Design of High-Reliability RF MEMS Switch for Reconfigurable 5G Antennas

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Approval

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Abstract

MEMS devices have gained importance during last few decades in different areas. These devices have been used in modern communication systems, radar technologies, imaging technologies and medical instruments. MEMS devices are low cost, reliable, small in size and easy to integrate with other IC fabrication technologies.

Switches are used everywhere in communication and satellite systems. Switching can be performed in different ways using PIN diodes, transistors and MEMS devices. Diodes and transistors are electronic components and provide high speed switching but having high insertion loss and low isolation. MEMS switches offer a lot of advantages over the conventional switches such as high isolation, low power consumption, low isolation, better harmonic rejection and reduced size. But the integration of RF MEMS switches with antennas is still very challenging due to dielectric discharge, stiction and parasitic problems.

This study focuses on the electrostatically actuated single pole double throw (SPDT) switch which will be used in future 5G communication systems. The proposed switch is composed of three different switches designed separately in order to reduce the space and enhance the performance. All the switches are actuated simultaneously hence no voltage switching is required. The complete design is composed of two shunt switches and one series switch. The air gap is provided as insulating layer to provide maximum isolation within the fabrication limits. The electrical parameters of the proposed switch were simulated in CST software while the mechanical parameters were analyzed using Comsol software.

Dedication

I dedicate this thesis to my family who always encourage me in completing my work. To all my teachers for their help and support specially Dr. Nosherwan Shoaib for his endless assistance and encouragement in doing this research work. I also dedicate this work to Dr. Fahimullah Khan who made my interest in MEMS and encourage me to work in this area.

Certificate of Originality

I hereby declare that this submission is my own work and to the best of my knowledge it contains no materials previously published or written by another person, nor material which to a substantial extent has been accepted for the award of any degree or diploma at NUST SEECS or at any other educational institute, except where due acknowledgement has been made in the thesis. Any contribution made to the research by others, with whom I have worked at NUST SEECS or elsewhere, is explicitly acknowledged in the thesis.

I also declare that the intellectual content of this thesis is the product of my own work, except for the assistance from others in the project's design and conception or in style, presentation and linguistics which has been acknowledged.

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Acknowledgment

I would like to pay my gratitude to Allah Almighty, the One Who bestows honor on whom He wills and in Whose hands lies the good. I would like to thank my supervisor, Dr. Nosherwan Shoaib and all RIMMS faculty, without their help and support I couldn't imagine to have this success.

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Chapter 1

Introduction

MEMS (Micro-Electro-Mechanical Systems) is comparatively new technology in the domain of RF/Microwave components. Nowadays, MEMS devices like capacitors, inductors, switches, tunable components and filters are widely used at RF/Microwave level. It enables simplification of front-end designs. This chapter covers the theory related to MEMS technology. Further it discusses the use of MEMS technology in RF/Microwave domain and how MEMS can be beneficial in this area. Specifically, the use of MEMS switches is discussed in detail. The issues related to MEMS switches are explained and available topologies are shown. The comparison between MEMS switches and transistor-based switches is presented.

1.1 5G Technology

5G technology is a new era in the field of communication. Up-till now, no clear specifications are given for 5G systems. But some of the early preferences have arisen. These include

- Mm-wave frequency range
- Small cells for better coverage and large number of users
- Massive MIMO for enhanced performance in congested areas
- Full duplex systems
- Beamforming for better coverage

Millimeter waves are the radio waves in the frequency range from 30-300 GHz. This frequency band is known as millimeter as their wavelength is of the size around 1-10 nm. In today's communication technology, the systems use frequencies around 2.1 GHz. While 5G communication systems are targeting at above 20 GHz [1]. The major disadvantage of high frequencies is that they cannot pass through walls or buildings hence the coverage area is reduced. To overcome this issue, small cells are used and directional antennas along with beamforming techniques are used to enhance the performance.

1.1.1 Critical Requirements of 5G Communication Systems

The following are the critical requirements of the 5G communication systems which should be taken care of while designing RF switch for such systems [2,3].

- Frequency range (around 20 – 30 GHz)
- Isolation (>20 dB)
- Single pole double throw
- Switching speed (< 20 or 30 usec)

Also these will be the design aspects for the proposed switch.

1.2 MEMS Technology

MEMS technology is basically to reduce the size of different sensors, mechanical actuators or systems. It takes the advantage of micro level production of mechanical elements commonly known as nanotechnology. It provides stimulating prospects to reduce the physical size of a lot of devices up-to micro level. The MEMS devices are gaining high importance in today's world and in near future a lot of devices will be replaced from MEMS devices specially MEMS sensors, accelerometers and actuators. MEMS switches are also very popular and a lot of research is being carried out in this domain [4]. Micro means the size of the devices while electro relates the electrical parameters and mechanical refers to the structure of the devices. It comprises the three technologies into one system. It uses micro level mechanical devices to implement electrical domain tasks. the devices are sensitive to physical changes like thermal or magnetic changes or piezoelectric effects. MEMS technology can be generally related to IC fabrication. MEMS devices fabrication which can be interfaced with IC technology. So the mechanical elements are interfaced along with IC components which results in low cost solution, less current consumption, low weight, reduced size and improved performance. Some of the major areas in which MEMS are used are given below.

1.2.1 MEMS Applications

Sensors gyroscope, accelerometers

Micro Engines highly efficient energy source

Pressure Sensors blood or fluid pressure sensors

Optical MEMS highly sophisticated integrated systems using Electrical, Mechanical and Optical Systems for manipulating optical signals

RF MEMS actuators, filters, capacitors, inductors, switches

1.3 RF Switches

Switch is any electrical or mechanical device that creates or breaks a connection between two elements. RF switch can be defined as any device that can route RF signal from transmission line path to another path. Generally, switches make the multiband or multimode receiver systems more reconfigurable. Switches along with other elements can be used as a low-cost solution e.g. two receivers can process signals coming from three or more antennas using switches hence reducing the cost of more receivers.

1.3.1 RF MEMS Switches

RF MEMS switches are becoming more popular due to their reduced size and enhanced performance. Modern receivers, transmitters, antenna arrays and other systems are using MEMS switches [5]. New technologies not only producing SPST switches but also SPDT and SPMT [6] switches with high precision and less loss. MEMS has proven to be cost effective in multi through applications as compared to other competitors. The switches at frequencies more than 100 GHz have been reported in the literature [7]. These switches have some crucial advantages over the old switches based upon GaAs or transistors. They use less power hence current consumption is reduced, low insertion and high isolation losses, linear behavior, high power handling capability, reliable and affordable. The differnt MEMS switches types are shown in figure 1.1 [8].

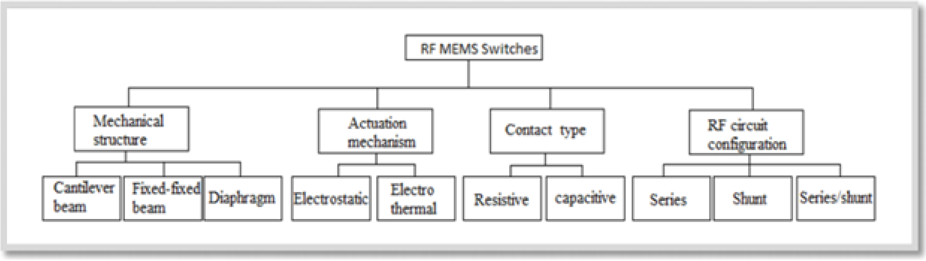

Figure 1.1: MEMS Switches Types

But they also have some disadvantages like low speed and high actuation voltage [4]. The actuation voltage can also be reduced using different mechanical assemblies and this is the hot area of research nowadays. Also there are some other issues like temperature instability, dielectric charging and contact failure which need to be considered while designing of any MEMS based switch.

The MEMS switches can be divided into two categories

- Series Switches
- Shunt Switches

1.3.2 Series Switches

These type of MEMS switches are also known as metal contact switches. In these switches, the main transmission line is disconnected. Mechanical beam is hanging over the disconnected part of the transmission line. The mechanical beam can be a cantilever beam i.e. fixed at one end while free from the other end. The beam consists of thin metallic strip and dielectric [9]. There is only air gap between transmission line and the beam. When the beam is actuated downward using voltage source, it connects the two ends of the transmission line resulting in the signal flow in the transmission line. This type of metallic contact has some disadvantages of stiction and slightly high insertion loss [9].

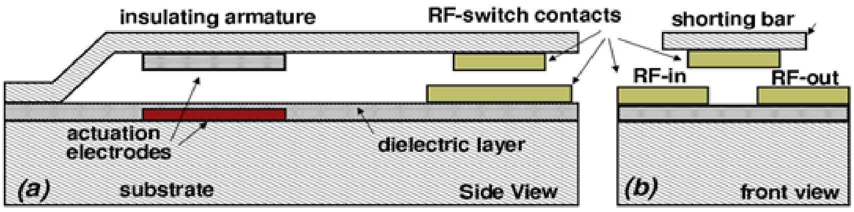

Figure 1.2: MEMS Series Switch (a)Switch Off State (b)Switch On State

1.3.3 Shunt Switches

These switches are generally ON i.e. the signal flows from input port to output port. The hanging beam is there above the main transmission line. The beam generally used in shunt switches is fixed-fixed beam but cantilever beams can also be modified to use in this topology as will be discussed further in the chapter 3. There is dielectric present above the transmission line. When the voltage is applied, the hanging beam comes down and lies above the dielectric forming a capacitor. Hence the signal goes to ground due to capacitive effect producing by dielectric between two conductors. It behaves like parallel plate capacitor [9]. DC voltage is connected to the switch while lower electrode is grounded. When voltage is applied, the switch plates are charged hence producing electrostatic energy. This energy causes the connection between upper and lower plates. Due to this connection, RF energy conducts to the ground due to dielectric layer but the electricity is prohibited to cross the dielectric material [4]. This topology has lower insertion loss and high reliability as compared to series switches. They can also be used at higher frequencies around 100 GHz [10].

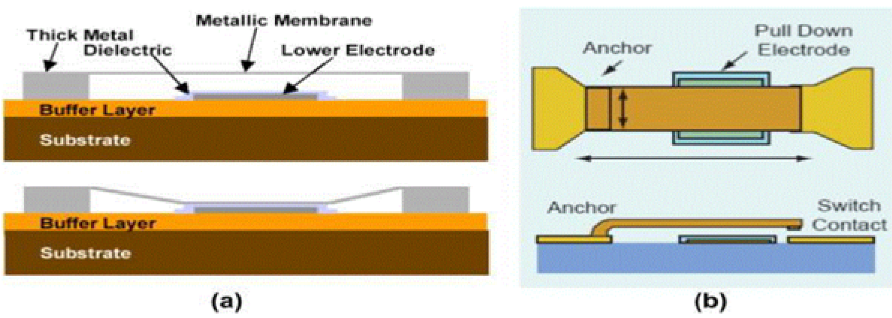

Figure 1.3: MEMS Shunt Switch (a) Fixed-Fixed Beam (b) Cantilever Beam

1.3.4 Actuation Schemes

As discussed earlier, MEMS switches use mechanical beams for switching. These mechanical beams are actuated using different topologies. The most common actuation schemes are as follows:

- Electrostatic
- Thermal
- Electromagnetic
- Piezoelectric

Among all, electrostatic is the most suitable and chosen option for MEMS switches [11]. This technique uses less power and very small current is consumed. Its fabrication is easy and also very small in size as thin metallic layers are used as electrodes [12]. Other benefits of this actuation scheme are low insertion loss, reduced area, fast switching speed, reliability and durability, life time of millions of cycles and easy to integrate with IC technology on single chip.

1.3.5 Motivation of MEMS switches

Low Power Consumption Very small power is required to actuate the MEMS switches hence making the scheme best for low power consuming systems.

High Isolation MEMS switches are fabricated using air gaps between upper and lower plates having very small capacitance of around 4 fF producing very high isolation.

