstrip antennas.

The pioneering work in the field of aperture coupled microstrip patch antennas was Published by Pozar [6]. Later publications about the theory of this feeding technique are given in [7], [8], [9], and [10]. Applications of aperture coupled microstrip patch antennas are presented in [11] and [12].

Reconfigurable antennas are a relatively recent phenomena in antenna design. The late 1990s marks the transition into viable reconfigurable antenna design and there

has been a rapid increase in the number of literature references containing reconfigurable designs and applications since that time. The current literature is divided into a few broad categories of reconfigurable antennas. Most reconfigurable antennas can be classified as either reconfigurable elements designs, fragmented apertures designs or reconfigurable arrays designs.

In radio systems, beam steering may be accomplished by switching antenna elements or by changing the relative phases of the RF signals driving the elements. Beam steering (also spelled beamsteering or beam-steering) is about changing the direction of the main lobe of a radiation pattern. Aperture coupled beam-steering antenna that uses a microstrip patch for radio applications is presented in this thesis.

1.4 Contribution of the Thesis

This work focuses on the design and implementation Reconfigurable aperture coupled microstrip patch antenna on silicon with Beam Steering capability. The main contributions of this research work are as follows:

- A comprehensive study about Microstrip antennas.
- Thorough Analysis of reconfigurable microstrip patch antennas on silicon .
- A novel structure designed for BST based Reconfigurable Microstrip patch antennas
- A novel structure designed for Beam steering capability.

1.5 Thesis Organization.

- **Chapter 1:** is the introduction describing the motivation behind the work, literature survey, objectives and contributions of the present work.
- **Chapter 2:** describes basics of microstrip patch antenna and aperture coupled coupled microstrip patch antenna is designed and simulated.

• **Chapter 3:** describes design of Reconfigurable Microstrip patch antenna on silicon.

• **Chapter 4:** describes design of Reconfigurable microstrip patch antenna array on silicon with its advantages and disadvantages.

• **Chapter 5:** describes Beam steering capability of a Microstrip patch antenna.

• **Chapter 6:** describes design and performance of Reconfigurable aperture coupled patch antenna on silicon with Beam Steering capability

• **Chapter 7:** presents the conclusion to the thesis as well as future directions of this work.

Chapter 2

Microstrip Patch Antenna

2.1 Introduction

Microstrips are printed circuits operating in the microwave range, over the gigahertz region of the electromagnetic spectrum [13]. Realized by the photolithographic process, they let designers reduce the size, weight, and cost of components and systems for low signal-level applications by replacing the more cumbersome wave-guide components and assemblies. The fabrication process is well suited for series production of circuits and antennas, since lumped circuit and active devices can easily be combined with sections of transmission line. At microwave frequencies, all dimensions become important, so the realization of microstrips requires more care than that of low-frequency printed circuits. Microstrip lines were first proposed in 1952 and were increasingly used in the late 1960s and 1970s to realize circuits, generally called microwave integrated circuits (MICs) since radiation leakage is most unwanted in circuits, particular care was taken to avoid it, even though its possible application to design antennas had already been suggested in 1953 [14]. Microstrip antennas appeared as a by-product of microstrip circuits, which by then had become a mature technology. Their design and realization took advantage of the techniques developed for microstrip circuits and used microstrip circuit substrates.

2.2 Basic microstrip patch antenna

2.2.1 Introduction

Printed patch antennas use radiating elements of a wide variety of shapes. Square, rectangle, circle, ring, triangle, more complex geometrical figures and combinations of simpler shapes are also used for some particular applications. The selection of a particular shape depends on the parameters one wishes to optimize bandwidth, side lobes cross polarization, and antenna size. Microstrip patches present a somewhat broader relative bandwidth than dipoles, of the order of a few percent. In contrast to thin dipoles, patches may excite some surface current flowing across the transverse direction, which then radiates an unwanted cross polarized component. Its amplitude is critically dependent on the kind of feed and on its location with respect to the axes.

2.2.2 Construction and working

Although there are many variations on patch antenna design, the basic configuration is shown in Figure 2.1, where *l* is then length(relative to the feedpoint) and *w* is the width. In the simplest configuration, *l* = *w* = λeff/2, or an electrical one-half wavelength, including the shortening effect of the dielectric constant (εr) of the material between the patch and the conducting surface (or *substrate*) below. The two edges of the patch that are connected to, and opposite from, the feed connection provide the radiation, acting as slot antennas, where each slot is the gap between the edge of the patch and the ground plane beneath the intervening dielectric layer. The arrows at the left and right edges of the patch represent the currents between the patch conductor and ground plane. At the edges, where they are not contained, these currents result in the desired radiation of electromagnetic waves from the two edge slots. We can easily see that the microstrip feedline excites the center of the slot formed by the edge of patch that to which it is connected. Between the underside of the patch and the substrate ground place, a low impedance transmission line is formed that subsequent feeds the slot at the opposite side. Since the electrical length of this line is λ/2, the impedance at the fed edge is repeated at the other, which effectively feeds the two slots in-phase with nearly equal antenna currents. Thus, the patch operates as an array of two slots with a free-space separation somewhat less than λ/2. Maximum radiation is normal to the plane of the patch. Polarization is at right angles to the length of the slots, parallel to the feedline orientation shown in Fig. 2.1.

Radiation toward the back of the substrate is greatly reduced by the shielding effects of the ground plane layer. The amount of reduction depends on the extent to which the ground plane extends beyond the patch area. To make a smaller product, many commercial antennas have ground planes that are only slightly larger than the patch. While they have less reduction of rearward radiation than a larger design, they still have useful gain and directivity[15].

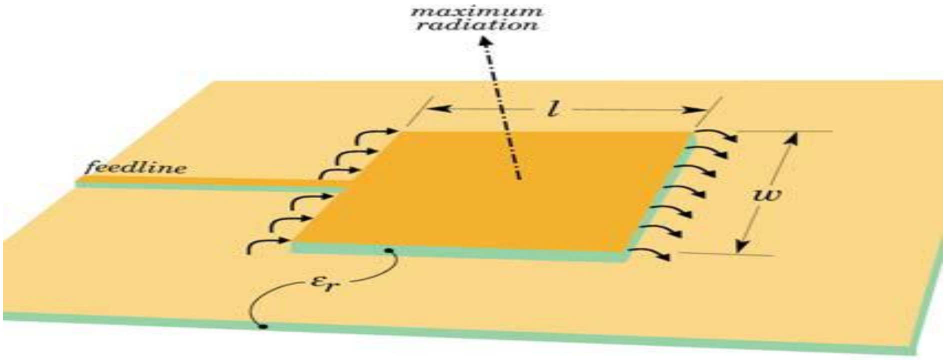


Figure 2.1 Basic microstrip patch antenna

2.2.3 Advantages and disadvantages

There is a tremendous number of advantages[16].

- lightweight, low volume, low profile

  Printed circuits are thin and thus require less volume than their waveguide or coaxial counterparts. Due to the fact that printed antennas consist mainly of nonmetallic materials and due to the frequent use of foam materials as substrates, such antennas have an extremely low weight compared to conventional antennas.
- Polarization

  With the versatility of patch geometries any polarization can be obtained. You can even realize antennas with multipolarization capability with single or multiple ports. These features can be exploited for dual polarization operation or polarization diversity.
- Dual frequency antennas possible.
- Excitation technique

  Patches allow a lot of different excitation techniques to be used, compatible with any technology of the active circuitry and beam forming networks.
- Suitable for integration with MICs (Microwave Integrated Circuits)

  This is important, since MICs are much easier to handle and less expensive than the alternative waveguides.

Beside these numerous technological merits, there is also an important economic reason that makes microstrip antennas attractive: Printed antenna technology is suitable for low{cost manufacturing, because photo etching and press machining are the lowest cost technologies for large scale fabrications.

Of course there are a few drawbacks: First of all there is a limitation in frequency. At low frequencies (100MHz), the need of a given thickness to achieve a high efficiency and bandwidth leads to bulky (but not necessarily heavy) radiators; at high frequencies, once more the (very small) thickness and the manufacturing accuracy limit the capability for low{cost production. Microstrip antennas are narrowband antennas compared to conventional microwave antennas, since the radiation is a consequence of a resonance. Nevertheless this drawback can be overcome by using thicker substrates with low permittivity.

One has to care about the power{handling capability of printed circuits in the high power stages of radar or in industrial equipment for microwave heating. But when signal amplitudes remain generally low, as for example as in mobile communications, they are an excellent candidate for employment.

Another fact is that the design engineer has always to keep an eye on losses (mainly dielectric and due to surface wave excitation), since this leads to a lower gain and a lower effciency. By selecting low loss{tangent substrates the dielectric losses will not be a serious issue anymore.

2.2.4 Applications

the advantages of microstrip antennas far outweigh their disadvantages and so lead to many system applications, such as:

- mobile communications
- satellite communications
- remote sensing
- doppler radar, automotive radar, etc.

2.3 Types of Microstrip patch antennas

There are four types of microstrip patch antennas

- End fed microstrip patch antenna

A microstrip antenna is basically a conductor printed on top of a layer of substrate with a backing ground plane as shown in figure 2.2. The length of the radiating conductor or patch is made approximately λg/2, so the patch starts to radiate. In this experiment the patch will be fed by a microstrip transmission line, which usually has a 50Ω impedance. The antenna is usually fed at the radiating edge along the width (W) as it gives good polarisation, however the disadvantages are the spurious radiation and the need for impedance matching

[17]. This is because the typical edge resistance of a microstrip antenna ranges from 150Ω to 300Ω [18]. The design of a microstrip antenna begins by determining the substrate used for the antenna and then the dimensions of the patch. Due to the fringing fields along the radiating edges of the antenna there is a line extension associated with the patch.

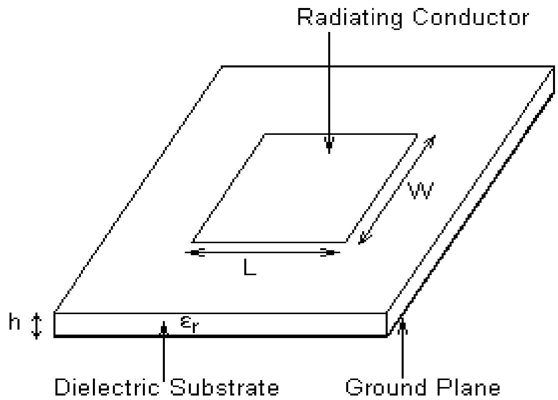


Figure 2.2 End fed microstrip patch antenna

- Inset fed microstrip patch antenna

In most microstrip end fed antennas the feed line impedance (50Ω) is always the same as the radiation resistance at the edge of the patch, which is usually a few hundred ohms depending on the patch dimensions and the substrate used. As a result this input mismatch will affect the antenna performance because maximum power is not being transferred. When a matching network is implemented on the feed network this improves the performance of the antenna as there are less reflections. A typical method used to match the antenna is the use of an inset feed, because the resistance varies as a cosine squared function along the length of the patch a 50Ω can be found which is a distance from the edge of the patch [19]. This distance is called the inset distance. A diagram of an inset fed patch is shown in figure 1, where xo represents the inset length. The analysis of the inset fed patch is summarised from the references [20] and [21] which uses a transmission line model network to analyse the antenna.

