Design and Analysis of a Capacitive In-Plane RF MEMS Switch for 5G Applications

Author

Hareem Fatima

00000203439

Supervisor

Dr. Muhammed Mubasher Saleem

DEPARTMENT OF MECHATRONICS ENGINEERING

COLLEGE OF ELECTRICAL & MECHANICAL ENGINEERING

NATIONAL UNIVERSITY OF SCIENCES AND TECHNOLOGY

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Author

Hareem Fatima

00000203439

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Thesis Supervisor:

Dr. Muhammad Mubasher Saleem

Thesis Supervisor's Signature: ___________________________________

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Declaration

I certify that this research work titled "*Design and Analysis of a Capacitive In-Plane RF MEMS Switch for 5G Applications"* is my own work. The work has not been presented elsewhere for assessment. The material that has been used from other sources it has been properly acknowledged / referred.

Hareem Fatima

<u>00000203439</u>

Language Correctness Certificate

This thesis has been read by an English expert and is free of typing, syntax, semantic, grammatical, and spelling mistakes. Thesis is also according to the format given by the university.

Hareem Fatima

00000203439

Copyright Statement

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Abstract

In the past years, RF MEMS devices have proven to be a vital part in development of complex essential devices which include consumer applications, wireless applications, industrial applications, and medical applications just to name a few. 5G is the key to the future. From communication applications to smart home solutions, 5G unlocks it all. We want to develop a switch for extremely high frequency band particularly focusing on 5G band and its applications.
This work targets the design of an in-plane capacitive switch that is compatible with 5G for applications in the EHF frequency band. The previous designs focus on shunt switches. Analyzing the complete working of the switch is also a focus in this research. The dual and quad mode of the switch presented provide ample payload distribution for satellite systems. A displacement actuation mechanism has been employed in the switch design to enhance displacement provided by electrothermal actuators which improves the performance of the switch. The performance of the switch is analyzed by performing electrothermal, structural and electromagnetic analysis on the switch such that all the parameters are optimized for close to ideal RF characteristics. The results are benchmarked against published data and show improvements made in the design.

Key Words: *In-plane switch, Displacement actuation mechanism, Electrothermal actuation, 5G applications*

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CHAPTER 1: INTRODUCTION

This dissertation presents research work in four major parts. First part is a detailed discussion of RF MEMS switch design and literature along with actuators and different actuation mechanisms. Second part is related to the design of all the elements of the RF MEMS switch. The third part focuses on mathematical modelling of electrothermal actuators and displacement actuation mechanism. The fourth part includes electrothermal and electromagnetic analysis of the proposed design. This is objective of this part is to optimize the switch to perform with close to ideal RF characteristics.

Since the 1970s, microelectromechanical systems have been an increasingly popular form of technology. Sensors, accelerometers, and other sensing devices were mainly used with these devices. A decade later, MEMS switches were discussed for applications requiring low frequency signal transmission. Several unique design features and working principles made these switches intriguing. The transmission line is opened or closed mechanically by MEMS switches by applying a small voltage. RF MEMS switches were first developed to work specifically for microwave applications in the 1990s. There have been hundreds of RF MEMS switch designs developed up until now, each with improved performance parameters or specialized for specific applications. MEMS is actually driven by small mechanical devices after merged with nanotechnology and the NEMS. MEMS are further considered to as micro machines or micro systems technology. The consideration of RF MEMS switches is of higher extent due to likely wide bandwidth operation and low-loss operation since they have explained adequate RF attributes than to diode-based switches and FET [1, 2]. A few properties of MEMS are that weight should be less, smaller in size, very low insertion loss but momentarily challenges like slow speed, high actuation voltage have presented themselves.