Low Insertion Loss the better the contact, the lower the insertion loss in series switch. While in shunt switch the insertion, loss is only due to transmission line hence very low insertion loss is present in MEMS switches.

Intermodulation Products MEMS based devices are very linear and offer very low intermodulation products. Performance: generally, the performance of MEMS switches is around 30-40 dB better than transistor-based switches.

Low Cost MEMS devices are fabricated using surface micromachining techniques and can be integrated on quartz, pyrex, low temperature cofired ceramic or GaAs substrates along with IC technologies which results in low cost production of such devices.

Comparison between MEMS vs Conventional Switches

Switches are everywhere in signal routers, antenna array systems, transmitter/receiver duplex systems. the general requirements of the systems are durability, reliability, power consumption and switching speed. MEMS switches perform better in most of the required aspects as compared to the conventional transistor or diode based switches. They have low loss, high isolation, better power handling capacity and less current consumption [4]. MEMS switches have performed not only at lower frequencies but also at mm-wave frequencies compared to old BJT or FET based switches. There are always some disadvantages of any technology. In case of MEMS based switches the major disadvantage is low switching speed (2-40 usec). This is very slow speed as compared to solid state switches. Due to low switching speed, MEMS switches are not used in the systems where very high switching speed within nsec is required. But there are systems where very high switching speed isn't required like Radar systems, satellite communication systems and instrumentation systems in which MEMS switches are widely used.

	MEMS	PIN	MOSFET
Frequency Range	DC to Max Frequency	1 MHz to Max	DC to Max Frequency
Insertion Loss	Low	Medium	High
Isolation	Good across all frequencies	Good at high end frequencies	Good at low end frequencies
Return Loss	Good	Good	Good
Switching Speed	Low	High	High
Settling Time	Slow	<50 usec	<350 usec
Power Handling	High	Low	Low

Figure 1.4: Brief Comparison among Different Switch Technologies

1.4 Thesis Objective

The objective of this research is to design a MEMS based switch which should be comprised with the upcoming 5G communication system requirements and also have the stability and reliability for using over the long period of time.

The proposed switch must have the best possible electrical and mechanical aspects. It should have the lowest insertion loss and highest isolation. The actuation voltage should be minimum and there must be no issue like stiction.

1.5 Thesis Structure

This thesis is divided into 6 chapters. The first chapter has the general theory related to MEMS technology and at the end the problem is defined. The second chapter presents the summary of the design theory of the MEMS switches. The third chapter summarizes the state of the art papers in the field of MEMS switches. In this chapter, detailed analysis of number of papers is presented for in-depth understanding of the MEMS switches and their working. The fourth chapter mainly comprises the mechanical design of the proposed switch. It discusses the complete mechanical and electrical design. The fifth chapter is about the mechanical analysis and electrical parameter analysis of the switch. The last chapter concludes the whole research and provides the summary of the work done and also the future work that can be done in order to enhance the scope of this research work.

Chapter 2

Literature Review

Modern world has high demand of components operating at high frequencies, larger bandwidth and smaller area. MEMS technology has potential to overcome all these challenges of modern era and hence rapidly increasing within the modern devices. The common benefits are low loss, better isolation, linearity over larger bandwidth and low cost for bulk production as compared to conventional technologies. According to [13] MEMS technology will have drastic growth in the areas of pressure sensors, measurement and fluid systems. but in recent years, RF MEMS has also gained importance and the devices are in great demand. Researchers are working on complex architecture related to 5G communication systems having small coverage area to accommodate large number of users and high bandwidth. There is a need of RF filters and switches within these systems due to which the growth of RF MEMS devices is increasing day by day. According to [13] the MEMS market will increase up-to 9Due to ease in fabrication, integration with CMOS technology and diminishment of chip area, the demand of MEMS devices will enhance. MEMS switches have actuators for switching mechanism. These switches can have different actuation techniques like electrostatic [14], electromagnetic [15], magnetostatic [16] and thermal [17]. Electrostatic actuation is the most commonly used schemes within the MEMS switches due to its easy design, low power consumption, small size, better capacitance ratio between OFF and ON steates and less forces requirement. Also, it only requires small metallic sheet and doesn't require deposition of any material as in piezoelectric actuation schemes. The only drawback of electrostatic technique is high actuation voltage. In [18] it is shown that the life span of any electrostatic actuation based MEMS switch is highly dependent upon the value of actuation voltage. This chapter covers the fundamental design parameters related to RF MEMS Switches technology. Different schemes to actuate the switch are discussed. The role of material in the working of MEMS switches is described. Extensive review of SPDT switches is presented.

2.1 Fundamentals of Switching

MEMS switches have different activation and working techniques. Two types of MEMS switches are

1. Resistive

2. Capacitive

The major principle in the design of resistive switches is the area of contact. As the contact area increases, the resistance lowers hence reducing the contact temperature. The contact area depends upon the force applied, air gap and material characteristics. The adhesive force which becomes applicable after the removal of actuation voltage must also be taken care of. The beams must be strong enough to sustain the adhesive force hence avoiding stiction [19]. These resistive switches are used at lower frequencies generally up-to 50 GHz. These switches have low resistance in the range 0̇15 to 0̇4 ohm while having very small force needed to actuate. But the control voltage is high [20]. These switches are mainly used in series configuration. It has disadvantage due to metal to metal contact that degrades the life span of the switch due to increased temperature at the contact area.

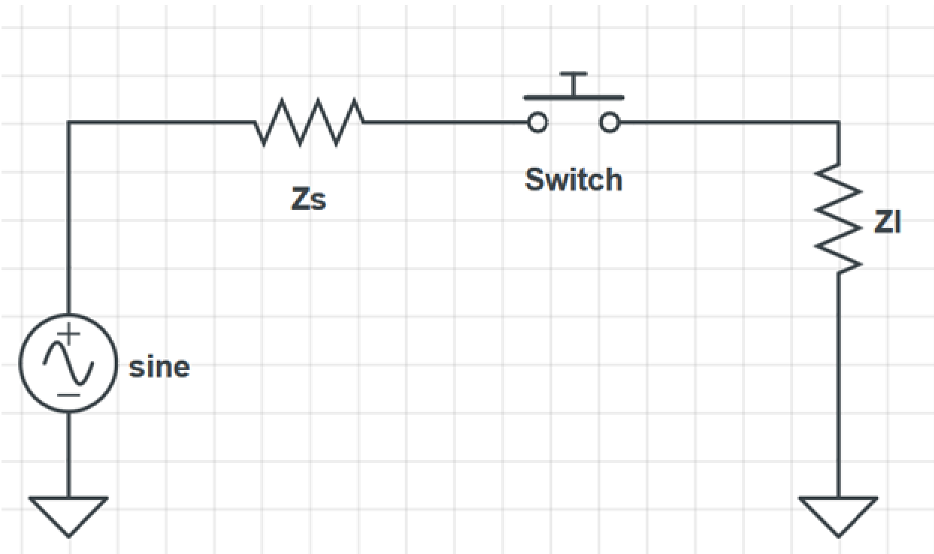

Figure 2.1: Equivalent of MEMS Series Switch

The other type of MEMS switch is the capacitive switches which work on the principle of parallel plate capacitor in which capacitance ratio between ON and OFF state is determined. These switches are generally used in shunt configuration and can be used more than 100 GHz frequencies. They are low loss and provide better isolation [21].

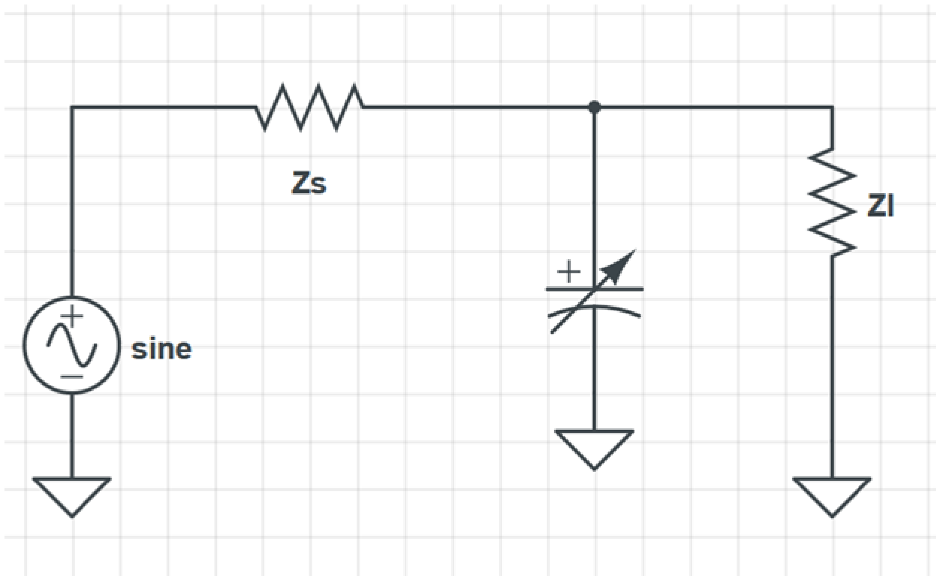

Figure 2.2: Equivalent of MEMS Shunt Switch

The benefit of capacitive shunt switch over the series switch is its capability of operating at low voltage. Though, these are subtle to surface irregularity and inner stress in the membrane.

2.2 Causes of Failure

Reliability is one of the critical parameters of any device. In order to maintain smooth running of any system, all the sub components must be reliable enough to work for longer period of time. MEMS switches have two types of causes due to which they can fail.

- Electrical Failure
  - Stiction
  - Dielectric discharge
- Mechanical Failure

- Fatigue
- Contact Heating
- Internal Stress

2.2.1 Electrical Failure Issues

The electric charge on the dielectric layer in the capacitive type switches is the major cause of the failure of MEMS shunt switches. This can be avoided using variable polarity of control voltage [22]. Switches that handle power in the range of 10-100 mW can be failed due to high current density. This problem is generally solved using thick beams. The main reason of failure of switches working at high power is the tripping and very high current densities. Actuation voltage or adhesive voltage (return voltage) have some irregularities. This issue can be avoided by increasing the stiffness of the beams and proper route of the control voltage [23]. Stiction is the force that hold the bridge arm down at ON state even after the removal of actuation voltage. This can be present due to charge present at the dielectric layer over the main transmission line. Due to these charges, electric field is produced that hold the beam at down position [24].

2.2.2 Mechanical Failure Issues

The main reason of failure of series switches is erosion at electrodes, contact acclimatization and the development of dielectric layers at contacts. This issue can be avoided using proper selection of material having unsurpassed connection characteristics. Heating of the contact area in series switches is another major contributor in failure of these switches. Again this problem can also be solved by choosing best material and proper cooling mechanism [25]. Fatigue is due to loading of any material below its fracture stress point. Such loading can cause cracks within in the layers of the structure hence causing reshaping or cracking the structure. It slowly changes the characteristics of the material an reduces the life of switch.

Residual Stress

The stress in the absence of any outside force is known as residual stress. Within the domain of materials, it can be divided into types of stresses

Extrinsic Stress

This stress is due to unwanted outside aspects like temperature changes. It generally remains even throughout the depth of the materials. Thermal mismatch stress is the main cause of extrinsic stress. It is more prominent in materials having inhomogeneous thermal coefficients.

Intrinsic Stress

This stress is due to inside changes of the materials. During deposition of the material, its internal structure may change causing the intrinsic stress. There are different reasons of this stress like deposition rate, temperature, pressure in the chamber, fabrication process and presence of impurities. This type of stress isn't uniform throughout the structure hence causing stress gradient.

2.2.3 Selection of Material

As discussed earlier, the selection of suitable material can reduce the risk of failure of switch. hence, the material has a vital role in the designing of the switch. The selection of material depends upon its characteristics. The major characteristics of any material are resistance and hardness. The conditions in which deposition of material occurs and the deposition technology also affect the material characteristics. As materials have different resistance in deposited form as compared to their inert form. Solid metals as molybdenum or tungsten are good for long life MEMS switches as they don't have stiction issue but due to metallic nature they are more prone to oxidation hence not suitable for MEMS devices manufacturing. On the other side, pure gold doesn't have oxidation issue and less resistance but it can not sustain multiple contacts due to soft nature. Hence it is also not suitable for long life MEMS switches. literature shows that Al is the best metal for contact material.