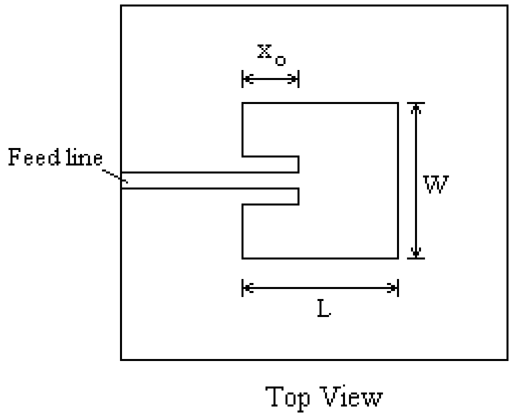


Figure 2.3 Inset fed microstrip patch antenna

- Proximity fed microstrip patch antenna

Electromagnetically coupled (EMC) designs such as proximity coupled and aperture fed antenna have many advantages over end fed and coaxial fed antennas. Some advantages are

• No physical contact between feed line and radiating element.

• No drilling required.

• Less spurious radiation.

• Better for array configurations.

• Good suppression of higher order modes.

• Better high frequency performance.

A proximity-coupled antenna consists of two layers: it has a feed layer which is just a 50Ω microstrip line with a backing ground plane and the upper layer is the main radiating patch. Here is a diagram of the proximity coupled antenna:

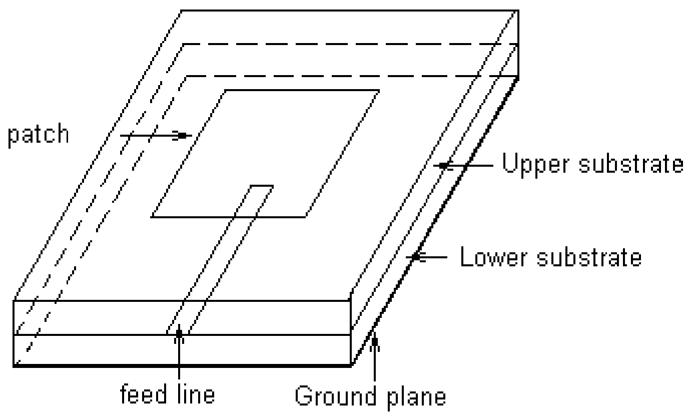


Figure 2.4. Proximity fed microstrip patch antenna

- Aperture coupled microstrip patch antenna

In an aperture coupled feed, which is another type of EMC feed, the RF energy from the feed line is coupled to the radiating element through a common aperture in the form of a rectangular slot. This type of feed was first proposed by Pozar in 1985 [4]. This type of antenna is discussed later in this thesis. The aperture coupled feeding mechanism is shown in figure 2.5:

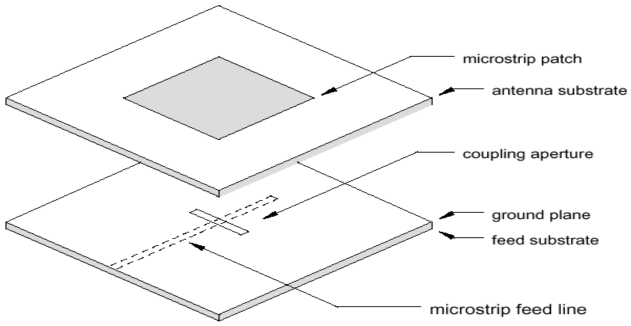


Figure 2.5. Aperture coupled fed microstrip patch antenna

2.4 Antenna on silicon substrate

The substrate of printed antennas plays a very important role in achieving desirable electrical and physical characteristics. For good antenna performance, a thick substrate with low dielectric constant is desirable since this provides better efficiency. However, to integrate the antenna with other MMICs at millimeter wave regions, a high dielectric substrate will be used, which causes high surface wave loss due to the thickness of substrates becoming electrically large [18]. This would impact negatively on the efficiency and bandwidth of the antenna. Although reducing the thickness of the dielectric reduces the amount of power launched into surface waves**,** it does not entirely eliminate them because the fundamental *TM0* mode has no cut-off and the radiation efficiency of antenna can therefore be greatly reduced.

As micromachining technology is developed, it offers an alternative scheme that satisfies the conflicting demands of the antenna and circuitry by using the same substrate without performance degradation of antenna or circuitry. It allows high performance antennas to be realised on high dielectric constant substrates such as silicon and GaAs. Several techniques have been reported using micromachining technology on high dielectric substrates to synthesise a localized low dielectric constant environment and thus reduce the surface wave excitation. The effective dielectric constant of silicon can be reduced by partially removing the silicon underneath the patch to form a mixed air-silicon region with a predetermined dielectric constant value[22].

2.5 Simulation software(HFSS)

The simulation is an important stage in modern antenna design and saves time and money before fabrication. It is an intermediate stage between design and fabrication. The simulation tool should be able to accurately characterize antenna performance and should also be able to simulate all the antenna parameters such as return loss and radiation pattern in all the planes with a high degree of accuracy. Hence, the selection of the proper simulation tool is a crucial task in the process of realizing a printed antenna[22].

There are many electromagnetic (EM) simulation software packages available for use in antenna design, which use different numerical techniques in the time or frequency domain, and it is often difficult to determine which program will work best for a given antenna geometry [23]. In order to streamline the antenna design process and generate accurate results before prototype construction, it is important to select an EM simulation program that will provide an optimal balance between a minimal simulation run time and a maximized correlation between the simulation results and the experimental data. High Frequency Structure Simulator (HFSS) by Ansoft is used to design and predict the performance of the printed antenna, since it provides 3-D full-wave electromagnetic field simulation. HFSS is based on Finite Element Method (FEM), it divides the geometric model into a large number of tetrahedral elements [24, 25].

2.6 Design of aperture coupled microstrip patch antenna on silicon

2.6.1 Proposed antenna

An Aperture coupled patch antenna is designed and design layout shown in Fig. 2.6, consists of two wafers.

In first wafer, Patch antenna (4.8mm*6.6mm) is designed on high resistivity (50 ohm-m), (110) Si wafer of thickness 0.4 mm and dimension 12mm x14mm. Window of 10 mm x 12 mm is open on back side of wafer and open a rectangular cavity of depth 0.3 mm in silicon.

The second wafer is a again high resistivity Si substrate with width of 0.2 mm which contain the antenna ground plane, coupling slot at front side and feedline at back side of the wafer as shown in Figure. 2.6(b).

Final device layout is shown in Fig. 2.6(c) in which back side of first wafer is bonded with front side of second wafer and layout was simulated using High Frequency Structure Simulator software(HFSS).

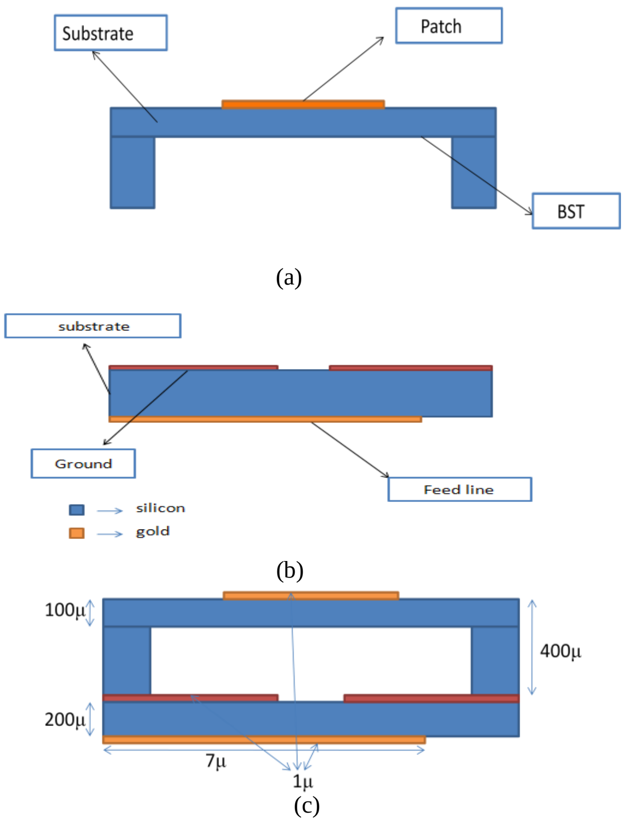


Figure 2.6. (a) Side view of 1st wafer of aperture coupled patch antenna (b) Side view of 2nd wafer of aperture coupled patch antenna (c) Dimensions of the MS fed aperture-coupled patch antenna using micromachining technology

2.6.2 Design and analysis

The synthesized effective dielectric constant ($\boldsymbol{\varepsilon}$eff) determines the antenna dimensions (W, L) to obtain a specified resonance frequency of 19.6GHz(when BST layer is not deposited). Expression (1) will give the synthesized dielectric constant, Xair is the ratio of cavity depth to the full top substrate thickness.

$$\boldsymbol{\varepsilon_{synth}} = \frac{\varepsilon_{air} * \varepsilon_{si}}{\varepsilon_{air} + (\varepsilon_{si} + \varepsilon_{air}) X_{air}} \qquad (1)$$

The size of patch can be determined by following equations:

$$W = \frac{c}{2f_o\sqrt{\frac{(\varepsilon_{syth}+1)}{2}}} \tag{3}$$

$$\varepsilon_{eff} = \frac{(\varepsilon_{synth}+1)}{2} + \frac{(\varepsilon_{synth}-1)^{-1/2}\sqrt{(1+12h/w)}}{2} \tag{4}$$

$$\Delta L = \frac{0.412h(\varepsilon_{eff}+0.3)\left(\frac{W}{h}+0.264\right)}{(\varepsilon_{eff}-0.258)\left(\frac{W}{h}+0.8\right)} \tag{5}$$

$$L = \frac{c}{2f_o\sqrt{\varepsilon_{eff}}} - 2\Delta L \tag{6}$$

In the above equations f_o is the normal frequency of operation of antenna, h is thickness of the top substrate, W and L are the width and length of patch.