There are many systems that use high frequency switches, such as mobile phones, local wireless networks, and radar and satellite systems. High frequency switches are essential components in many types of systems operating at microwave frequencies. In wireless communication, switches are used mainly for choosing the appropriate antenna to receive and transmit signals, and for switching between transmitting signal and receiving signal paths or routing signals to various elements in multi-band/multi-standard phones. The phase shifters or time delay units that are used in phased array antennas consist of an array or matrix of switches [3, 4].

Mechanical switches and semiconductor switches are mechanical switches deployed as the common microwave switches in the microwave industry. The demand of device components has been increased with prompt development of the wireless communication systems in the range of 100MHz to 6 GHz with minimal size, high performance, and low cost [5, 6]. The licensed and unlicensed bands are covered in this frequency and explores majority of adequate applications in short and medium range along with terrestrial radio communication in distinctive urban environment. An adequate frequency bands are entirely possessed in developed and developing countries by mobile phone system, WLAN, WiMAX, TV broadcasting, Bluetooth, and military and governmental applications [7, 8]. RF filters are very important as well as vital for preventing interference between all higher selectivity applications [1].

Due to the electrostatic force generated by larger voltages, switching time is greatly affected by voltage, since the electrostatic force is already high, pull-up time is greater in plane switches are usually large in size due to lateral movement [9, 10, 11]. In addition, manufacturers can reduce costs with batch fabrication, improve consistency of devices through advanced lithography and etching techniques, and achieve general performance improvement through downscaling of dimensions, resulting in reduced size and weight. The selectivity of RF filters indicates the level of safety margin between adjacent bands needed. The RF filters show estimation for 80% of the entire market with respect to unit sales and market size. The sensitivity of receiver from interference should be protected for all mobile phones by transmitted signals from other users as well as noise generated from different RF sources. The down to up capacitance ratio of a switch determines the RF response of that particular device [12, 13]. Down-state isolation is limited by surface roughness and overlap. Contact resistance determines the insertion loss in ohmic contact switches [4, 15].

1.1 Background, Scope and Motivation

There has been a lot of progress in the design of MEMS switches in the last 30 years however, the literature and research available for in-plane switches with close to ideal characteristics is still inadequate. Switches designed so far have considerable displacement at the expense of high actuation voltage. The purpose of this research was to design an in-plane switch with significantly low actuation voltage so as to cater high power consumption. The design should not interfere with the RF characteristics and be operable in 5G frequency band. This was accomplished by combining the design of an RF in-plane switch with a displacement actuation mechanism which enhanced the actuation keeping the operating voltage low.

CHAPTER 2: LITERATURE REVIEW AND RF MEMS CHARACTERISTICS

MEMS has made its way to every filed related to novel technology with its use in various applications. The MEMS devices consist of microgrippers, actuators, gyroscope, switches etc. Microswitches have their use in the pieces of technology where large mechanical switches don't fit. A MEMS switching device resembles a mechanical relay powered by an electric voltage these switches are made of semiconductors on a very small scale (mm-nm) [16]. These switches generally have 2 stable states, ON and OFF however, a few designs have more than 2 states which have been discussed in the literature. These switches can be modified according to specific application keeping in mind the characteristics of the switch. These characteristics help design the switch to work particularly with low losses.

2.1 Types of RF MEMS switch

RF switches can be categorized in two ways, by the no. of inputs and outputs and by the plane of design. various switches with multiple inputs and multiple outputs have been designed so far. They can also be called MIMO switches. The most common are single pole double throw or double pole double throw. In terms of plane of design, the switches are in-plane or out of plane. This depends on the actuation mechanism. In-plane switches have the actuation mechanism in the same plane as the signal line. For out of plane switches, the actuator moves normal to the signal line.

2.2 Mechanical characteristics of RF MEMS switch

The mechanical characteristics of a switch are determined by its design and function. Application specific MEMS devices are designed to ensure better life cycles and reliability of the product however, the product does have some disintegration factor. These mechanical characteristics are viable for any design.