The choice of structural material depends on the hardness, resistance and complexity of the process. The properties of the materials significantly depend on the conditions and deposition technology of the material. For example, the specific resistance of the deposited metal film is almost twice that of the original material. Pure Au provides the lowest contact resistance and is inert to the formation of oxides, but it has been empirically found that the predominant number of failures are associated with pure Au due to the point destruction of the contact area under repeated efforts. Hence, pure Au is not suitable as a structural material of RF MEMS switches that require a long lifespan. Solid metals, such as tungsten or molybdenum, are capable of processing sufficiently high-frequency signal power and do not exhibit any stiction problems [26]. However, they are more sensitive to oxidation and require a relatively high initial contact force. Thus, tungsten and molybdenum are not suitable as structural material. From the obtained results, it was found that the evaporated aluminum is one of the suitable candidates as a contact material. However other metals can be used in making shunt switches in which direct metal to metal contact is not present. For choosing best material for shunt switches, following performance parameters must be taken care of

- Actuation voltage
- RF losses
- Thermal stress

The major material characteristics are Poisson's ratio, Young's modulus, thermal conductivity and thermal expansion coefficient.

2.3 Critical Design Parameters

For MEMS switches, critical design parameters can be sub divided into two parts i.e.,

- Electrical Parameters
  - Insertion loss
  - Isolation
  - Return loss
  - Capacitance ratio
  - Transmission line characteristics
- Mechanical Parameters
  - Pull-in voltage
  - Spring constant
  - Switching time

2.3.1 Electrical Parameters

Insertion loss It is the loss inserted by any RF device while transmitting the signal. Ideally, the device should not add any loss and it should be 0 dB but practically less than 1dB loss is considered to be good.

Isolation It is measure of the signal present at the output port while no signal is present at the input port. It should be as much higher as possible.

Return loss It is the loss which occurs at input port due to mismatch reflections.

Capacitance ratio In shunt switches, due to effect of parallel plate capacitor, capacitance is calculated in ON and OFF state known as capacitance ratio. It should be as much higher as possible.

Transmission line characteristics These are important to be considered for calculation of all of the above parameters.

2.3.2 Mechanical Parameters

Pull-in voltage It is the voltage required to pull down the suspended bridge arm. It should be as much lower as possible.

Spring constant it is the ratio of the force applied and the displacement due to this force. Commonly expressed as

$$k = F/x \tag{2.1}$$

Switching time time required by the suspended bridge arm to come to contact when voltage is applied.

2.4 Analytical Modeling of MEMS Switches

2.4.1 Pull-in Voltage Analysis

The shunt switches actuators have an important parameter of pull-in voltage. It is related to the equilibrium between the force pulling the beam structure down and the force pulling back the beam to original position. If voltage isn't present across the electrodes, the upper beam is in rest position at a distance denoted by g0 from the lower electrode. As the voltage across the electrodes increases, the electrostatic force is generated that pulls the movable upper electrode downwards. When the voltage levels the spring constant, the two layers are in contact shunting the signal. This voltage is known as pull-in voltage. This voltage is designed in such a way that the movable electrode just touches the lower electrode. Equation 2.2 is used to calculate the pull-in voltage [27].

$$v_{pull-in} = \sqrt{\frac{8kg_o t}{27A\epsilon_o}} \tag{2.2}$$

where K is spring constant by membrane along Z-direction
g_o is the gap between two electrodes
A is the area of actuation
ϵ_o is the permittivity of air

The voltage that holds the movable beam at down position is slightly higher from the spring force and the return force is responsible that brings the beam at initial position [21].

2.4.2 Switching Time Analysis

Switching time is very critical parameter of MEMS switches as these devices have not fast switching speed. Hence this is another hot area of research within the field of MEMS switches. This is greatly dependent upon the applied voltage. Commonly, the applied voltage is slightly higher from the pull-in voltage in order to achieve small switching time. It can be calculated using equation 2.3 [21]

$$t_(pull-down) = 3.67\frac{v_{pull-down}}{v_s}\sqrt{\frac{m}{k}} \tag{2.3}$$

2.5 Electromagnetic Model Analysis of MEMS Switches

2.5.1 Design of CPW Transmission Line

Coplanar waveguide commonly known as CPW transmission line is a combination of three parallel conductors placed on transmission line. Normally the center conductor is the main line having signal while the other two lines are used to ground the signal. This configuration helps in minimizing the effect of coupling while maintaining integration of parallel and series elements. CPW lines are also used in integrated circuited technology due to their coplanar architecture. In microwave components, these type of configuration lines have smaller conductors and low losses [28]. An estimated formula for the calculation of impedance of CPW line as described in [29] is shown in 2.4.

$$Z_(o) = \frac{30\pi^2}{\sqrt{\frac{\epsilon_r+1}{2}}}[ln(2\frac{1+\sqrt{p}}{1-\sqrt{p}}]^{-1} \tag{2.4}$$

Where $p = \frac{w}{w+2x}$
,w=width of center transmission line, x=width of the slot

2.5.2 Circuit Model of the MEMS Shunt Switch

The model of the MEMS shunt switch consists of two segments of transmission lines along with lumped components model having values of RLC of the beam with up and down capacitances. The shunt impedance of the switch is calculated in equation 2.5 [30]

$$Z_(s) = R_s + j\omega l + \frac{1}{j\omega C} \tag{2.5}$$

C is the capacitance which depends upon the position of the switch whether in up-state or down-state. The resonance frequency can also be calculated using equation 2.6

$$f_o = \frac{1}{2\pi\sqrt{LC}} \tag{2.6}$$

Up-State Capacitance

The up-state capacitance of the shunt MEMS switch is specified in equation 2.7

$$C_o = \frac{\epsilon_o \omega W}{g + \frac{t_d}{\epsilon_r}} \tag{2.7}$$

The term $t_d \epsilon_r$ is due to the thickness of the dielectric layer present in shunt switch. ωW is the area of actuation and g is the air gap. Also in up-state capacitance, fringing field capacitance have critical role. According to as [30] it is around 20 – 60 % part in the total up-state capacitance. The up-state capacitance can also be found using S parameter analysis. For this, return loss plot is produced and assume the switch is working below cut off frequencies and ignoring the effect of inductance and resistance on the impedance, the return loss can be calculated using equation 2.8

$$S_{11} = -20\log\left|\frac{-j\omega C_{up} Z_o}{2 + j\omega C_{up} Z_o}\right| \tag{2.8}$$

Down-State Capacitance

The down-state capacitance of the MEMS switch can be found using equation 2.9

$$C_d = \frac{\epsilon_o \epsilon_r A}{t + d} \tag{2.9}$$

Capacitance ratio can be calculated using up and down states capacitances. In order to make this ratio higher, the dielectric layer must be kept small. The isolation using down-state capacitance can be calculated using equation 2.10 [Multiresponse Optimization of a RF-MEMS Switch Considering Residual Stress by Sadia Younis]

$$S_{21} = -20 \log \left| \frac{2}{2 + j\omega c_d Z_0} \right| \tag{2.10}$$

From equations 2.8 and 2.10, it becomes vibrant that to have high isolation when the switch is in off-state, the down-state capacitance must be large and for low insertion loss when the switch is in ON state, the up-state capacitance must be small.

2.6 Circuit Model of the MEMS Series Switch

When the voltage isn't applied, the air gap is present and the transmission line is disconnected hence the series switch is in OFF state. When the voltage is applied and the tip of the switch comes down and connects the two ends of the transmission line, shorting the signal path hence the switch is in ON state. These types of switches can work at low frequencies as compared to shunt switches.

2.6.1 Up-State Capacitance

In series switch, the up-state capacitance is due to series capacitance between the metallic part of the switch and the transmission line plus parasitic capacitance due to discontinuity in the transmission line as shown in equation 2.11 [30]

$$C_u = \frac{C_s}{2 + C_p} \tag{2.11}$$

For switches having two contacts as in cantilevers the first term will not be divided by 2. Also the isolation can be calculated using up-state capacitance using equation 2.12

$$S_{21} = \frac{2j\omega C_u Z_0}{1 + 2j\omega C_u Z_o} \tag{2.12}$$

2.6.2 Down-State Resistance

The down-state resistance is due to metal to metal contact plus the transmission line resistance. The contact resistance depends upon the area of contact, the material properties and the force applied. The overall series resistance can be calculated using equation 2.13

$$R_s = 2R_c + 2R_{s1} + R_l \tag{2.13}$$

Generally, the total resistance is of the order of 1-2 ohm. Also the reflection can be found using this series resistance as shown in equation 2.14

$$|S_{11}|^2 = (\frac{R_s}{2Z_o})^2 \tag{2.14}$$

Chapter 3

Current State of the Art

This chapter presents the detailed review of latest research in the domain of MEMS switches. Critical analysis of different research papers is presented. Comparison is performed in order to understand the current state of the art trends in MEMS switches domain.

3.1 MEMS Shunt Switches

In [31] MEMS shunt switch is proposed using NIMOS technology. The switch was electrostatically actuated. The switch was designed using Taguchi Method in order to adjust the dimensions of the switch. Coplanar waveguide transmission lines are used. Actuating mechanism consists of combination of folding and straight beams. DC bias was applied on the ends of straight rods. The complete view of the switch is shown in fig 3.1.

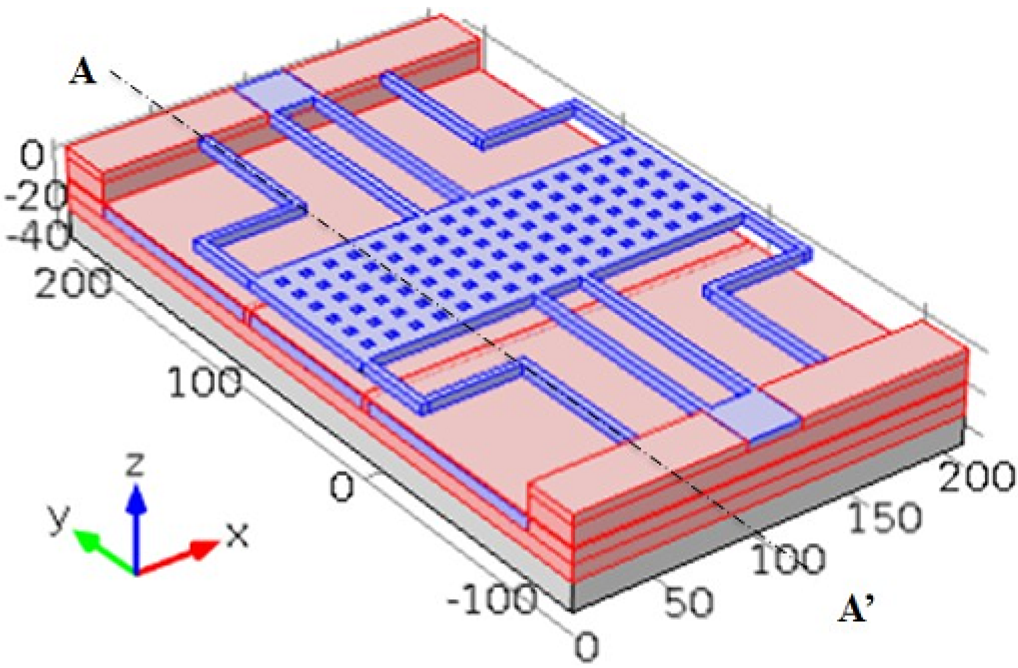

Figure 3.1: Complete View of the Switch

Beams length and width were optimized for long life as well as low actuation voltage. For low actuation voltage, beam width should be small but it ill enhances the chances of bridge breakdown. The spring constant also depends upon the structure of beams. Low spring constant will have low actuation voltage. After optimization the actuation voltage of 2.9V was achieved and displacement was 1.39 um at actuation voltage which was required according to the fabrication technology. The switch has insertion loss of -9 dB at 55 GHz. -23 dB isolation was achieved at 55 GHz. As in MEMS switches, the main drawback is the high actuation voltage. In [32] author has claimed another novel design for low actuation voltage. The main contribution of this research paper is the detailed analysis of suspended meanders and presented the solution of residual and gradient stress. Again CPW lines were used as they are easily integrable with IC fabrication technology. In proposed design, CPW main transmission line of 1um thickness was used. Substrate was high resistive silicon. The whole geometry was matched to 50 ohm impedance. The beam was designed using combination of serpentine structure with torsional anchors. Two different beam structures were simulated as shown in figures 3.2 and 3.3.