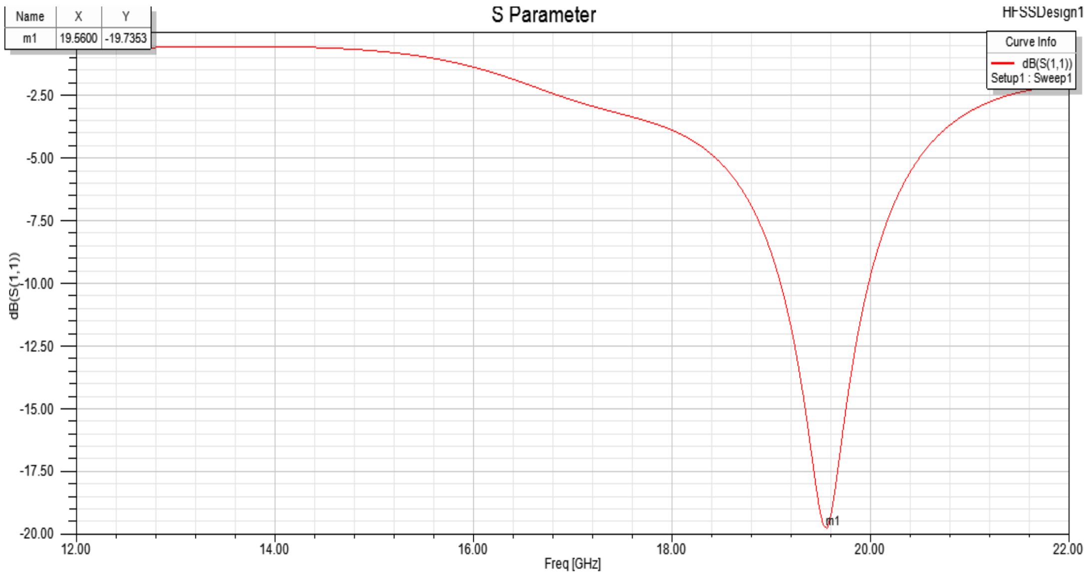
The dimensions of the proposed antenna based on are:

Patch: L x W= 4.8mm x 6.6mm, Cavity depth: 0.3mm,

Slot: L_s x W_s x d= 2.68mm x 2mm x 0.001mm,

2.7 Simulation Results

Simulations are done on HFSS(high frequency structure simulator) software. It's a good solver for planar antennas and has good accuracy.



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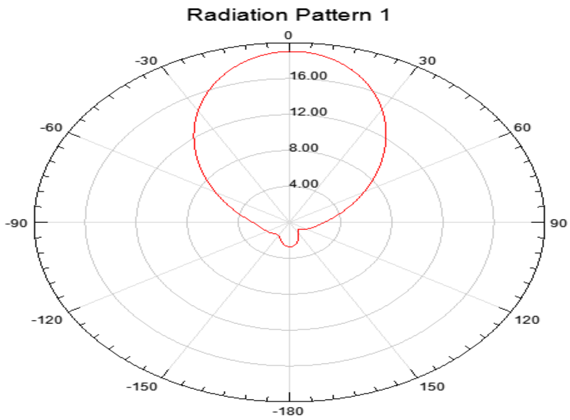

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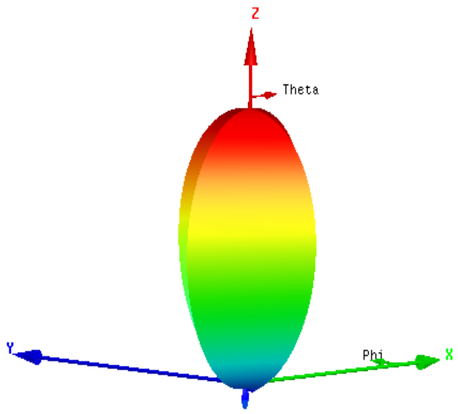

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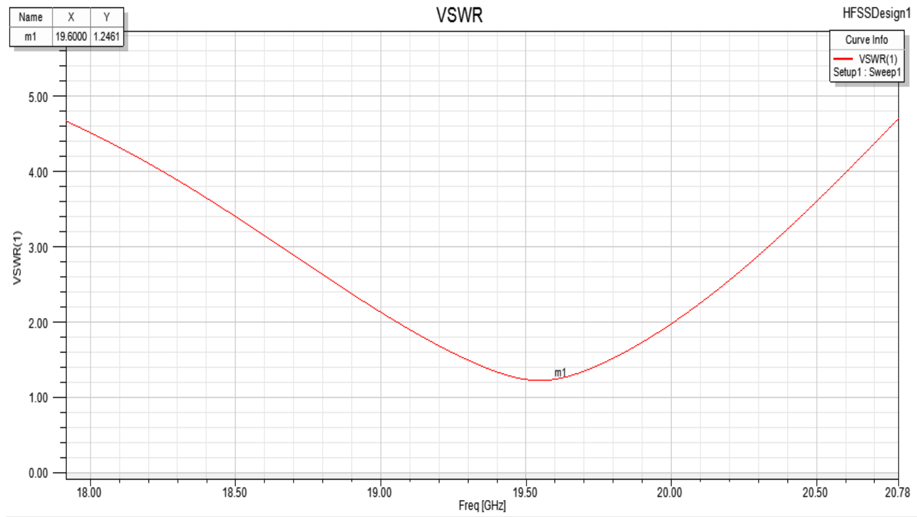

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Figure 2.7: (a)S-parameter , (b)Radiation pattern , (c) 3D polar plot and (d) VSWR for aperture-coupled patch antenna using micromachining technology

TABLE 1

MEASURED ANTENNA PARAMETERS

Antenna parameter	Value
Resonating frequency	19.6 GHz
Directivity	6.6 dB
Gain	6.0 dB
Radiation Efficiency	92.2 %
Front to Back ratio	48.2

Figure 2.7 shows the S-Parameter, radiation pattern & VSWR of the proposed antenna and results are tabulated in table. All results are comparable with the antennas on non silicon substrate like duriod or FR4. This proposed antenna with some modifications will be used for Reconfiguring frequency which is shown in next chapter**.**

2.8 Conclusion

Hence a Aperture coupled microstrip patch antenna on silicon is simulated here. Micromachining technique is used for reducing the effective permittivity of the silicon. Simulated results shows high directivity(> 6 dB), Good gain(> 6 dB), larger bandwidth (upto 900 MHz), low VSWR(<1.5) , Good front to back ratio & efficiency.

Chapter 3

Reconfigurable aperture coupled microstrip patch antenna on silicon

3.1 Introduction

First reconfigurable antenna came into existence in early 1980s [1]. Reconfigurable antennas have become more attractive as the demand for multiband antennas has increased. They provide greater levels of functionality to a system by eliminating the need for complicated wideband antenna solutions. Common antenna designs not involving re-configurability impose restrictions. Reconfiguring antennas can enhance their performance by providing the ability to adapt to new operating scenarios.

3.2 Different types of Reconfiguration

Reconfigurable antennas provide various functions in operating frequency, polarization & radiation patterns since it can be used to avoid noise sources, improve system gain & security [1]. Reconfiguring the Frequency is the major issue & lot of recent work has been done on frequency reconfigurability. Frequency reconfigurable antenna has the reconfiguration of resonant frequency by the change of the structure, while the radiation pattern remains unchanged [2]

3.3 Different ways to achieve frequency Reconfiguration

Reconfigurable frequency can be achieved by different techniques such as using switches (MEMS, pin diode etc), material properties (ferroelectric materials) or mechanical/ structural changes. Reconfiguring the frequency using material properties is one of the best technique. Barium strontium titanate (BST) is one of the ferroelectric material which gives excellent tunability range[26].

3.4 Frequency Reconfiguration using BST material

Barium Strontium Titanate (BST) is one of the most researched ferroelectric materials for tunable applications at high frequencies as it demonstrates a superior tradeoff between loss and tunability. The composition-dependent Curie temperature and bias-dependant dielectric permittivity of Barium Strontium Titanate (BST) makes it very attractive for tunable application in the RF/Microwave regime[26]

3.4.1 Working Principle

A BST has an excellent property called dipolar relaxation which is used for reconfiguring the frequency of the antenna. This typical property that changes its permittivity whenever there is a change in voltage applied across the BST layer. The dielectric permittivity of ferroelectric materials can be represented as the derivative of field dependent polarization(P)

$$\varepsilon = 1 + \frac{dP}{dE}$$

At 0V BST has a permittivity of around 510 and at 40V it changes to 250. Using BST the tuning range can be obtained around 500MHz to 40GHz [26].

3.4.2 Advantages and Drawbacks

The disadvantages of other technologies such as GaAs varactor diode has low Q-values, high RF loss and cannot handle high RF power loss and MEMS based designs have unproven their reliability at this point , difficult biasing requirements and have stringent packing needs. Ferroelectric materials are flexible for changes in operating conditions such as impedance environment, frequency and RF drive level.

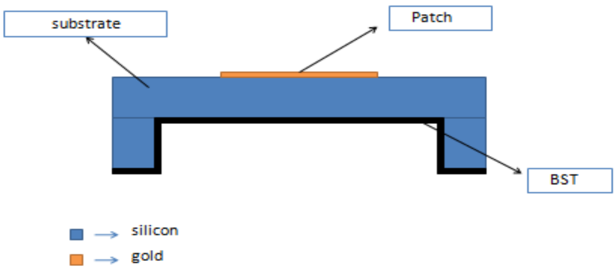
3.5 Proposed antenna structure

In present work the reconfigurable aperture coupled patch antenna is designed and design layout shown in Fig. 31, consists of two wafers.

In first wafer, Patch antenna (4.8mm*6.6mm) is designed on high resistivity (50 ohm-m), (110) Si wafer of thickness 0.4 mm and dimension 12mm x14mm. Window of 10 mm x 12 mm is open on back side of wafer and open a rectangular cavity of depth 0.3 mm in silicon. Further 0.005 mm thin BST layer is deposited in cavity shown in Fig. 3.1(a).

The second wafer is a again high resistivity Si substrate with width of 0.2 mm which contain the antenna ground plane, coupling slot at front side and feedline at back side of the wafer as shown in Figure. 3.1(b).

Final device layout is shown in Fig.3.1(c) in which back side of first wafer is bonded with front side of second wafer and layout was simulated using High Frequency Structure Simulator software(HFSS).