2.2.1 Pull-in voltage

Pull-in voltage or actuation voltage is one of the most important factors of any switch. For a switch, when voltage is applied between an actuation electrode and a beam, it connects or disconnects the signal route. This varies from design to design depending on the actuator used, design of whole switch and application. Figure 1 shows pull-in for a conventional MEMS switch.

2.2.2 Size of switch

Size of a MEMS switch is very small as compared to traditional switches. It ranges between millimeter and nanometer and rests on a small chip which is manufactured under special conditions. The size depends on size of the beams that are required for actuation [18,19]. A comb tooth actuation mechanism is usually smaller in size due to cascaded layout in comparison with other actuation designs which use actuation method other than electrostatic. Overall device size is dependent on the specific design of the switch according to application. Some fabrication issues also effect the size of switch. In-plane switches are typically larger in comparison due to lateral movement.

2.2.3 Switching time

Switching time is another characteristic that needs novelty and research. Decreasing the switching time is still a challenge for MEMS regime. The time in which the system is actuated depends greatly on the voltage that is applied to the actuators. Pull in time is usually greater than the pull up time since there is already some force present surrounding the actuators.

2.3 RF characteristics of RF MEMS switch

The RF characteristics of a switch are determined by its design and function just like mechanical characteristics. These usually depend on the signal that needs routing using the switch. Performance of a switch is measured in specific frequency bands using RF characteristics commonly known as s-parameters of a switch. Switches have several main characteristics, such as in the on-state; insertion loss, in the off-state; isolation, return loss both in the on and off states, power handling capability, power consumption, and linearity. [20, 21, 22].

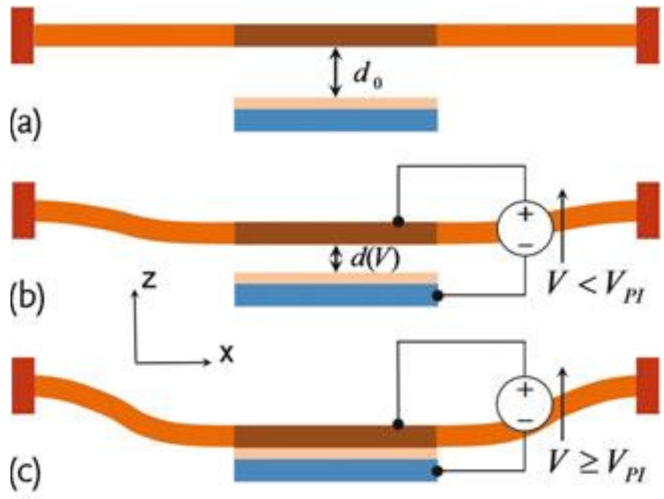

Figure 1: Actuation voltage

2.3.1 Insertion loss and isolation

Insertion losses are usually measured when the input signal is being routed to output (ON) while isolation is measured in OFF state. These signify the leakage of signal and tells about its power handling capabilities. For an ideal switch infinite isolation and zero insertion losses are desirable.

2.3.2 Return loss

Similar to insertion loss, a zero return loss or reflection coefficient is desirable.

2.3.3 Frequency band

The frequency band of a switch determines the operating frequency of that switch. All the RF characteristics are modeled such that the switch operated in the desired frequency band.

2.4 Applications of RF MEMS in 5G

Microwave switches are vital components in a variety of systems, including mobile phones, wireless local area networks, and systems operating in the millimeter wave range, such as radar or satellite systems. In wireless communications, switches are primarily used as antennas for RF signal routing, switches between transmit and receive paths, or switches to route different blocks of signals in multiband phones. For phased array antennas, many phase shifters and time delay units consist of arrays of switches that form their basis.