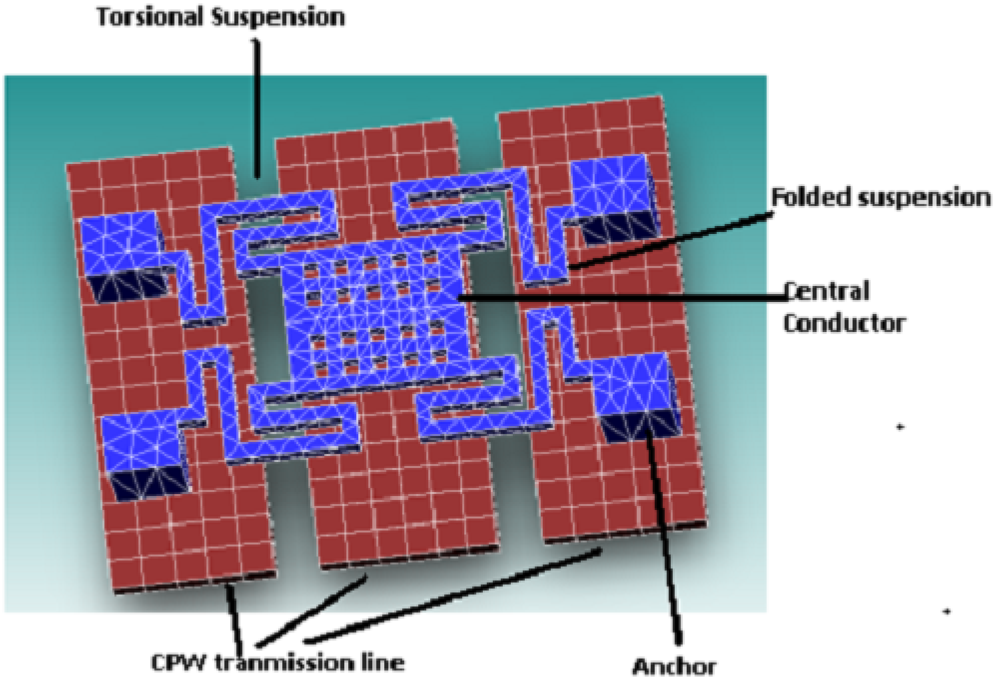

Figure 3.2: Simulation of First Beam Structure

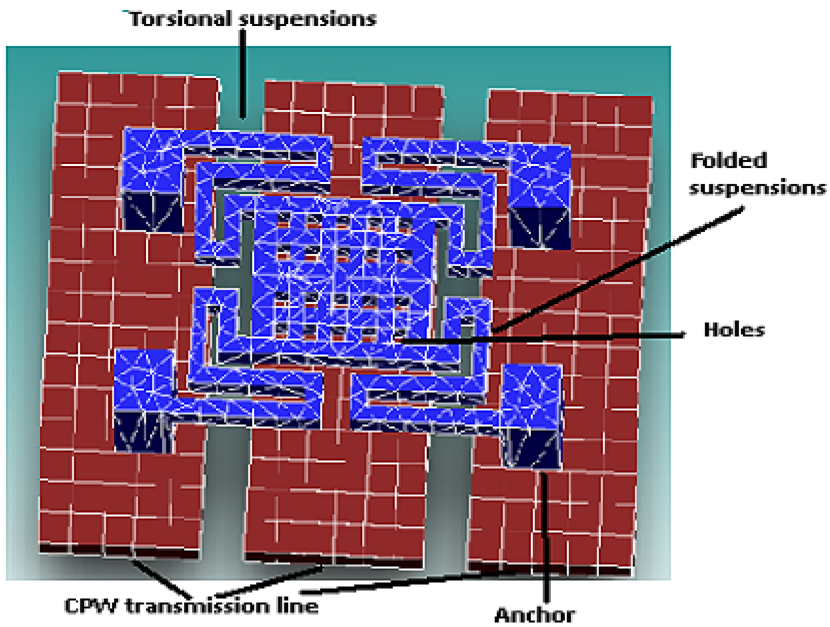

Figure 3.3: Simulation of 2nd beam structure

The minimum pull-in voltage of 6.5V was achieved. But the drawback of the structure having voltage 6.5V was not efficient in term of life span. Gold was used as conductor in the whole geometry. The best isolation of -78 dB at 10 GHz was obtained while the insertion loss was .003 dB at the same frequency.

In [33]

Authors have discussed switching time along with other performance parameters of uniform meander and non-uniform meander based MEMS shunt switches. Shunt switch having dimension 60/100/60 um was designed using fbk process. In this process, gold is used as a conductor while silion nitride is used as dielectric layer.

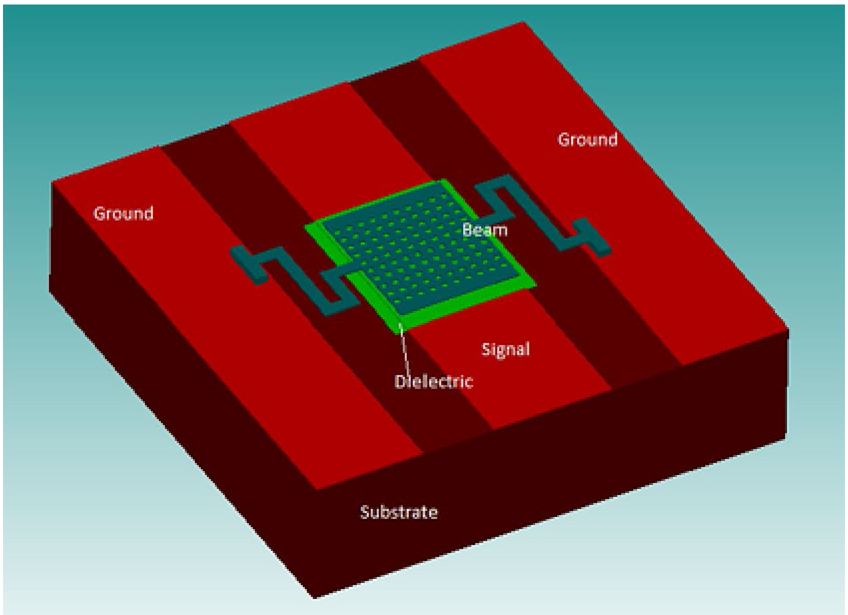

Figure 3.4: switch Model

The up-state and down-state capacitances were calculated. The pull-in voltage was found to be 2.3V while the capacitance ratio was 8.69. isolation of -14 dB and insertion loss .2 dB was measured at 20 GHz frequency. Switching time was calculated using MATLAB and found to be .12 msec.

In [34] authors have claimed a new design having wider bandwidth while maintaining the good isolation and insertion loss values. The main theme of the paper is that the beam network on both side of the center conductor line has been divided into two separate parts. One can actuate one sided beam or both sided beams simultaneously in different frequency bands.

Table 3.1: Bandwidth of the Proposed Switch

Sno	Dimensions	f1(GHz)	f2(GHz)	Bandwidth
1	Left Bridge Down	7.85	9.05	1.2
2	Right Bridge Down	9.55	10.85	1.3
3	Both Bridge Down	10.5	18.15	7.65
4	Conventional Switch	11.4	19.20	7.8

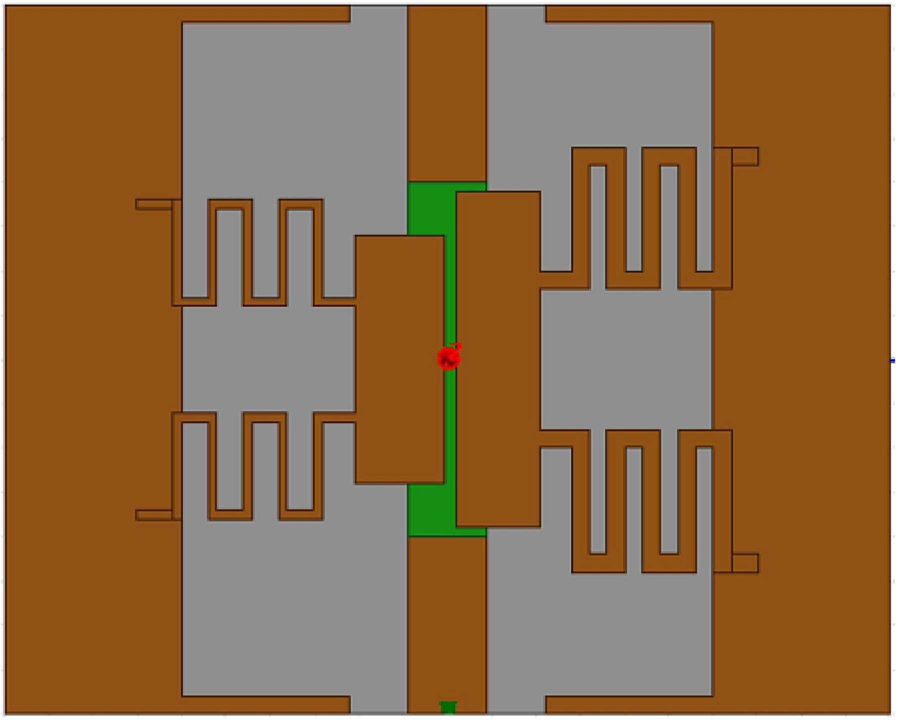

Figure 3.5: Proposed Switch Model

The switch is designed on CPW line. Normally the switch is in ON state i.e. signal flows from input port to output port. When the voltage is applied, the one of the central parts of the switch can be forced to come down. Both central parts can also be actuated simultaneously which will make switch work at different frequency band.

The insertion loss in ON state was observed around 1.3 dB while the return loss was observed to be -5 dB to -31 dB upto 20 GHz. The maximum isolation was simulated to be around -40 dB at 15 GHz.

In [35], the authors focus on reliability of the switch. Major drawbacks of MEMS switches are reliability, low switching speed and high actuation voltage. So there is a need of design which can cover major portion of the drawbacks. A novel design using insulator-metal-insulator was introduced. Using this new design, low actuation voltage was achieved along with high reliability in terms of life span.

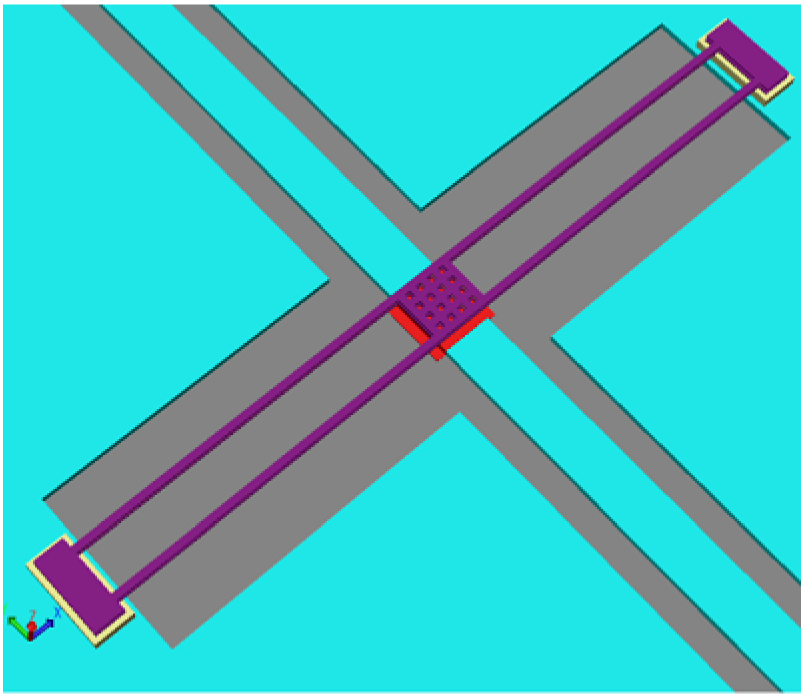

Figure 3.6: Proposed Switch Model

This switch was also designed using 60/100/60 topology. Switch can be made off using shunt structure and applied voltage hence grounding the signal. The switch was also fabricated silicon substrate. Results are measured practically and insertion loss was found to be 1.98 dB at 40 GHz while isolation was around 18 dB at 40 GHz. The actuation voltage was measured 11 V. The switching time was found to be 76 usec. the reliability of the switch was calculated and found to be one billion cycles and 6 Hours continuously working.