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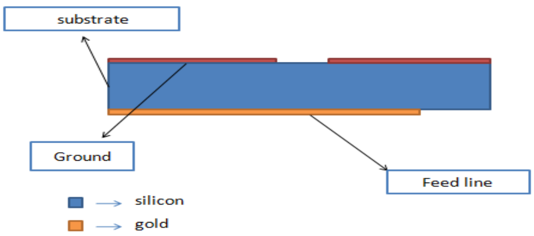

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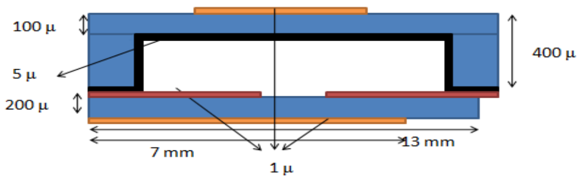
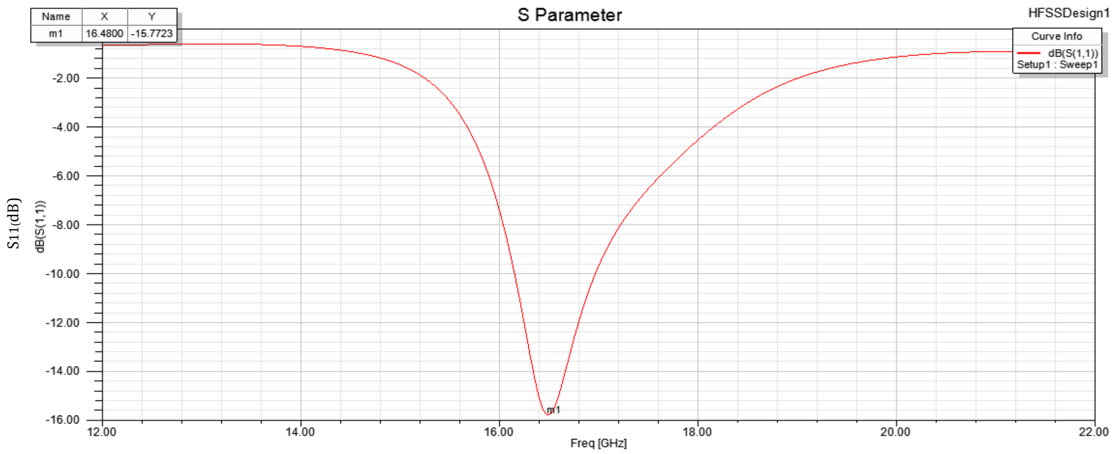


(c)

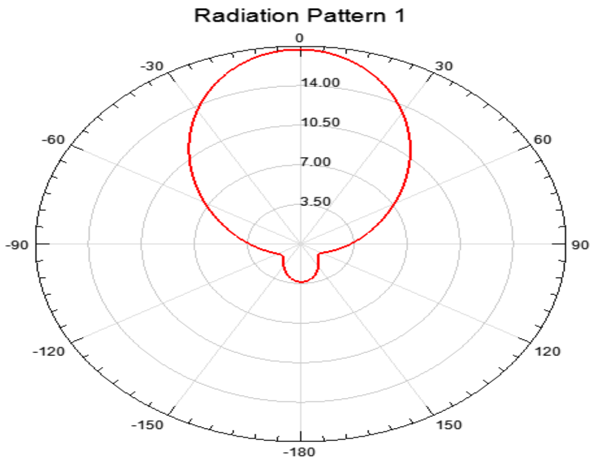
Figure 3.1. (a) Side view of 1st wafer of aperture coupled patch antenna (b) Side view of 2nd wafer of aperture coupled patch antenna (c) Dimensions of the MS fed aperture-coupled patch antenna using micromachining technology

3.6 Simulation Results

Simulations are done using high frequency microwave simulator. Simulations are shown for 0V, 40V and 70V applied across BST layer of thickness 0.005 mm.

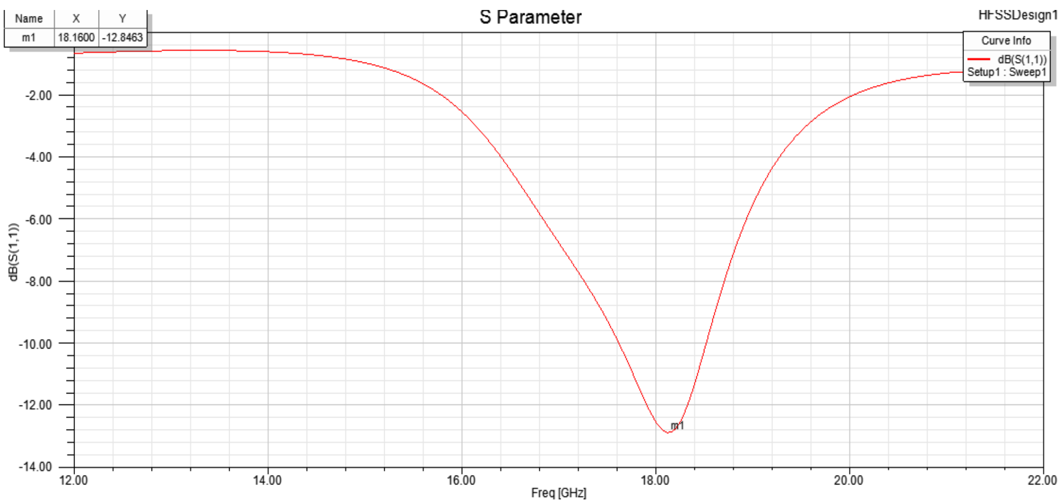


(a)

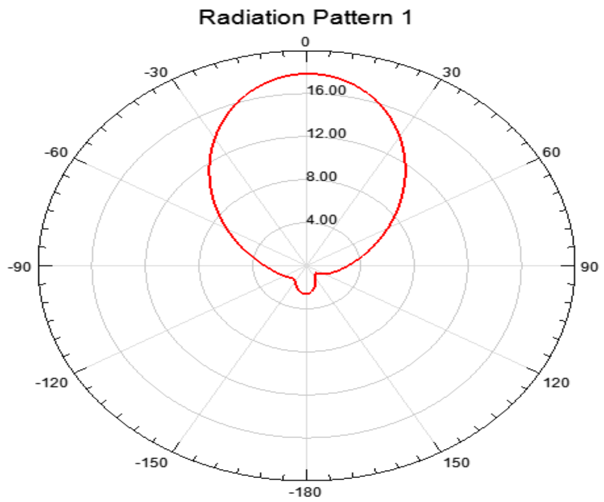


(b)

Figure 3.2. (a) S-parameter and (b) Radiation pattern for 0V applied BST material with permittivity of 510 of an aperture-coupled patch antenna using micromachining technology.

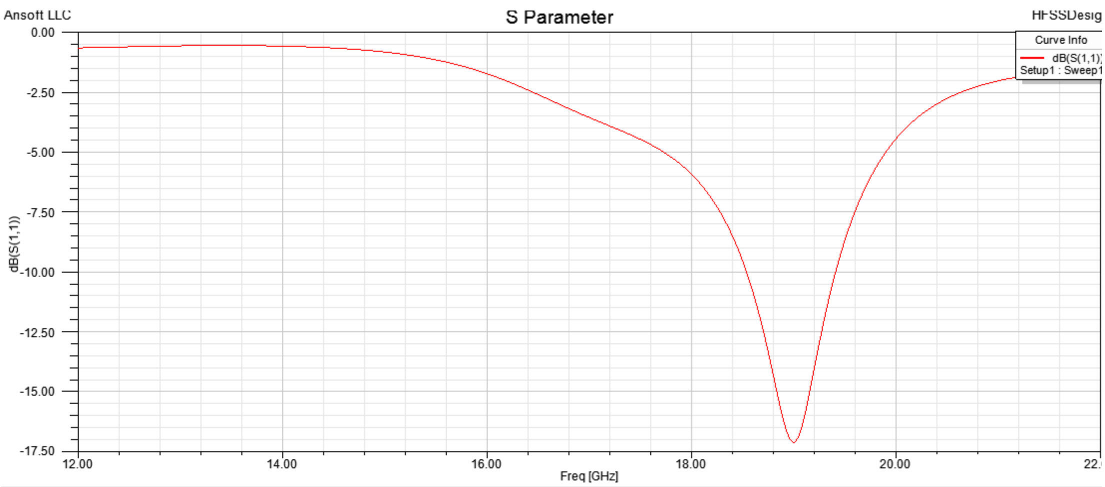


(a)

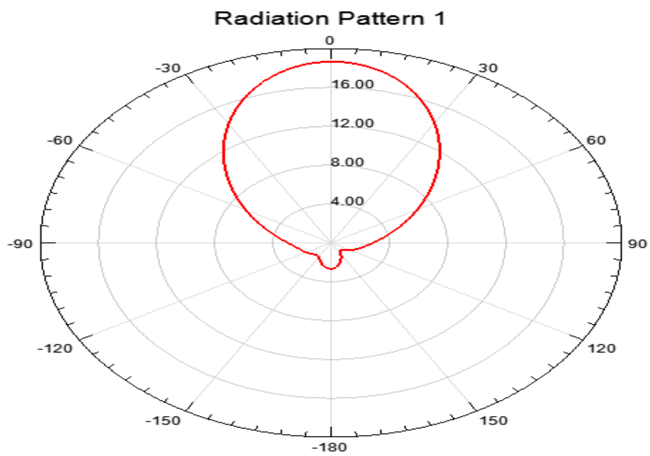


(b)

Figure 3.3. (a) S-parameter and (b) Radiation pattern for 40V applied BST material with permittivity of 250 of an aperture-coupled patch antenna using micromachining



(a)



(b)

Figure 3. 4 (a) S-parameter and (b) Radiation pattern for 70V applied BST material with permittivity of 100 of an aperture-coupled patch antenna using micromachining

TABLE 2

ANTENNA PARAMETERS FOR DIFFERENT BST THICKNESS

BST	Voltage Applied	Permittivity	Resonant Frequency	Directivity	Gain	Radiation Efficiency	Front to Back Ratio
0.001	0 V	510	19.0 GHz	6.5 dB	5.9 dB	91.4%	43.5
	40 V	250	19.32 GHz	6.6 dB	6.1 dB	91.0%	45.5
	70 V	100	19.56 GHz	6.7 dB	6.2 dB	91.5%	47.5
0.005	0 V	510	16.56 GHz	5.5 dB	5.1 dB	91.0%	24.8
	40 V	250	18.16 GHz	6.1 dB	5.6 dB	91.4%	43.0
	70 V	100	19.0 GHz	6.5 dB	6.0 dB	91.0%	50.1
0.010	0 V	510	15.2 GHz	5.0 dB	4.5 dB	91.3%	21.0
	40 V	250	16.48 GHz	5.4 dB	5.0 dB	91.9%	21.27
	70 V	100	18.44 GHz	6.2 dB	5.6 dB	92.7%	43.6

Aperture coupled antenna is tuned to different frequencies by varying the voltage as shown in fig 3.2-3.4. Results in Table 2 clearly shows that the tunability range is directly proportional to the thickness of BST material and around 3GHz tunability can be achieved using 70 volts change. This tunability range is used for various applications in commercial sector such as radars, satellite communication, wireless LAN etc.

Simulated results can be further improved by using U-shaped cavity and H-shaped slot in the proposed antenna. H-shaped slot will make higher coupling efficiency than rectangular slot [4].