- MEMS in Consumer Appliances
    a. Phones and tablets
    b. Remote control and gaming devices
    c. Notebooks and Ultra books
    d. Cameras
- MEMS in Wireless Applications
    a. Pedometers and watches
    b. Barbells and Tread Mills
- MEMS in home appliances
    a. Car Garages and home automation systems
    b. White Goods
    c. Electric, Gas or Water Meters
- MEMS in Cars
    a. Telematics
    b. Security
    c. Navigation and safety
- MEMS in Industrial Applications
    a. Automation and Robotics
    b. Monitoring of industrial equipment
    c. Monitoring and Parcel Tracking
    d. Building Monitoring
    e. Geo Phones and Seismic Exploration
- MEMS in Medical Applications
    a. Implantable Medical devices
    b. Concussion detection in sports
    c. Motion detection and body motion reconstruction
    d. Wheelchairs and health care
    e. Instrument guidance surgery

There are multiple reasons why the impact of RF-MEMS solutions has been limited on the market, even beyond the most conservative predictions. Due to increased complexity and costs, the use of RF-MEMS became less attractive as a result of neglecting aspects related to reliability and packaging/integration. In contrast, early mobile device generations (up to 3G) were not too demanding of the enhanced performance exhibited by RF-MEMS [21-23]. Due to the integration of the antenna with numerous component parts, the widespread use of smartphones with 4G-LTE has adversely affected the quality of voice and data transmission. In order to rectify this, the smartphone antenna should adapt (rather than static) its impedance to the RF front end (RFFE), and Cavendish Kinetics' RF-MEMS tuners (one of first commercial applications of this technology) mitigate this problem. A high operating frequency, wide tunability, as well as reduced hardware redundancy and power consumption, are essential for 5G to be successful. It is believed that RF-MEMS technology will enable 5G (RFFE) smartphones and base stations by providing passives with exceptional features. RF-MEMS basic attenuator modules with two states (ON/OFF) are demonstrated and verified using FEM (Finite Element Method) modeling. A design variant is proposed in two variations. There is a resistive load on the RF line that is connected in series or shunt configuration [25-27]. Attenuation is either activated, or the micro ohmic relays reset, by electrostatic MEMS. The attenuation levels for both models are quite flat over a wide frequency range (when ON), as well as relatively limited losses (when OFF). To the best of our knowledge, this is the first experimentally tested RF-MEMS attenuator capable of operating at 110 GHz. By implementing more functions on the same hardware, this result may represent a step towards building multi-state RF MEMS networks capable of meeting the demanding requirements of future 5G applications. In this context, 5G beamforming requires attenuation and phase shift functions.

It appears that 5G will be a field of convergence for a variety of needs and requirements that has never been witnessed before in the research and industrial community. The trend of integrating multiple wireless services through one device has been unstoppable since the rapid spread of cell phones some two decades ago. As a result, 5G systems will be 1,000 times more capable than existing wireless technologies. The data rates required for broadband wireless applications, including the streaming of high-resolution video and the tactile Internet, could be tens of times faster than the ones offered by 4G networks today.

An Internet of Things (IoT) paradigm at a different level describes a path of continuous technological development that allows any object or environment belonging to our daily lives to be connected to the Internet. life experience, gains its identity in the digital world, through the Internet. With IoT supporting a wider range of wireless connectivity, 5G mobile systems are expected to support new applications such as machine-to-machine as well as the quality of service required for them. Quality of service (QoS), including reliability, spectral efficiency, energy consumption, etc. The foregoing premises make it clear that no single technology will be able to meet all the challenging (and often conflicting) requirements of the next generation of 5G. Innovative and reengineered network architectures and algorithms are required. Both software and hardware solutions will be required to achieve this goal. The current orthogonal frequency multiple access (used for 4G applications) waveform will need to be replaced with more efficient solutions at the architectural level and the implementation level. For gigabit (Gb) communication, additional techniques include network diversification, the use of large multi-input, multi-output devices, and the use of millimeter wave spectrum (mmW). Considering the market scenario that has made RF-MEMS solutions successful (for impedance matching tuners), 5G communication protocols are expected to require higher operating frequencies (e.g., over 6 GHz) and extensive reconfigurability, reducing hardware redundancy and power consumption. As a result, passives with enhanced characteristics (low losses, high isolation, etc.) are required to solve these challenges [28]. RF-MEMS technology has shown promise for 5G smartphones (e.g., RFFE), as well as base stations. As a matter of fact, no matter what technology is applied, RF components must always be packaged and integrated into more complicated systems and subsystems. Packages are important primarily for protecting devices from potentially harmful factors (environmental), but they are gaining more and more functionality. For years, RF systems for mobile communications have been rapidly growing, resulting in miniaturization, high integration density, and low-cost manufacturing solutions.