3.2 MEMS Series Switches

In [36] the focus of the author is on the optimization of overall geometry of the series switch in order to reduce the pull-in voltage and improve the RF parameters. MEMS series switches are resistive in nature and broadband.

They can be used at low as well as medium level frequencies. At very high frequencies, they offer very high resistive losses. Switch is designed on CPW lines having cantilever at center. In absence of voltage, the cantilever beam is in up-state and the switch is disconnected i.e. no signal passes through the line. When voltage is applied and the beam deflects downwards connecting the two ends of transmission line and hence signal flows from input port to output port.

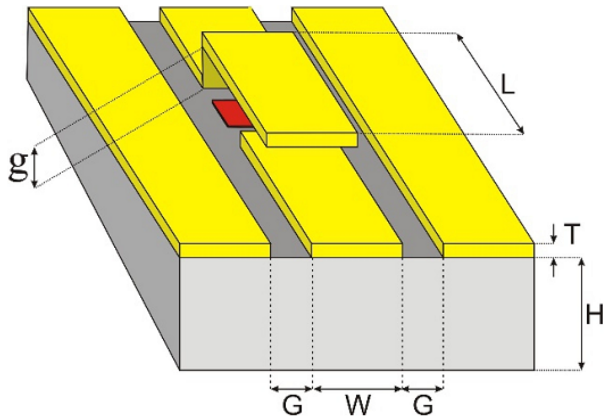

Figure 3.7: Proposed Switch Model

The parameters W and G are fixed due to characteristic impedance of the transmission line. g is the gap which is a fabrication technology parameter. Hence the only remaining parameter L can be optimized. How the value of L will impact overall size of the switch and the insertion loss, so it should be kept as small as possible. Four different values for L are simulated and fabricated in this paper. The minimum pull-in voltage was observed 5V at the 500um length. The best insertion loss is at the smallest value of L=200um. while the best return loss is again the longest length of L=500um is -18 dB.

In [37] author has introduced a new pi shaped cantilever beam for series switch. This switch design is focused on the frequency band from 8-12 GHz. Again the goal of the paper was to reduce the actuation voltage. The design is focused on small size cantilever to obtain low actuation voltage with good RF parameters and very less sensitive to stress.

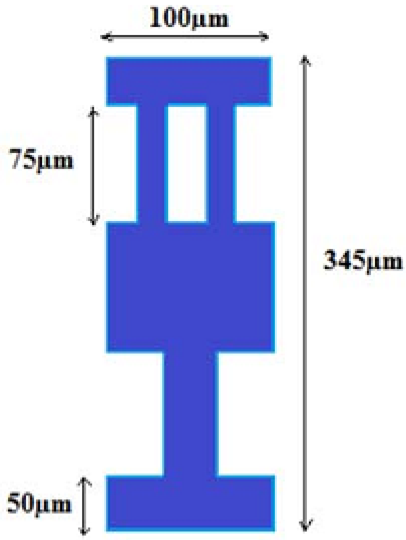

Figure 3.8: Proposed Cantilever beam

The π shaped beam is fixed at one end while free to move from another end hanging upon CPW line. Due to this π shaped beam, the spring constant is reduced. The area of actuation was 100 x 100 um2. The thickness of the beam was 1 um. Stress analysis shows that minimum 30 MPa stress is required to make the switch ON. The 10 V pull-in voltage was obtained. The isolation of -90 dB was achieved at 12 GHz while the return loss was -3.3 dB. The insertion loss was -9.4 dB at 12 GHz which is very much higher.

In [38] a switch was proposed working in the band of 500-750 GHz. It is DC contact switch made on 50 π CPW line. the main challenges of this design are impedance mismatch in ON state, isolation in OFF state and the fabrication design measurements restrictions.

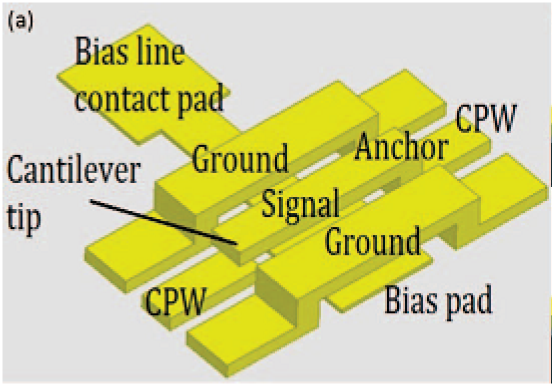

Figure 3.9: Proposed Series Switch

A small value of capacitance was required at the overlapping area between the cantilever beam and the transmission line. but due to fabrication technology limitation, it was causing misalignment. So specially designed gradually decreasing tip was used. Due to this tip, isolation was improved about 4 dB at 625 GHz. The analysis shows that the actuation voltage of 60V was achieved. Insertion loss was .7-2.7 dB in ON state having return loss ¿12dB. Isolation of better than 17 dB was achieved through out the band.

In [39] gold was used as conductor lines to have low actuation voltage and low stress value. The proposed switch has three major components; i) two beams to hold the overall structure ii) contact part that is effective in the measurement of capacitance. There are holes in this part which results in low stress iii) the DC contact pads. The contact area is kept small in order to have low stiction and high isolation.

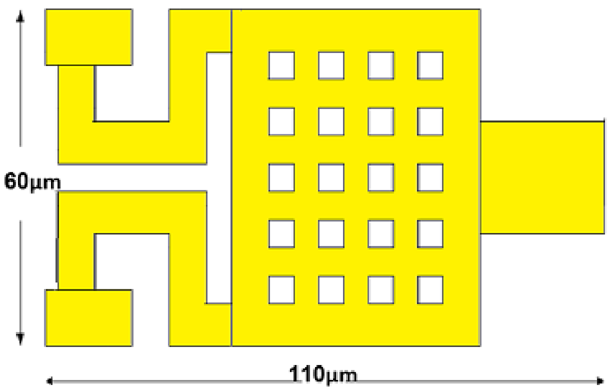

Figure 3.10: Proposed Cantilever Beam

The thickness of the beam was varied and simulated at .6 um, .8 um and

1 um. actuation voltages 4.05, 6.3 and 8.8 were measured against respective beam thickness. The physically calculated voltages were very near to the simulated values having error less than 5The insertion loss was .067 dB while the return loss was 26 dB in ON state. The best isolation of 16 dB was achieved at 40 GHz.

In [40] meander based cantilever beam was used to actuate the series switch. This meander structure has low spring constant hence low actuation voltage. The switch was designed to work in X-band. Voltage was applied using DC contact pads attached below the cantilever beam. When the voltage is increased the electrostatic force becomes greater than the spring force resulting in the bending of the beam.

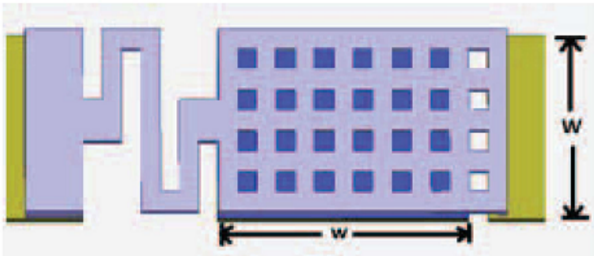

Figure 3.11: Proposed Cantilever Beam

The meander design of the cantilever beam reduces the strength hence causing breakdown of the switch. To overcome this issue, the holes are placed on the contact part for reducing weight. These holes reduce minimize the damping and making switching faster. The CPW transmission line was chosen to be 559055 um. The isolation of 20 dB was obtained at 10 GHz, return loss was -21 dB while the insertion loss was .08 dB at the same frequency. The actuation voltage was obtained 6.4 V. The fundamental frequency of the structure was found to be 3815 Hz.

In [41] a novel technique was proposed to make SP4T switch using single Series and shunt switches in serial path. The two switches i.e. series and shunt switches were separately simulated and then combined to make SP4T switch. The proposed SP4T switch was designed using CPW line and matched to 50 ohm impedance. The topology proposed using cascaded approach in which one series and one shunt switch is placed in each signal path in SP4T switch.

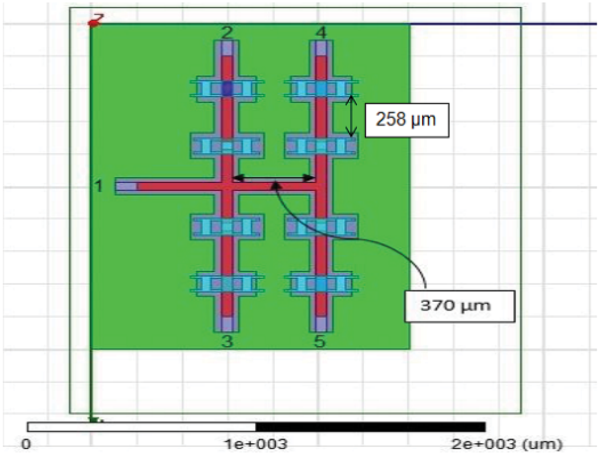

Figure 3.12: Proposed SP4T Switch Model

The working of the switch is that when series switches are ON the shunt switches are OFF. As discussed earlier the individual working of series and shunt switches i.e. shunt switches grounds the signal in ON state while series switch connects the signal path in ON State. So in this proposed model, in each path there is a series switch and shunt switch. Whenever the signal has to travel in one arm, the series switch becomes down to connect the signal path and the shunt switch becomes OFF to leave the path for signal. The analysis shows that series switch had the actuation voltage of 13.7 V with switching time of 7.8 usec. The shunt switch was analyzed to have actuation voltage of 12 V with switching time of 7.5 usec. The insertion loss of each arm was .7 dB at 10 GHz. Isolation of 52 dB was achieved in all paths within the switch.

In [42] single pole single throw and single pole triple throw switches are presented. A novel in-plane movable structure was proposed which was designed on single layer using silicon on insulator fabrication process. The proposed design has three separate switches having separate actuation voltage circuit. Each switch is electrostatically actuated. Multiple switch contacts are placed in parallel to each other in order to have low contact resistance. This will result in enhanced power handling capability of the over all switch. The power handling capability of the switch was simulated by putting 1 W input power and simulating the net current distribution effect. It was observed that only + .2% variation exists in the current distribution. This small variation is due to multiple paths present in the signal flow. As all three switches are of the same type. So the same voltage i.e. 47 V was achieved to actuate all the switches. Insertion loss of .9 dB was observed in each signal path while the isolation was 29 dB at 6 GHz.

Table 3.2: Comparison among State of the Art Research Papers

S. no	Topology	Frequency(GHz)	Voltage	Insertion Loss	Isolation	Area(mm2)
1	Two Shunts in T Configuration	110-170	60	1.23-1.86	18.25-54.5	0.9-0.8
2	Series Shunt	55-65	66	2.83	15.3	25
3	Rotary Comb drive	80-100	50	0.73	23	0.5
4	Torsional Bridge Capacitance	20-30	15	0.4	20	0.88
5	Series Shunt Configuration	13-17	40	1.45	45	1.25
6	Metal Contact	0-20	15	0.2	42	1

As clear from the comparison in Table 3.2, in series shunt switches, area and insertion loss are the parameters which can be further focused in order to have better and optimized performance. Generally the area of SPDT switches is bigger than 1 mm2 . it can be further reduced while maintaining the optimized values of insertion loss and isolations.