In comparison with the structure in [26], our proposed structure provides almost similar performance, but this has the advantage of onchip integration, since this is in silicon substrate.

3.7 Conclusion

Hence an BST based reconfigurable aperture coupled microstrip patch antenna is simulated in this paper. Using BST , antenna is reconfigured to different frequencies by varying voltage applied across BST material. Simulated results shows high directivity(> 6 dB), Good gain(> 5 dB), larger bandwidth (upto 900 MHz), low VSWR(<1.5) and low control voltages(<80V).

This antenna structure can reconfigure upto 3 GHz of resonant frequency without changing the radiation pattern. One can see the radiation patterns of all the frequencies are one and the same.

Chapter 4

Reconfigurable Microstrip Antenna Array for beam scanning

4.1 Introduction

Microstrip patch antenna is important as a single radiating element, but the major advantages are realized in applications that require moderate size array. When discrete radiators are combined to form an array, some characteristics can be achieved or enhanced; such as high gain and beam scanning[27].

The microstrip antenna arrays can be classified with different criteria. The elements of the array can be distributed to form lines, planar or volume array. Several ways of feeding can be used to obtain certain characteristics. The feed network of phased arrays or SISO arrays(single input single output) can be categorized into parallel and series feed. The parallel(corporate) feed has single input port and multiple feed lines. If the array has multiple inputs and multiple output ports so it is called Multi-element-array(MEA) or MIMO arrays.

4.2 Proposed antenna array structure

Reconfigurable frequency with beam scanning capability is a novel thing. Here is the proposed antenna array structure which can reconfigure its frequency with beam scanning capability. An 9 element array is made of the antenna in chapter 4 with a spacing of .8 lamda.

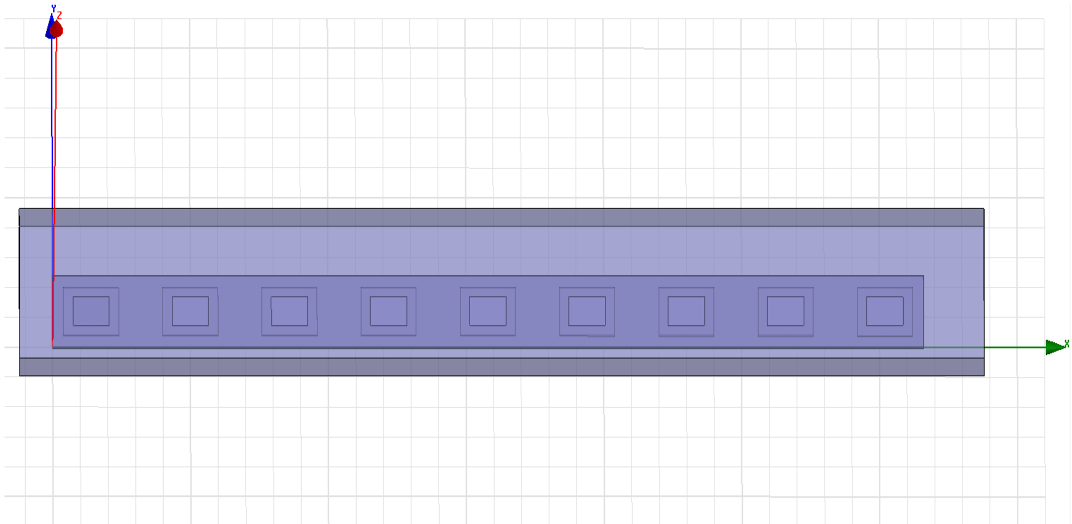


Figure 4.1. Reconfigurable aperture coupled microstrip patch antenna array

Figure 4.1 shows the 9 element array it made to reconfigure its frequency with good gain and directivity for beam scanning. Here all feed lines are active and based on phase difference between adjacent elements beam scanning capability is achieved. Reconfiguring the frequency is done using BST material which is discussed in chapter 4.

4.3 Simulation Results

All simulations are done in HFSS simulator. Simulation results are for proposed antenna array with 500 micron BST material thickness.

- When 0V is applied across BST material(antenna is radiating at 17.8 GHz)

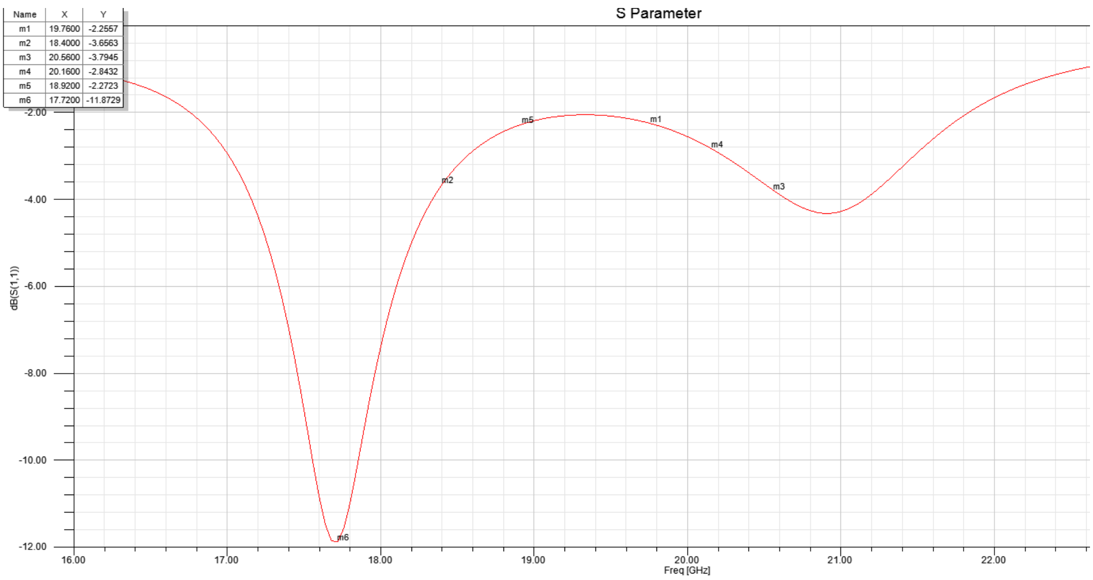


Figure 4.2 S-Parameter of reconfigurable aperture coupled patch antenna array when 0V is applied across BST material

- When 40V is applied across BST material(antenna radiating at 18.3 GHz)

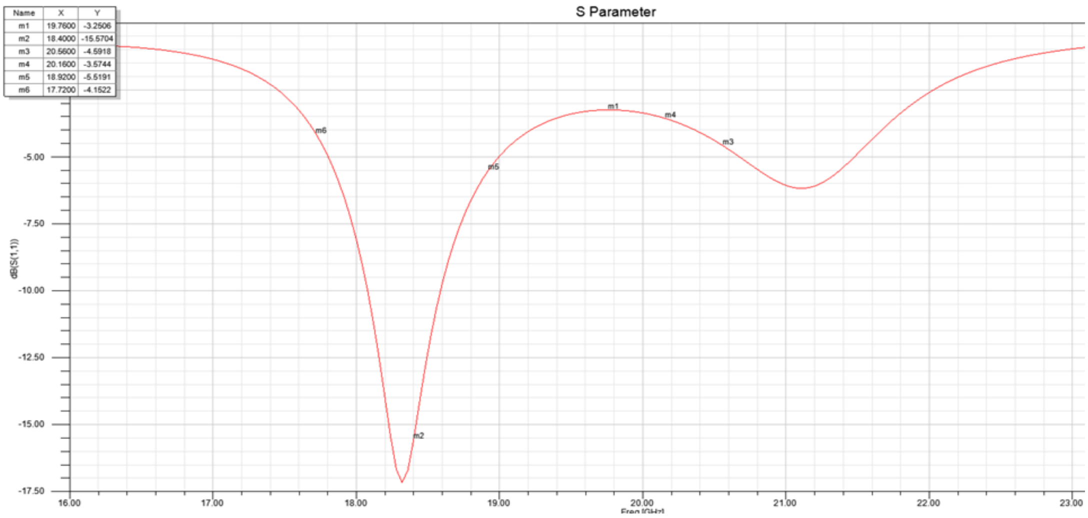


Figure 4.3 S-Parameter of reconfigurable aperture coupled patch antenna array when 0V is applied across BST material

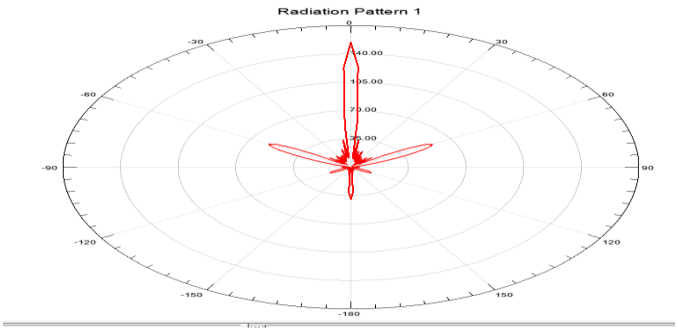


Figure 4.4 Radiation pattern with zero phase shift difference between adjacent elements(for all voltages across BST material)

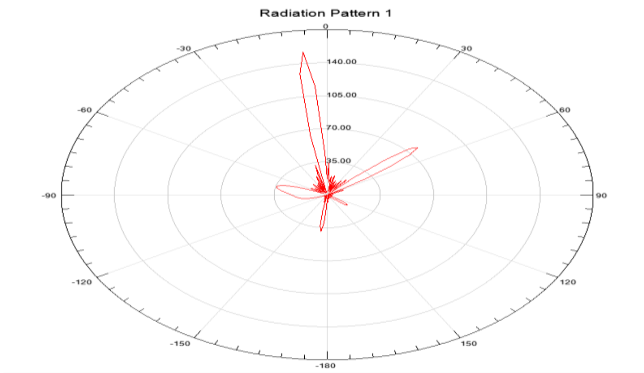


Figure 4.5 Radiation pattern with 45^{o} phase shift difference between adjacent elements(for all voltages across BST material) gives -5^{o} scan angle

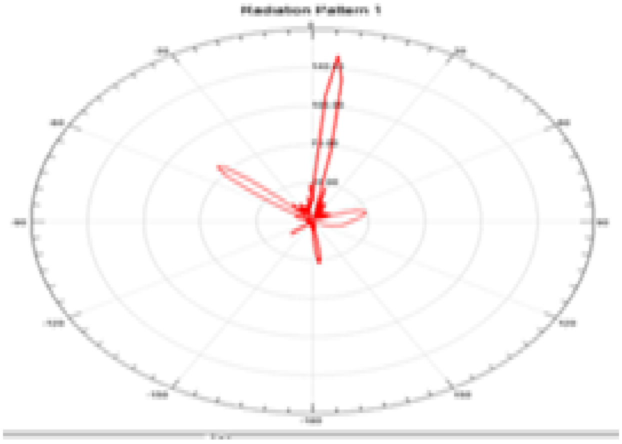


Figure 4.6 Radiation pattern with -45^o phase shift difference between adjacent elements(for all voltages across BST material) gives 5^o scan angle .