A modern RF system typically employs hundreds of passive components rather than a few dozen integrated circuits (ICs). Since these components are frequently manufactured using a variety of incompatible technologies, wafer-level packaging (WLP) solutions provide high-performance, high-density solutions that enable them to be successfully integrated. In order to design and build a package that is very reliable, integrates at a high density, and has little impact on passive RF performance (MEMS and non-MEMS) is quite difficult. Due to this, it is usually more expensive to implement RF packaging / integration than to create the real RF components to package, as previously mentioned. However, despite all the challenges to be met, it is evident that future developments are driven by integrating heterogeneous technologies, limiting monolithic production of functional radio frequency blocks and radio frequency subsystems to the harshest of environments, where breakthrough performance improvements are crucial to success.

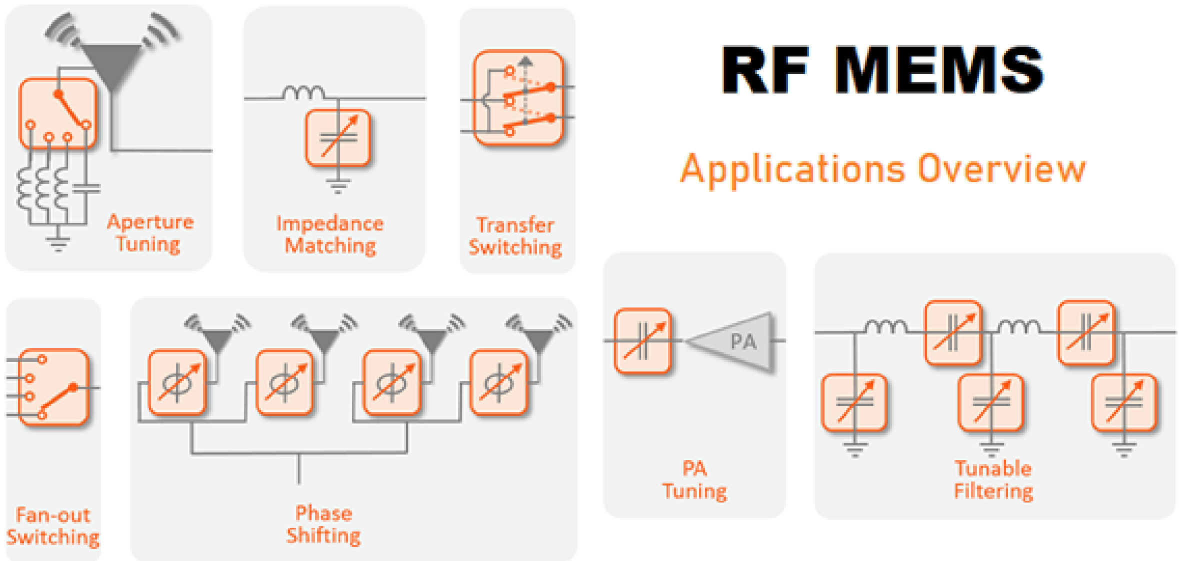

Figure 2: Application of RF MEMS

Optical technology is swiftly replacing traditional magnetic storage technology. In the communication network, switches play an integral role as they possess the capability to transfer data from node to node until they reach their destination. Optical switching integrates into the switching of optical signals, using optical switching components instead of electronic signals recognizing the significance of switching. Integrating the switches assists in the effective functioning of the network that routes traffic to different destinations [6, 49, 50]. Moreover, in contrast to traditional communication technologies, optical switching technology is a more economical broadband transport network construction and also provides flexible services [14].