3.3 Review Summary

Following design parameter were finalized after comprehensive study of requirements for switch which could be used in 5G communication systems

- Frequency range (around 25 – 40 GHz)
- Isolation (>25 dB)
- Single Pole Double Throw
- Small size
- Less voltage

It is a challenging task to have all characteristics in a SPDT switch for future 5G communication requirements.

Chapter 4

Proposed Design of SPDT MEMS Switch

In this chapter, a novel design is presented for MEMS switch in Single Pole Double Throw (SPDT) topology. In this work, a unique SPDT switch is designed using a combination of shunt and series MEMS switch. There is a common practice in the designing of SPDT MEMS switches that only one switch is designed and then make copies of that switch at several positions to make SPDT switch. That practice takes a lot of space. In this work, a smart design is presented in which only three switches are used. One shunt switch is common in both paths making the isolation better at higher frequencies.

4.1 Design Detail

In this proposed switch design, electrostatic actuation methodology was used. The switch was designed on FBK process. In this process, the Silicon was used as substrate having height of 525 um. Over the substrate the Silicon Dioxide of thickness 1um was used as dielectric layer. Over the dielectric layer CPW transmission line was designed. The GSG measurements of the CPW line were 30/40/30. The width of the main transmission lien i.e. from port 1 to port 2 is 40 um. The width of the secondary transmission line i.e. from port 1 to port 3 is 95 um. The ground layer having gold material is of the height of 5 um. The overall dimensions of the switch are 850x600 um2. The switch is shown in figure .

Table 4.1: Complete Switch Parameters

Sr #.	Component	Length (um)	Width (um)	Height (um)	Material
1	Substrate	850	600	525	Silicon
2	Dielectric	850	600	1	Silicon dioxide
3	Ground Thickness	850	90	5	Gold

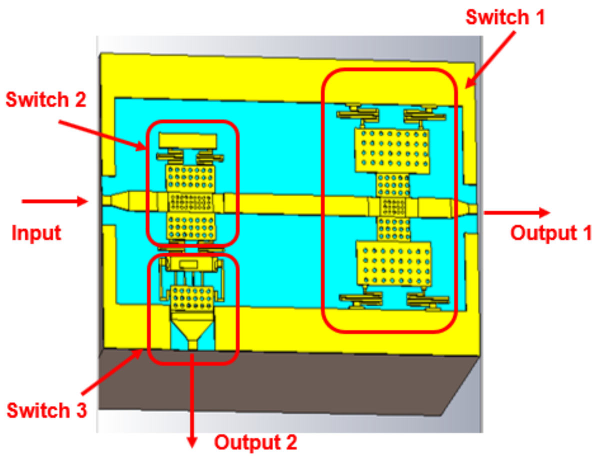

Figure 4.1: Proposed SPDT Switch Design

The complete switch is composed of three switches. Switch 1 as a shunt switch in the path from port 1 to port 2. Switch 3 as a series switch from port 1 to port 3. While the switch 2 is common in between port 1 and ports 2 and 3.

4.1.1 Switch 1

The switch 1 is a capacitive type shunt switch. The purpose of the switch is to isolate the signal from port 1 to port 2 when signal is going toward port 3. This switch isolates the signal by providing easy path towards the ground. The beams are designed in serpentine structure in order to minimize the stress and to work at low voltage. The actuation area is optimized for maximum transmission and minimum insertion loss. The complete design parameters of switch 1 is shown in table 4.2. The close-up view of switch 1 is shown in figure 4.2. The dimensions of the switch 1 are given in table 4.2.

Table 4.2: Switch 1 Design Parameters

Sr #.	**Component**	**Length (um)**	**Width (um)**	**Height (um)**	**Material**
1.	Center plate over the transmission line	56.5	40	2	Gold
2.	Side plates x 2 (attached to central plate)	75.3	50	2	Gold
3.	Plate attached to beams x 2	169	90	2	Gold
4.	Spring Beams	90	5	2	Gold
5.	CPW (GSG)	40	30	5	Gold

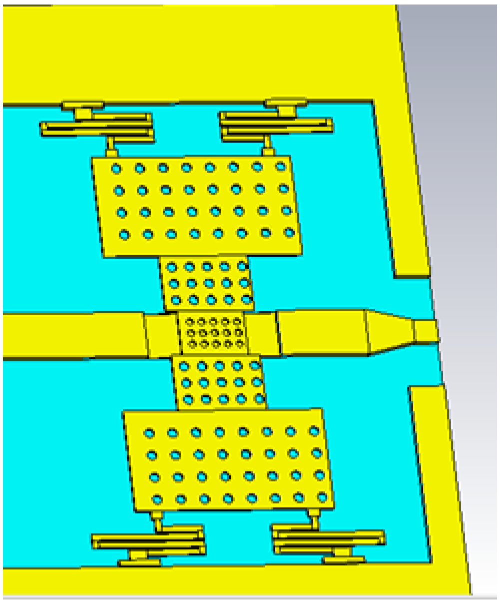

Figure 4.2: Switch 1 Close-up View

4.1.2 Switch 2

Switch 2 is also shunt switch. This switch is common in between two output ports i.e. port 2 and 3. It connects the signal from input port to port 3 when in actuated state and hence isolates the signal from port 2. While in up-state the signal goes to port 1 and hence isolating from the port 3. The close-up view of the shunt switch is as shown in figure 4.3.

Table 4.3: Dimensions of the Proposed Switch 2

Sr #.	Component	Length (um)	Width (um)	Height (um)	Material
1.	Center plate over the transmission line	100	40	2	Gold
2.	Side plate (attached to central plate)	110	46	2	Gold
3.	Spring beams	55	5	2	Gold
4.	Gap between beams	-	2	-	Gold

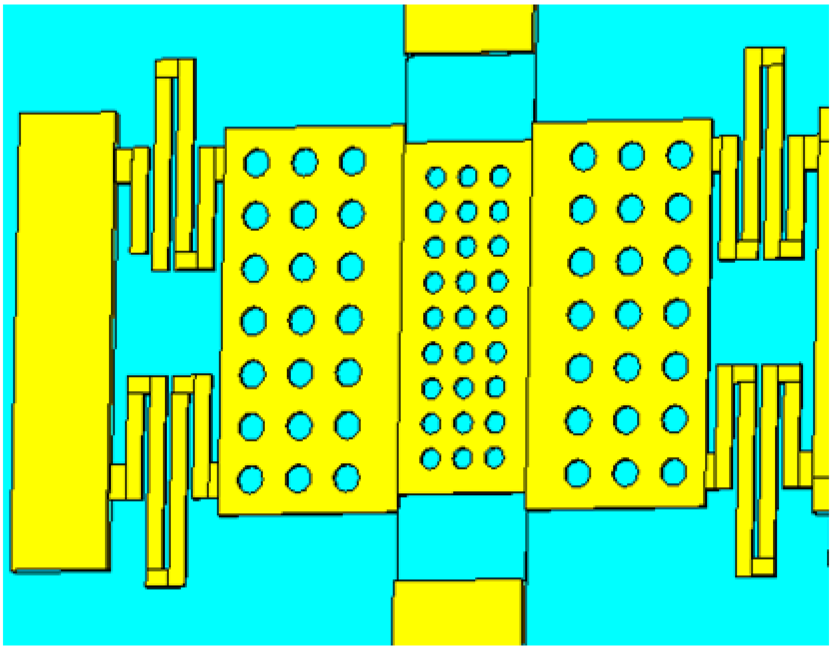

Figure 4.3: Proposed Switch 2 Design

The dimensions of the switch are given in table 4.3.

4.1.3 Switch 3

Switch 3 is series switch in the path from port 1 to port 3. it is resistive in nature and have stiction problem so a very small dimple was designed in order to avoid the issue. As the area was very small so the beams were designed very tactfully in order to have low spring constant. The four thin beams were designed to connect the movable beam to the transmission line. while the side beams were designed in order to provide the strength and to make low spring constant. The straight beams are made think so that they

Table 4.4: Dimensions of the Proposed Switch 3

Sr #.	Component	Length (um)	Width (um)	Height (um)	Material
1.	Series plate	95	40	2	Gold
2.	Series dimple	95	7	.3	Gold
3.	Spring beams (straight)	30	3	1.7	Gold
4.	Spring beam (side)	80	5	1.7	Gold

can be deflected easily but it can also risk the life of the switch. The close-up view of the switch is as shown in figure 4.4.

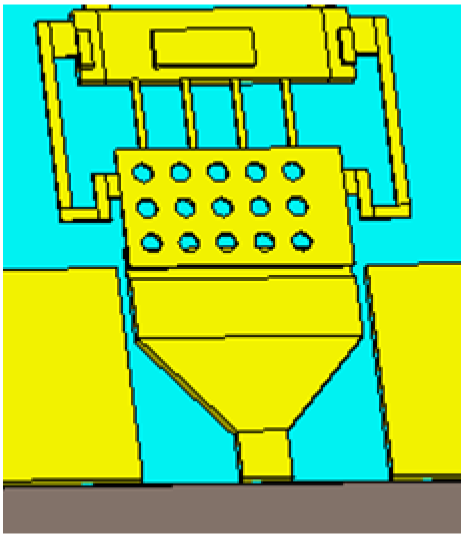

Figure 4.4: Proposed Switch 3 Design

The dimensions of the switch are given in table 4.4.

4.2 Working of the Switch

The electrostatic actuation is used to actuate the switches. The novel design is that only single voltage source is required to actuate all the switches at one time. When voltage is applied all three switches came in down position. In this position, signal from input port 1 couples to the secondary transmission line from switch 2 and goes towards port 3 via series switch 3. When voltage is removed, all three membranes go to the up-state. In this position, signal goes towards port 2. The common switch 2 and the series switch 3 provides isolation from port 1 to port 3. The air gap between the lower and upper electrodes is 2.7um.

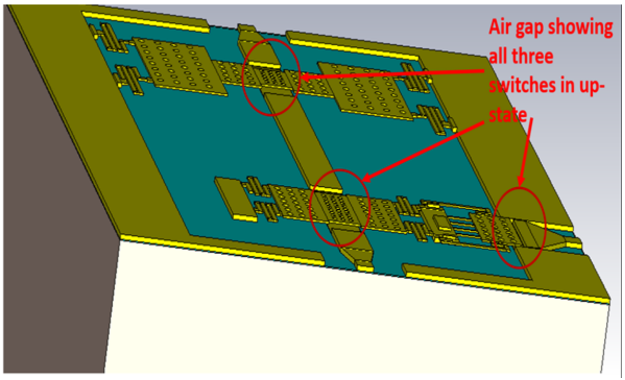

Figure 4.5: All Switches in Off Condition

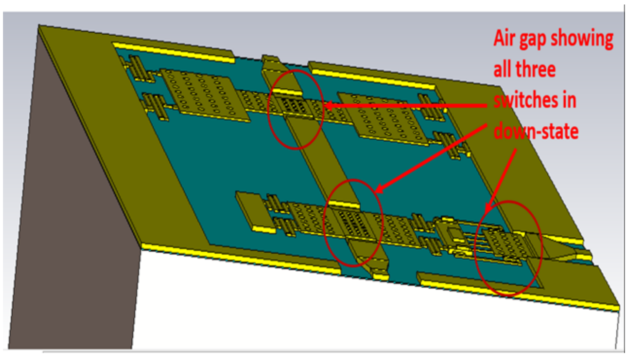

Figure 4.6: All Switches in Down Position showing Contact with Transmission Lines

Chapter 5

Analysis & Results

5.1 Electrical Analysis

The S-parameters of the switch are analyzed and optimized in order to have maximum isolation and minimum insertion losses. CST design software was used in order to simulate the switch. Different dimensions of switch like transmission line width and length, over all dimensions of the switch and actuation area of the switches were optimized. Some critical design parameters are discussed in detail.