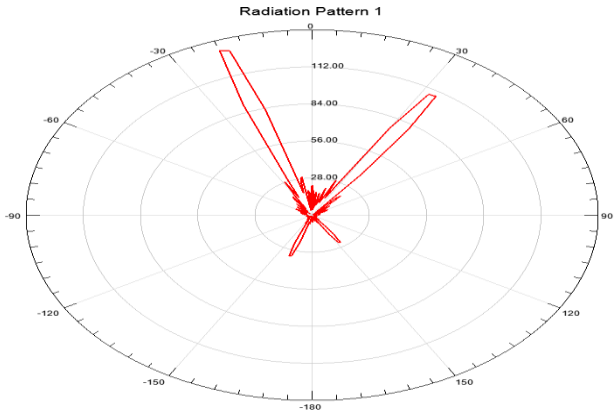


Figure 4.7 Radiation pattern with 135^o phase shift difference between adjacent elements(for all voltages across BST material) gives 40^o scan angle

When there is no phase shift difference between adjacent elements then no shift in main lobe so no scan angle is achieved. When there is a 45 degree phase shift between adjacent elements then one can see a 5 degree scan angle is achieved as shown in figure 4.5. Similarly for – 45 degree, again 5 degree scan angle is possible. So maximum of 40 degree scan angle is possible with this antenna.

So the proposed antenna is a reconfigurable antenna having beam scanning capability. But when one try to achieve more scanning angle then this antenna is not used because at some point side lobe will dominate the main lobe this is the main disadvantage with this structure.

4.4 Advantages and disadvantages

although microstrip single antenna has several advantages, it also has several disadvantages such as low gain, narrow bandwidth with low efficiency. These disadvantages can be overcome by constructing many patch antennas in array configuration. But this array has also some disadvantages like more feedlines are used there by more power is required and at some point of time side lobe is considerably more which makes difficult for beam scanning.

4.5 Applications

Beam scanning systems can have a wide range of applications in many areas of science and technology, including a number of important applications relevant to the area of robotics and autonomous agents, such as automated control systems, robotic laser surgery, object identification, target tracking, display systems, etc

4.6 Conclusions

A reconfigurable aperture coupled microstrip patch antenna array with beam scanning capability is proposed . Here almost 40 degree scanning angle and BST based reconfiguring frequency is achieved with good gain and directivity. It has its own advantages and disadvantages but till 30 scanning angle without any drawbacks this antenna can be used for tracking purpose and many other applications.

Chapter 5

Aperture coupled microstrip antenna with Beam Steering Capability

5.1 Introduction

In radio systems, beam steering may be accomplished by switching antenna elements or by changing the relative phases of the RF signals driving the elements**.** Beam steering (also spelled beamsteering or beam-steering) is about changing the direction of the main lobe of a radiation pattern. Aperture coupled beam-steering antenna that uses a microstrip patch for radio applications is presented. The proposed antenna can steer the maximum beam direction in the yz plane using two artificial switches.

5.2 Proposed structure

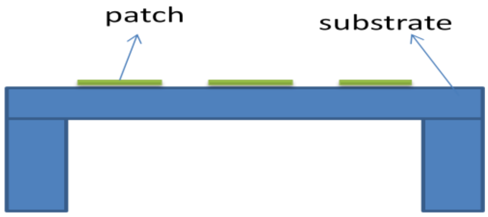
A aperture coupled patch antenna on silicon with beam steering capability is designed and design layout shown in Fig. 5.1, consists of two wafers.

In first wafer, three Patch antennas (4.8mm*6.6mm) are designed on high resistivity (50 ohm-m), (110) Si wafer of thickness 0.4 mm and dimension 12mm x 29.2mm. Window of 8mm x 25.2mm is open on back side of wafer and open a rectangular cavity of depth 0.3 mm in silicon.

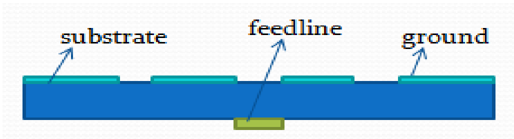
The second wafer is a again high resistivity Si substrate with width of 0.2 mm which contain the antenna ground plane, three coupling slot at front side and feedline at back side of the wafer as shown in Figure. 5.1(b).

Feedline dimensions are shown in Figure. 5.1(c). It has one main feedline and two sub feedlines. Main feedline is connected to two sub feedlines by two PIN diodes D1 and D2. By switching D1 and D2 beam steering is done.

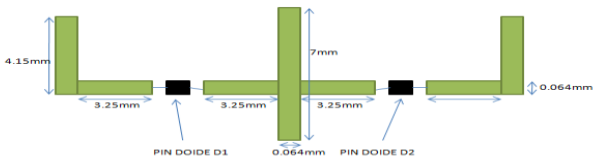
Final device layout is shown in Figure 5.1(d) in which back side of first wafer is bonded with front side of second wafer and layout was simulated using High Frequency Structure Simulator software(HFSS).



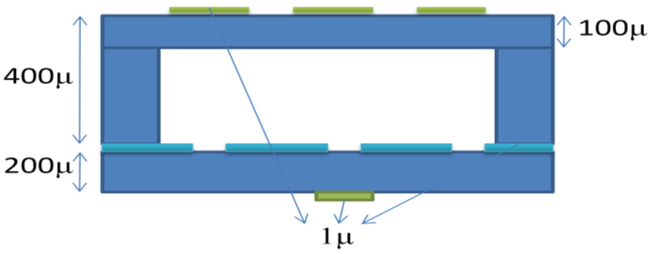
(a)



(b)



(c)



(d)

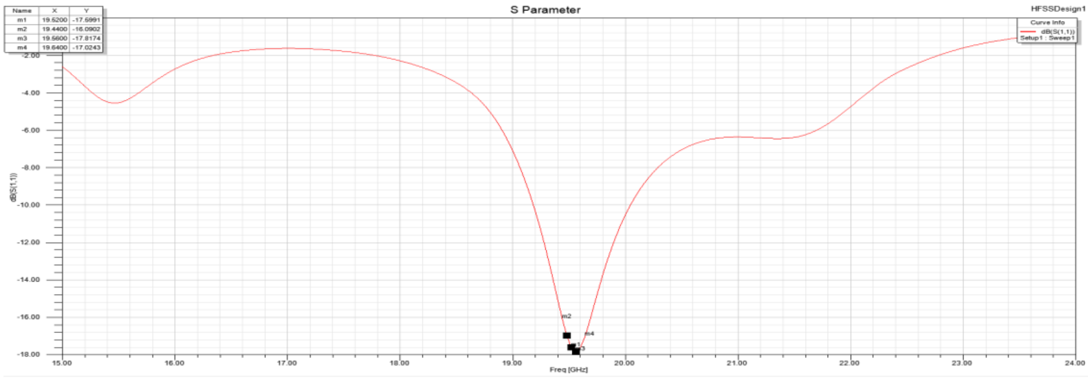
Figure 5.1.(a) Side view of 1st wafer of aperture coupled patch antenna, (b) Side view of 2nd wafer of aperture coupled patch antenna, (c) dimensions of feedline, (d) Dimensions of the proposed patch antenna using micromachining technology

5.3 Simulation Results

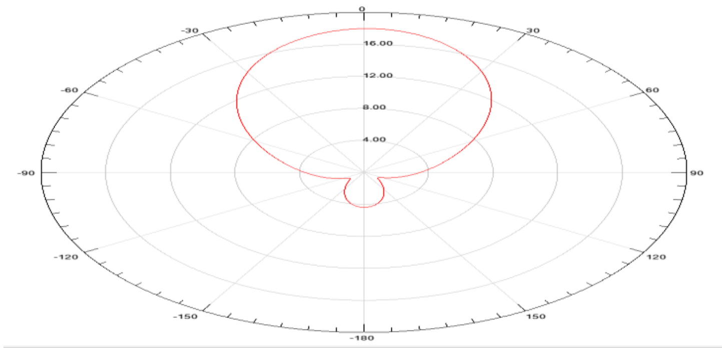
For the proposed antenna three conditions are simulated and results tabulated.

- When D1 & D2 P-I-N diodes are in OFF condition

Antenna radiating at 19.56 GHz and main beam lobe is straight.



(a)

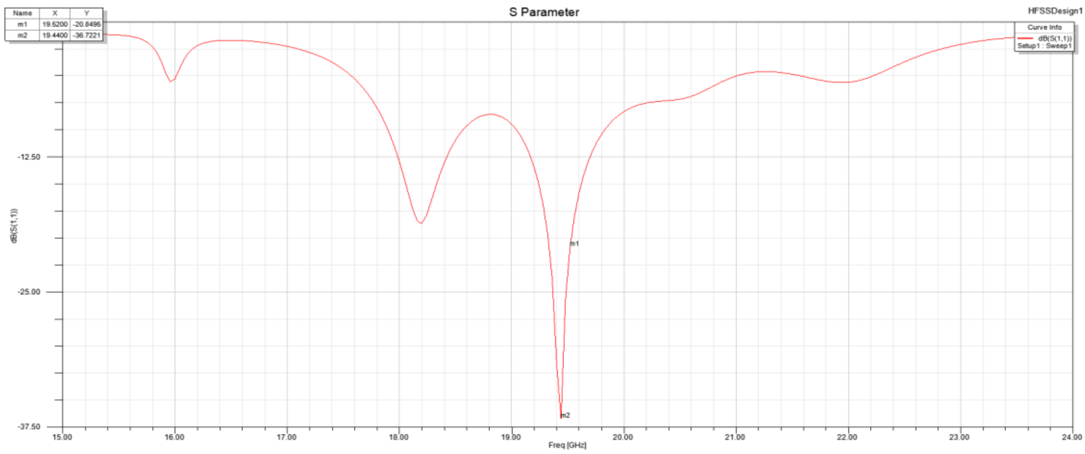


(b)

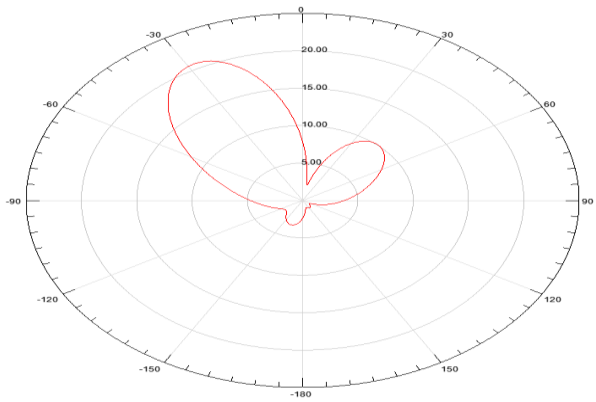
Figure 5.2 (a) S-parameter and (b) Radiation pattern when D1 and D2 are in OFF condition of an aperture-coupled patch antenna using micromachining technology.