2.4.1 Requirements for 5G communication

The 5G band is divided into two sets, sub-6 GHz range, millimeter-wave (mmWave) frequency range (24.25 GHz and above). There are certain requirements for operation in any frequency band. There are parasitic capacitances, inductances, resistances, and conductance's in any switch. Parasites degrade the signal that is being routed by the switch as a result of these components. By measuring the insertion loss specification of each switch module at the frequency in which the component attenuates power and voltage, power loss can be quantified with respect to frequency. It is therefore essential to ensure that an application's bandwidth requirements allow for a switch to have a fair insertion loss. Operation frequency is the optimum signal frequency that can be routed through the switch. An isolation better than -30/-40 dB is required for frequencies as high at 50 GHz. On the contrary the insertion loss should be less than 1 dB on widest set of frequency, ideally the whole frequency band. Other requirements include characteristics like low actuation voltage, less switching time, better lifetime and reliability and packaging and integration of the switch [1].

Figure 3: 5G spectrum

2.5 Actuation mechanisms for RF MEMS Switches

Microdevices are ideally suited to electrostatic actuation since it offers numerous benefits, including compatibility with manufacturing processes, small air gaps (10 *m), high speed operation, low power consumption, and easy electrical control of the various parts [2]. Additionally, the material is resistant to temperature and humidity changes. Despite this, electrostatic activation is susceptible to particulate matter, even though particulate matter can be filtered through an input filter, which requires high operating voltages (> 80V).

The use of electrothermal actuators enables a lower control voltage, a linear C-V curve, and eliminates the buildup of static charge on the capacitor plates compared to electrostatic actuators. In order to displace the suspended membrane, different beams with differing thermal expansions are used. Adapting the vibration waveform in electrostatic actuation can improve reliability and reduce contact area pitting and hardening caused by impact energy. Two different friction problems also plague DC contact switches [19]. Using electrostatic activation pulls down the electrodes. Nonetheless, series switches don't have this problem, as the pull-down electrodes barely even contact the hanging beam. In high-current designs, micro-welding and material transfer occur as another mechanism of friction.

Whenever a breaker is in the raised position, the stand-off voltage is described as the breaker gap voltage before a fault occurs. In capacitive switches such as those with large areas, open circuit voltage can affect the switch to bring it to the down state. This is known as self-actualization. Electricity and electromagnetic actuation both benefit from the availability of a lower actuation voltage, for example 5V. Although latching mechanisms are convenient, there is a major drawback in that they consume large amounts of power [50]. Most electrostatic devices operate at a voltage greater than 15 volts. Several semiconductor systems with standard voltage sources require up-converters for connections to switches. Additionally, switches with a high actuation voltage tend to have reliability issues such as friction. At 10-100mW of RF power, the majority of electrostatic switches only produce 10 to 1000 million cycles. Electrostatic drives can achieve small contact and reset forces (50*1001N) mainly because of their small contact forces. RF switches operating typically in the thermal range can handle up to 6W of RF power, but they require large quantities of DC power (50-330 mW) which makes them unsuitable for many applications [67].