5.1.1 Up-State Results

In this state, the signal travels from port 1 to port 2 via switch 2 and switch 1. The gap of the shunt switch 1 was optimized in order to make minimum insertion loss when all three switches are in up-state i.e. OFF state. In figure **??** the gap of the shunt switch 1 is varied and the result on the insertion loss is measured. It is clear from the figure that if the gap is becoming higher the insertion loss is slightly changed from .686 to .7 at 40 GHz.

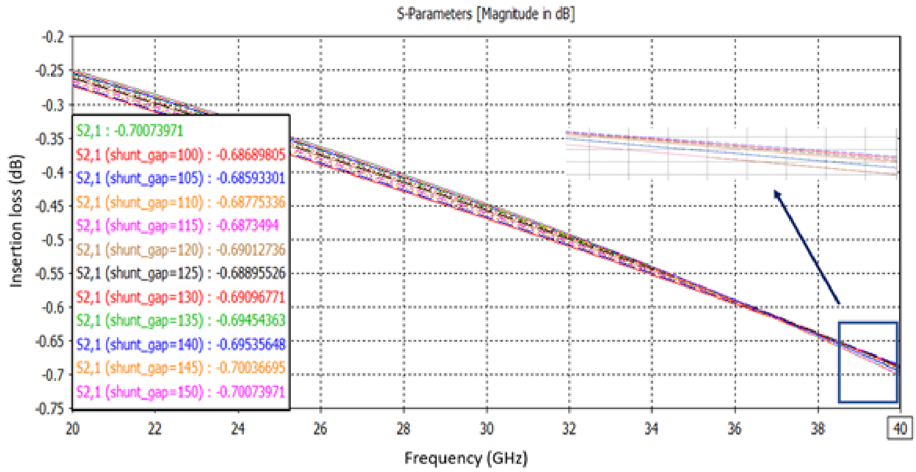

Figure 5.1: Varying Shunt Switch 1 gap vs Insertion Loss from Port 1 to Port 2

Also isolation from port 1 to port 3 is critical when all the switches are in up-state. in this topology, the isolation from port 1 to port 3 is shown in figure 5.2.

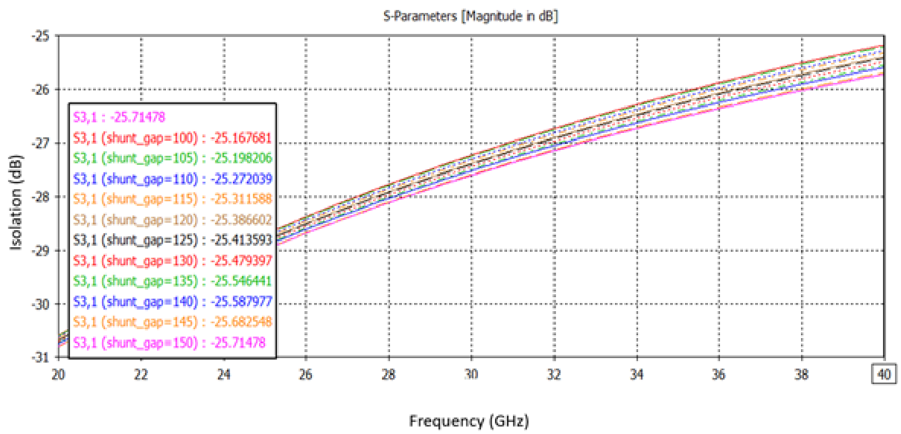

Figure 5.2: Varying Shunt Switch 1 gap vs Isolation from Port 1 to Port 3

As clear from the figure 5.2 that increasing the gap decreasing the isolation. The isolation in up-state greatly depends upon the series switch configuration i.e. the width of the secondary transmission line. By varying the width of the secondary transmission line, the isolation is measured as shown in figure 5.3.

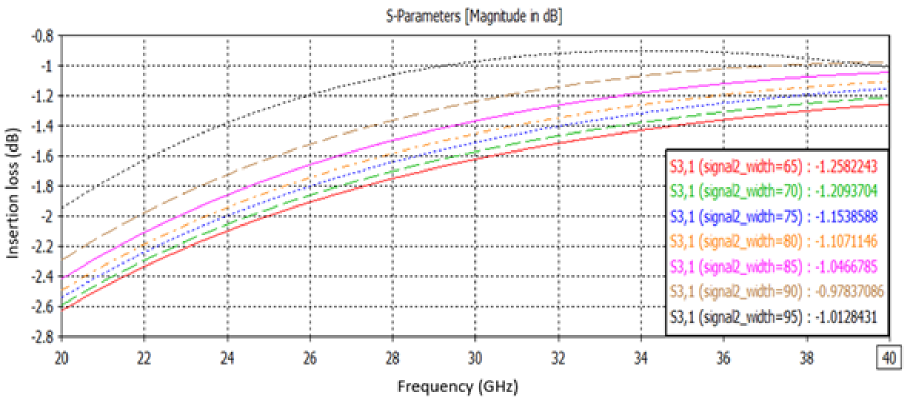

Figure 5.3: Varying Secondary Transmission Line Width vs Insertion Loss from Port 1 to Port 3

5.1.2 Down-State Results

In down-state, the isolation from port 1 to port 2 is critical. While the insertion loss of switch 3 is measured. As shown in figure 5.4 that increasing transmission line width decreases the insertion loss up to 90 um and at 95um the loss is slightly higher but as shown in figure 5.11 that at 95 um the isolation is very much better than all so 95 um was chosen to be optimized value.

Table 5.1: Optimized Parameters for SPDT Switch

Sr #.	**Component**	**Length (um)**	**Width (um)**
1.	Shunt Switch 1 gap	113	40
2.	Series Switch width	95	50
3.	Shunt Switch 2 gap	150	40

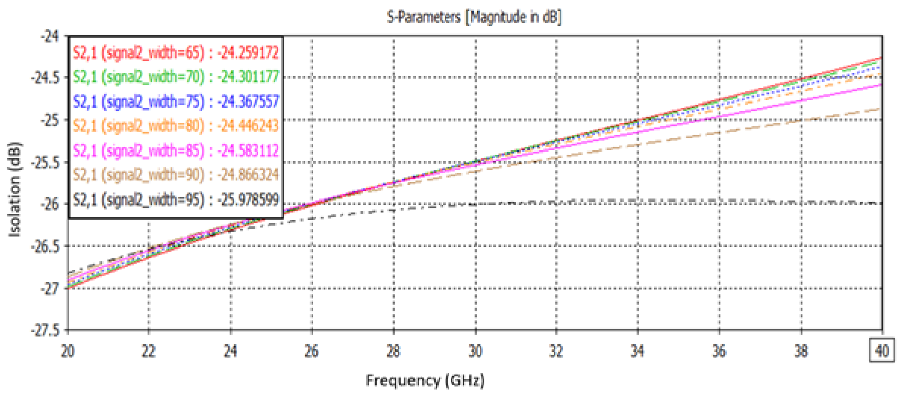

Figure 5.4: Varying Secondary Transmission Line width vs Isolation from Port 1 to Port 2

5.2 Optimized Results

Detailed analysis of different parameters of SPDT switch was performed in order to optimize all the insertion losses and improved isolation. The final switch parameters are shown in table 5.1.

5.2.1 S-Parameters

The best results in up-state condition i.e. OFF condition are as follows: Insertion loss from port 1 to port 2: .72 dB at 40 GHz Isolation from port 1 to port 3: -25.7 dB at 40 GHz

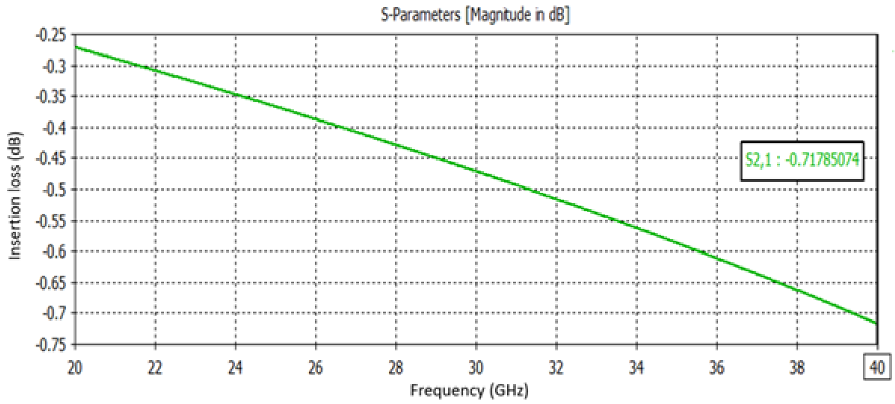

Figure 5.5: Optimized Insertion Loss in up-state Configuration

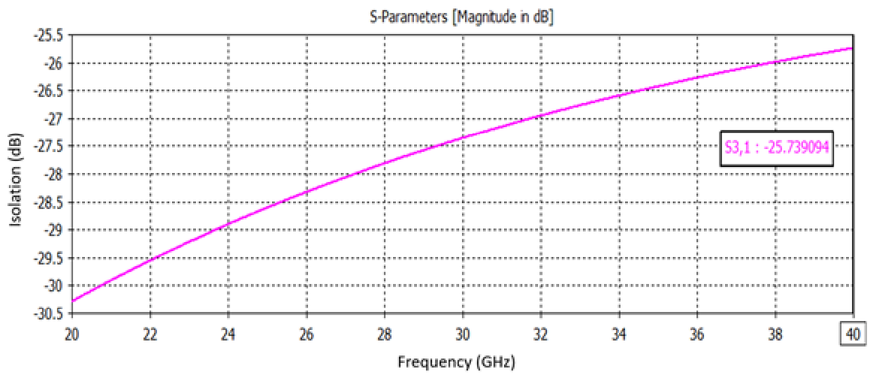

Figure 5.6: Optimized Isolation in up-state Configuration

The best results in down-state condition i.e., when switches are in ON condition Insertion loss from port 1 to port 3: .99 dB at 40 GHz Isolation from port 1 to port 2: -25.4 dB at 40 GHz

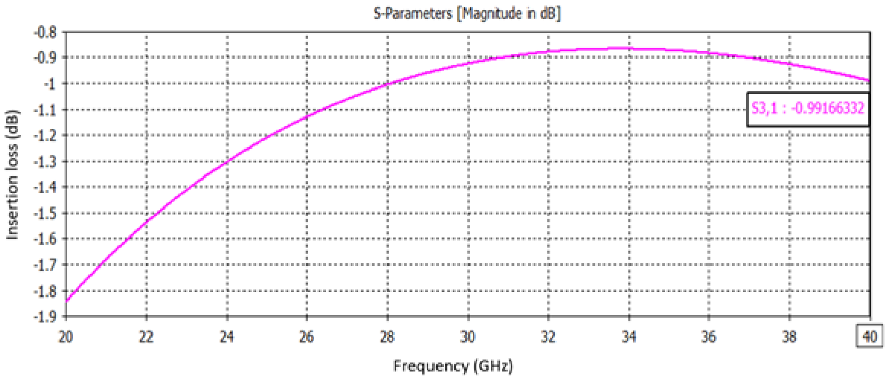

Figure 5.7: Optimized Insertion Loss in down-state Configuration

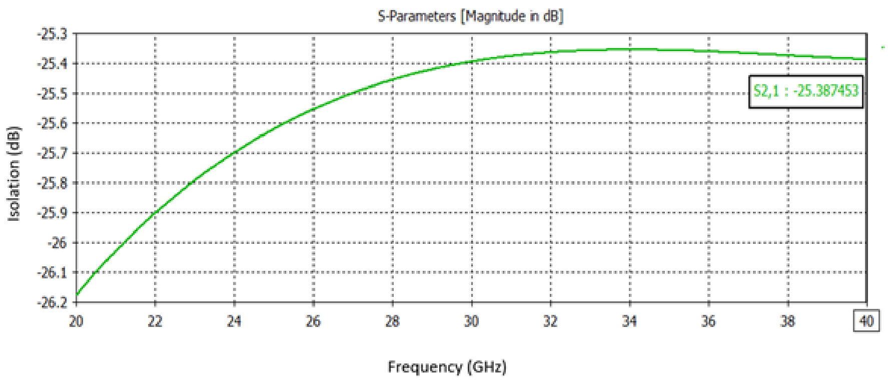

Figure 5.8: Optimized Isolation in down-state Configuration

5.2.2 Surface Currents

Current flow in the conducting metals can be described using surface currents in CST. In SPDT switch current will flow either voltage applied or not but in opposite directions. When voltage is applied and the switches are in down-state the current will flow from port 1 to port 3 as shown in figure 5.9. When voltage isn't applied and the switches are in up-state, the current will flow from port 1 to port 2 as shown in figure5.10.