- When D1 is ON & D2 is in OFF condition

Antenna radiating at 19.44 GHz and main beam lobe is tilted to left.



(a)

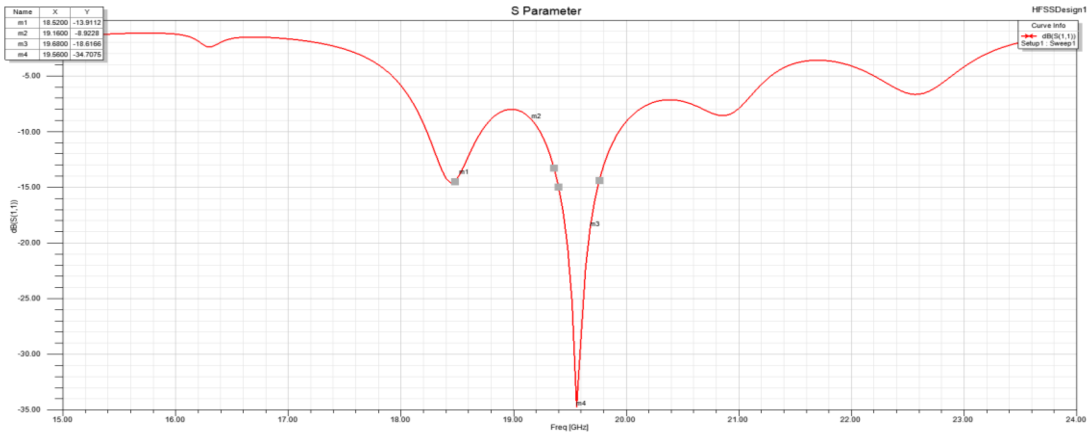


(b)

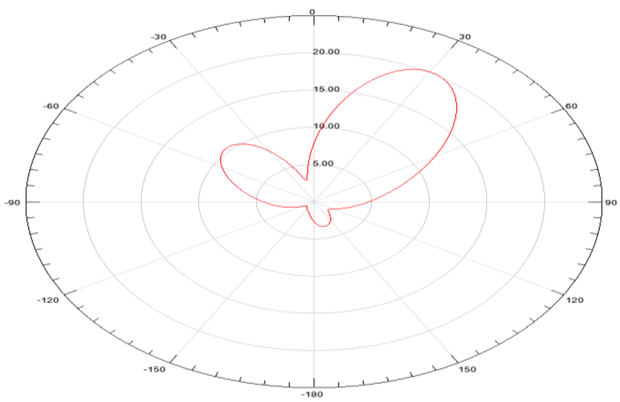
Figure 5.3 (a) S-parameter and (b) Radiation pattern when D1 is ON and D2 is in OFF condition of an aperture-coupled patch antenna using micromachining technology.

- When D1 is OFF & D2 is in ON condition

Antenna radiating at 19.52 GHz and main beam lobe is tilted right.



(a)



(d)

Figure 5.4 (a) S-parameter and (b) Radiation pattern when D1 is OFF and D2 is in ON condition of an aperture-coupled patch antenna using micromachining technology.

TABLE 3

MEASURED ANTENNA PARAMETERS

S.No	Switching Combinations		Resonant Frequency	Directivity	Gain	Radiation Efficiency	Front to Back Ratio
1	D1 & D2 OFF		19.56 GHZ	7.2 dB	6.6 dB	87.4%	16.1
2	D1 ON & D2 OFF		19.44 GHz	8.6 dB	7.2 dB	83.0%	373.25
3	D1 OFF & D2 ON		19.52 GHz	8.4 dB	7.1 dB	83.7%	241.4

5.4 Comparison with other techniques

In comparison with the other technique [28] this has good gain as well as directivity. The proposed antenna also has good front to back ratio and radiation efficiency.

TABLE 4

COMPARISON OF ANTENNA PARAMETERS WITH OTHER TECHNIQUE

Switching Combinations	Gain in reference [28]	Gain of proposed antenna	HPBW in reference[28]	HPBW of proposed antenna
D1 & D2 OFF	6.6	6.6	60	60
D1 ON & D2 OFF	6.69	7.2	55	60
D1 OFF & D2 ON	6.11	7.1	65	60

5.5 Conclusion

In this a beam-steering method using a aperture coupled microstrip patch antenna was designed, fabricated, and analyzed. The measurement results proved that the proposed antenna can steer the maximum beam direction with good gain, directivity, radiation efficiency and front to back ratio. It was also found that the operation frequencies of all the states were identical.

Chapter 6

Reconfigurable aperture coupled patch antenna with beam steering capability

6.1 Introduction

A reconfigurable scanning antenna is proposed in this chapter. This also has the feature of reconfiguring frequency with beam scanning capability. This structure uses two PIN diodes(D1 & D2) for beam steering purpose and BST for reconfiguring frequency. PIN diodes are connected in between the feedlines which is used as switches.

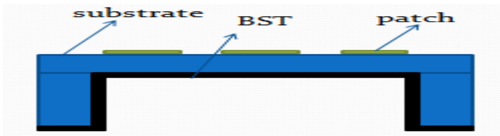
6.2 Proposed antenna structure

In present work the reconfigurable aperture coupled patch antenna is designed and design layout shown in Fig. 6.1, consists of two wafers.

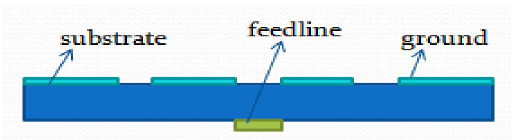
In first wafer, three Patch antennas (4.8mm*6.6mm) are designed on high resistivity (50 ohm-m), (110) Si wafer of thickness 0.4 mm and dimension 12mm x 29.2mm. Window of 8mm x 25.2mm is open on back side of wafer and open a rectangular cavity of depth 0.3 mm in silicon. Further 0.004 mm thin BST layer is deposited in cavity shown in Figure. 6.1(a).

The second wafer is a again high resistivity Si substrate with width of 0.2 mm which contain the antenna ground plane, three coupling slot at front side and feedline at back side of the wafer as shown in Figure. 6.1(b). Feedline dimensions are shown in Figure. 6.1(c). It has one main feedline and two sub feedlines. Main feedline is connected to two sub feedlines by two PIN diodes D1 and D2. By switching D1 and D2 beam steering is done.

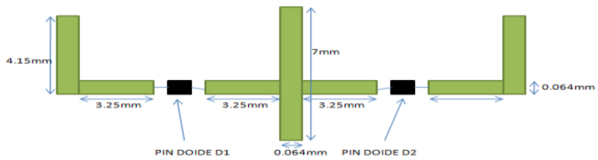
Final device layout is shown in Figure.1d in which back side of first wafer is bonded with front side of second wafer and layout was simulated using High Frequency Structure Simulator software(HFSS).



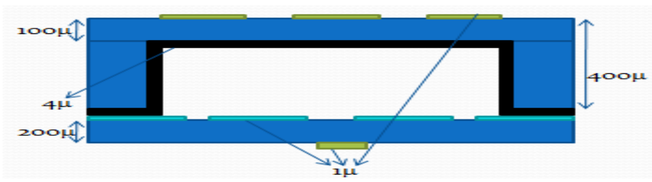
(a)



(b)



(c)



(d)

Figure 6.1 (a) Side view of 1st wafer of aperture coupled patch antenna, (b) Side view of 2nd wafer of aperture coupled patch antenna, (c) dimensions of feedline, (d) Dimensions of the proposed patch antenna using micromachining technology.

The dimensions of the proposed antenna based on are:

Patch: L x W= 4.8mm x 6.6mm, Cavity depth: 0.3mm,

Slot: L_s x W_s x d= 2.68mm x 2mm x 0.001mm,

6.3 Simulation Results

Simulations are done using high frequency microwave simulator. Simulations are shown for 0V, 40V and 70V applied across BST layer of thickness 0.004 mm

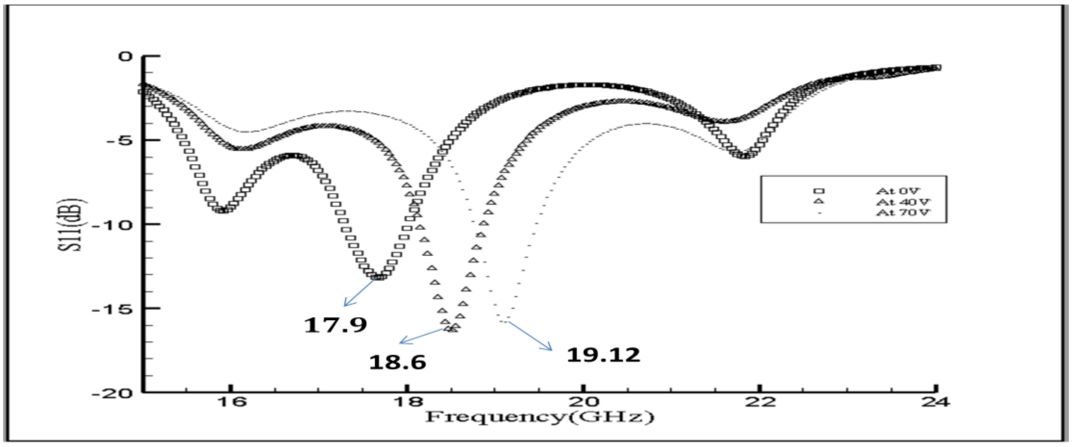
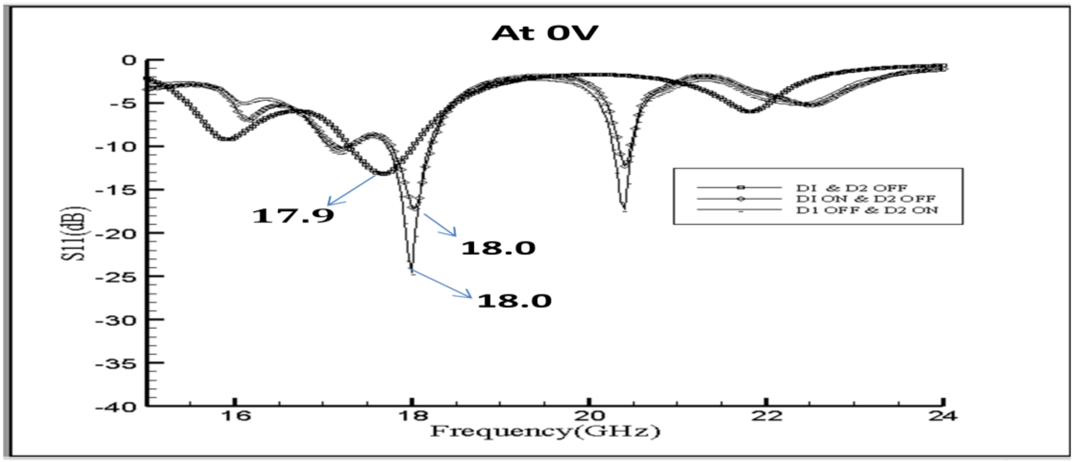
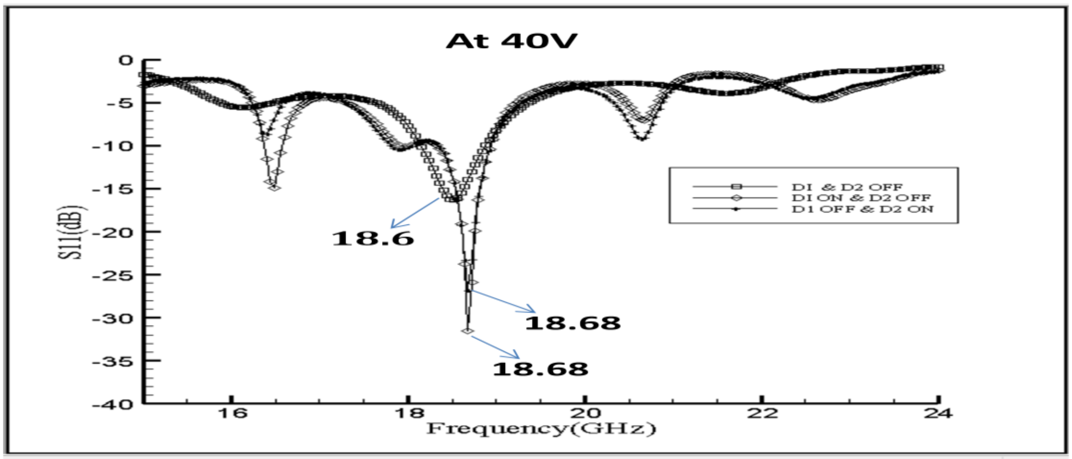