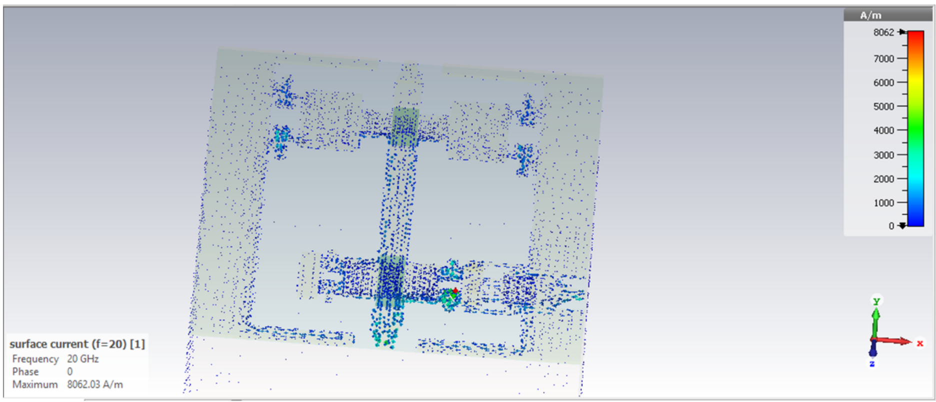

Figure 5.9: Surface Current in Down-State Configuration

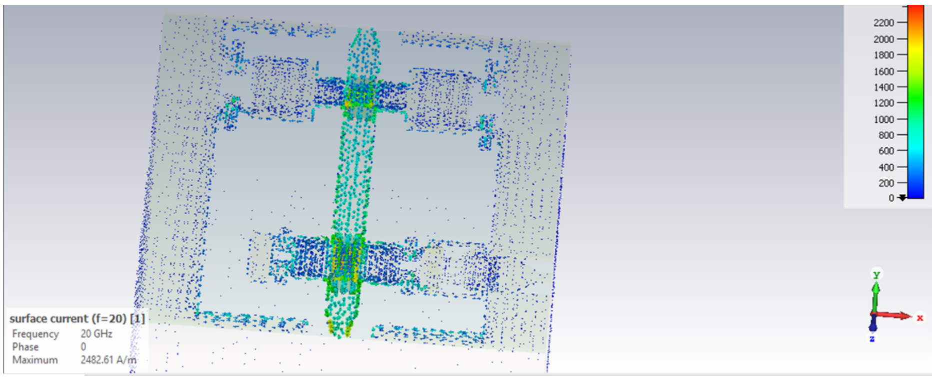

Figure 5.10: Surface Current in up-state Configuration

5.3 Mechanical Analysis

In this section, mechanical aspect of the proposed design is presented. All the three switches are mechanically analyzed using FEM analysis tools. Comsol and Ansys are used to analyze the mechanical parameters. Mechanical displacement using voltage source and stability are measured.

5.3.1 Actuating Mechanism

When biasing voltage is applied across the electrodes, the both electrodes attract each other causing mechanical movement. Hence there are two forces in action i.e. electrical and mechanical. At some voltage, mechanical force equals the electrical force. This voltage is known as pull-in voltage. This voltage has a critical role in modeling any electrostatically actuated MEMS device. When this pull-in voltage is further increased, the beam is further deflected downwards and finally collapse.

5.3.2 Displacement Analysis

Displacement of the mechanical beams varies by varying the voltage. Electrostatic force is generated between the fixed and movable electrode causing the varying capacitance. Initially the voltage applied don't deflect the beam significantly as the mechanical force is higher compared to electrical force. Upon increasing the applied voltage, there comes a point when the movable beam deflects downwards and comes to desired displacement of 2.7 um (FBK Process). Further increasing the voltage, the beam is exponentially deflecting causing the switch collapse. Figures 5.11 shows the displacement of switch 1. The color graph at the side shows the maximum deflection occurring is 2.72 um from the center plate while side plates are showing less deflection.

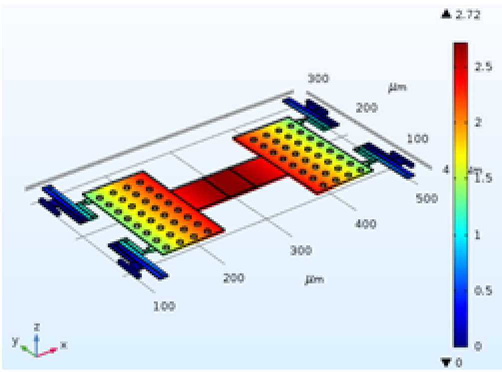

Figure 5.11: Switch 1 Displacement

Figure 5.12 showing the deflection of switch 2. Again, as it is shunt switch so its deflection is same i.e. 2.7 um from the center plate.

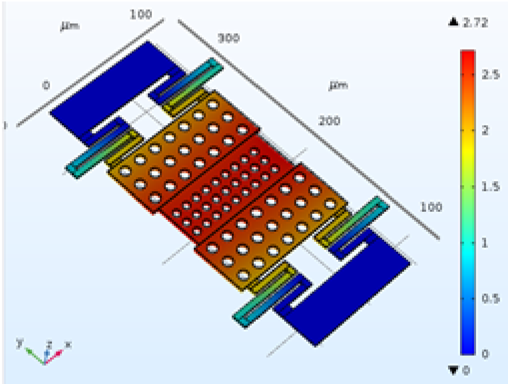

Figure 5.12: Switch 2 Displacement

Figure 5.13 shows the deflection of switch 3. It is displaced at 2.5 um because there is a dimple at lower side of the series switch which is of the thickness .2 um in order to avoid stiction issue. Only a tip of the series switch is at maximum deflection which is the requirement of series switch.

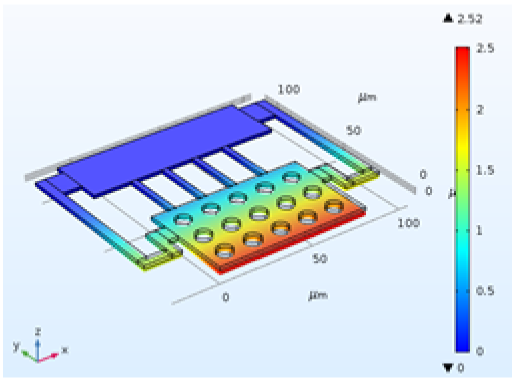

Figure 5.13: Switch 3 Displacement

5.3.3 Stress Analysis

Stress analysis of the proposed switches is performed individually. It shows the ability of the switch to sustain the pressure or tension. It is observed that the parts of the switches which are attached to fix beams are under maximum stress. The maximum observed stress was 70 MPa which is much less as compared to the critical strength of the silicon which is 7 GPa. Figure 5.14 shows the stress measurement at switch 1. The minimum stress is obtained at the center plates of the while the maximum stress is gained by the beams structure.

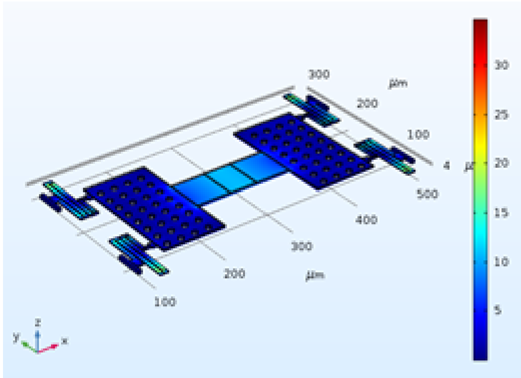

Figure 5.14: Stress Analysis of Switch 1

Figure 5.15 also shows the stress measurement at the switch 2. This structure has slightly higher stress as compared to switch 1. It is due to slightly smaller structure in limited space. The maximum stress is present at the beams.

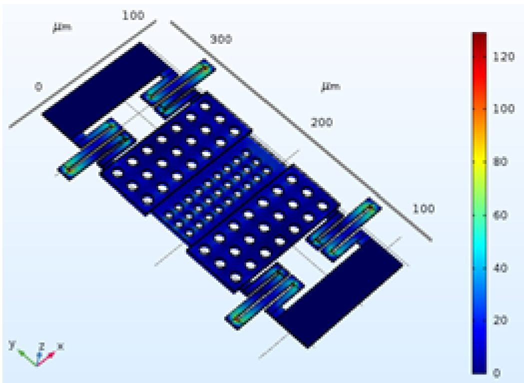

Figure 5.15: Stress Analysis of Switch 2

Figure 5.16 shows the stress analysis of series switch 3. Stress is within limits of the material. The maximum stress is present at the straight beams as was predicted in proposed design. While the tip of the switch touches the lower Tx line.

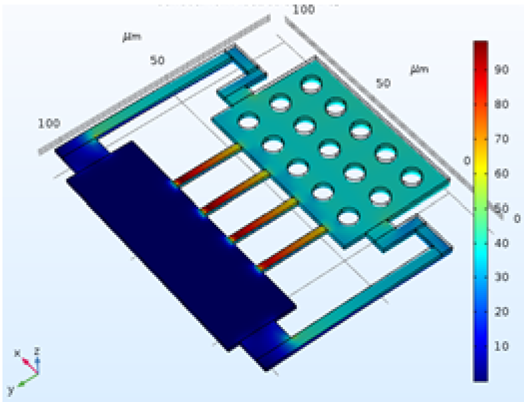

Figure 5.16: Stress Analysis of Switch 3

Chapter 6

Conclusion

The demand of highly sophisticated communication systems having reliability and performance is increasing day by day. MEMS devices were found to be very strong candidate to be used in such high performance communication systems and radars.
In this study, the use of electrostatic actuation methodology in RF MEMS switches is discussed. MEMS devices has a lot of advantages in terms of size, flexibility, low loss, high isolation, reliability and compatibility along with other IC fabrication technologies. MEMS devices can be made on same silicon substrate on which integrated circuits are fabricated.
RF switches are one of the RF devices which can be built on MEMS technology. These are miniaturized devices that can be used in modern flexible systems. These devices consume very small current and minimum power consumption in OFF state. These are the hybrid of better performance and less power consumption.
In this research, electrostatic actuation based SPDT switch is proposed. The complete switch is based upon three switches. All the three switches are separately designed and analyzed. The switches are simultaneously actuated and only single voltage source is used. The combined effect of three switches is simulated in CST for isolation and insertion loss simulations. This covers the electrical performance parameters of the complete switch. The insertion loss was 1dB in ON state and the isolation of -25 dB was achieved at 40 GHz. Further the switches are separately simulated in Comsol for mechanical performance parameters of displacement and stress analysis. Maximum stress was found to be 90 MPa which is very less as compared to critical strength of the material. Observed Displacement is 2.7 um in case of shunt switches while 2.5 um in case of series switch was achieved.

6.1 Future Recommendation

Every research work needs improvement and can be enhanced for better performance and reliability. A lot of work has been done in the area of MEMS switches but still there are some areas where efforts can be put to get more benefits. In this work, there is a scope to enhance the two output ports to multi output ports. The switch is designed for maximum 40 GHz and can be further enhanced to work upto 100 GHz with maximum possible isolation and minimum insertion loss. A comprehensive work is required to make switching time better which is the only drawback of MEMS switches.

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