Figure.6.2 Return losses vs Frequencies for various voltages when D1 and D2 are at OFF condition



(a)



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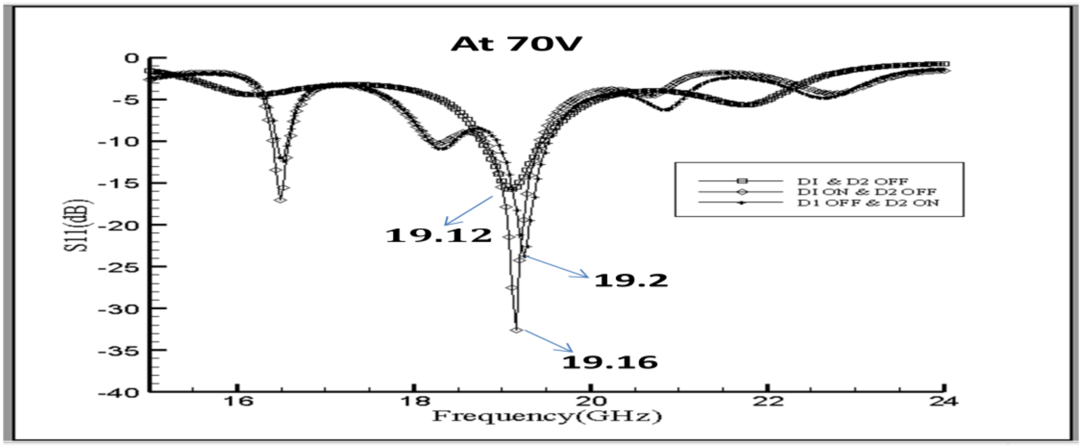
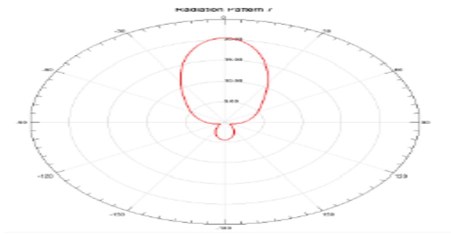
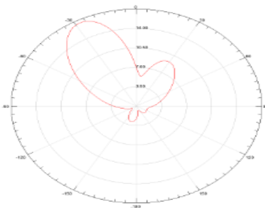


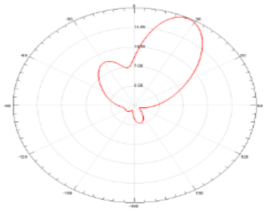
(c)

Figure 6.3 Return losses vs Frequencies for various voltages



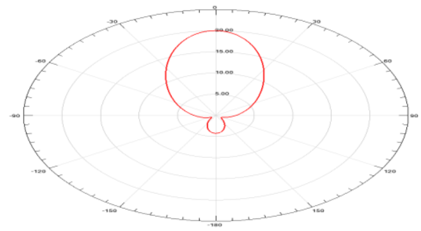
(a)



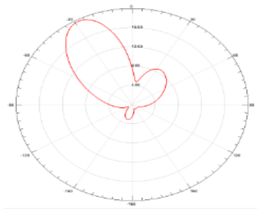


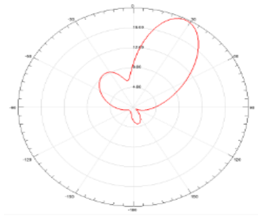
(b) (c)

Figure 6.4 Simulated Radiation pattern at 0V. (a) D1 & D2 OFF, (b) D1 ON & D2 OFF, (c) D1 OFF & D2 ON



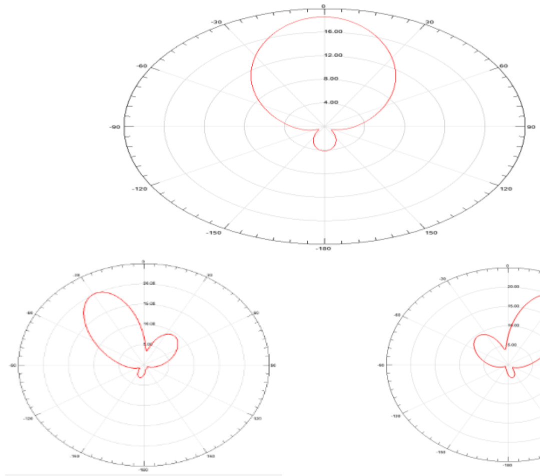
(a)





(b) (c)

Figure 6.5: Simulated Radiation pattern at 40V. (a) D1 & D2 OFF, (b) D1 ON & D2 OFF, (c) D1 OFF & D2 ON



(a)

(b) (c)

Figure 6.6: Simulated Radiation pattern at 70V. (a) D1 & D2 OFF, (b) D1 ON & D2 OFF, (c) D1 OFF & D2 ON

TABLE 5

MEASURED ANTENNA PARAMETERS

Voltage applied	Switching Combinations	Permittivity	Resonant Frequency	Directivity	Gain	Radiation Efficiency	Front to Back Ratio
0V	D1 & D2 ON	510	17.9 GHZ	8.7 dB	7.3 dB	84.2%	21.5
	D1 ON & D2 OFF		18.0 GHz	6.8 dB	5.0 dB	71.8%	295.8
	D1 OFF & D2 ON		18.0 GHz	6.9 dB	5.1 dB	73.7%	241.4
40V	D1 & D2 ON	250	18.6 GHz	6.7 dB	5.75 dB	85.4%	18.21
	D1 ON & D2 OFF		18.68 GHz	8.0 dB	6.4 dB	80.6%	450.1
	D1 OFF & D2 ON		18.68 GHz	8.0 dB	6.5 dB	81.5%	392.5
70V	D1 & D2 ON	100	19.12 GHz	5.7 dB	4.8 dB	85.5%	16.4
	D1 ON & D2 OFF		19.16 GHz	8.2 dB	6.8 dB	82.6%	349.7
	D1 OFF & D2 ON		19.2 GHz	8.3 dB	6.9 dB	83.2%	346.7

Figure. 6.3 shows that all diode switching combinations has almost same resonating frequency at a particular voltage and Figure 6.4-6.6 shows that all have almost 60° HPBWs.

Results in Table 5 shows measured antenna parameters as a function of applied voltage and switching combinations. This tunability range(1.2GHz) is used for various applications in commercial sector such as radars, satellite communication, wireless LAN etc.

Simulated results can be further improved by using U-shaped cavity and H-shaped slot in the proposed antenna.[4].

In comparison with the structure in [26],[28] our proposed structure provides almost similar performance, but this has the advantage of onchip integration, since this is in silicon substrate.

6.4 Applications

Beam steering systems applications are same as scanning system applications, it can have a wide range of applications in many areas of science and technology, including a number of important applications relevant to the area of robotics and autonomous agents, such as automated control systems, robotic laser surgery, object identification, target tracking, display systems, etc

6.5 Conclusion

Hence an BST based reconfigurable aperture coupled microstrip patch antenna with beam steering capability is simulated in this paper. Using BST , antenna is reconfigured to different frequencies by varying voltage applied across BST material. Simulated results shows high directivity(> 6 dB), Good gain(> 5 dB), low VSWR(<1.5) and low control voltages(<80V).

This antenna structure can reconfigure upto 1.2 GHz and has an extra advantage of beam steering which makes it a complete antenna for tracking.

Chapter 7

Conclusion and Future Work

7.1 Conclusion

We have presented a comprehensive view on the reconfigurable microstrip antennas. an BST based reconfigurable aperture coupled microstrip patch antenna is simulated in this paper. Using BST , antenna is reconfigured to different frequencies by varying voltage applied across BST material. Simulated results shows high directivity(> 6 dB), Good gain (>5dB), larger bandwidth (upto 900 MHz), low VSWR(<1.5) and low control voltages(<80V).

This antenna structure can reconfigure upto 3 GHz of resonant frequency without changing the radiation pattern. One can see the radiation patterns of all the frequencies are one and the same and can be even beam steering capability is achieved with small modifications.

The proposed reconfigurable aperture coupled microstrip patch antenna array with beam scanning capability has almost 40 degree scanning angle and BST based reconfiguring frequency is achieved with good gain and directivity. It has its own advantages and disadvantages but till 30 scanning angle without any drawbacks this antenna can be used for tracking purpose and many other applications.

7.2 Future Work

The future work for the proposed antenna structure is fabrication. Two double sided polish silicon wafers will be used for fabrication of BST based reconfigurable aperture coupled antenna. Both wafers are silicon(110) with 50 ohm-m resistivity. 5 MASKs will be required to fabricate the proposed structure. finally 3D bonding completes the fabrication work of proposed antenna.

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