A number of benefits associated with electrothermal fabrication include material flexibility, low manufacturing costs, and the ability to manufacture large volumes. Various electrothermal actuator designs are discussed, including heating and cooling arm types, chevron shapes, and bimorph shapes, along with others. There are some benefits associated with electromagnetic actuators, making them an important part of MEMS [97]. Thermoelectric actuators need a relatively low drive voltage to generate large horizontal and vertical forces and displacements. Since these devices do not use electrostatic or magnetic fields for operation, they can handle biological samples and electronic chips. Unlike piezoresistive or SMA actuators that exhibit significant hysteresis, electrical actuators are much easier to control. A magnetic actuator can be easily scaled up in size and usually includes a more compact structure than either electrostatic (which uses comb drives with large arrays) or electromagnetic actuators (which can't be implemented in small sizes) [93]. As well as operating in liquid or air, electrothermal actuators can also be used in dusty environments, vacuums, or under electron beams in SEM (scanning electron microscopy). The large time constants of thermal processes, however, result in these actuators' low switching speeds. Nevertheless, the likelihood of thermal activation on a high frequency level has been demonstrated. Electrothermal excitation is also becoming increasingly attractive because of its advantages for actuation in resonance mode in microcantilever-based sensing and probing applications. High quality and wide tuning range MEMS resonators were obtained from these devices. Force feedback can be provided by piezoresistive or piezoelectric sensors in conjunction with electrothermal actuation.

Originally developed for micromanipulation, positioning, material testing, and MEMS switches, the electrothermal chevron actuator has been widely used for many applications, including RF applications. Recently, chevron-based designs have emerged in addition to the traditional V-shape. With respect to hot-and-cold arm actuators, chevron actuators have distinct advantages, including the direct rectilinear movement, the absence of a "cold" arm (no parasitic resistance heating), and the ability to stack and cascade structures. In addition to producing large displacement and forces (hundreds of mN and _N), chevron designs can also be designed to operate at lower driving voltages; amplification can also facilitate large displacement. Innovative chevron shapes increase design flexibility and bidirectional bending. chevron actuators are primarily characterized by buckling out-of-plane, which reduces the range of temperature that can be reached during actuation. Due to insufficient mask resolution and stiction problems, the chevron actuators have a larger footprint than the other electrothermal types [2].

The current state of electrothermal actuators has been discussed, as well as some trends. In the past two decades, the hot-and-cold-arm, chevron, and bimorph designs of electrothermal actuators have received considerable attention. As opposed to electrostatic and piezoelectric actuators, they can offer certain advantages. In applications that require simple fabrication and control techniques, low voltage operation, strong force output, or compatibility with a variety of environments, electric actuators are preferred. Generally, such actuators are designed based on electro-thermal-mechanical calculation models that can be combined to solve a numerical or analytical problem.

Performance has been enhanced greatly with improvements to conventional hot-and-hold actuators. The influence of geometrical (beam geometry and heater shape), electrical (selective doping and modified resistance) and topological (bidirectional or multimode operation) parameters in differential thermal expansion has been demonstrated. Compact, flexible, easy to fabricate and easy to implement, hot-and-cold arm actuators typically produce a small amount of force. Linear motion and scalability are sought in chevron actuators [98]. We discuss chevrons that have kink- or Z-shaped legs as new shapes for actuators based on chevrons. There are limitations to conventional V-shaped chevrons. They can be overcome by these shapes. There are no limitations to design capabilities. Quality performance enhancements can be realized. Performance, however, is limited by the aspect of reliability. The high localization of heating and the buckling due to internal stress redistribution are factors affecting the in-plane electrothermal actuators. As a result of the shear stress created by dissimilar structural layers, the reliability of bimorph actuators declines. These actuators can be fabricated using standard IC and MEMS fabrication technologies, e.g., PolyMUMP, MetalMUMPs SUMMiT, post-CMOS, SOI, and even MEMS can be built directly onto a PCB. Microfabrication typically uses planar deposition. Graphene, polymers, and polymer composites are among the high-performance materials being tested in actuators at present. A low driving voltage and low operating temperature is possible, allowing actuation. Designing electrothermal actuators has been shown to be a versatile field where the requirements are largely determined by the application. The advantages and disadvantages of each actuation method are summarized in table 2.

Table 1: Actuation Mechanisms

Actuation Mechanism	**Advantages**	**Disadvantages**
Electromagnetic	• Low actuation voltage • Relatively large displacement	• Difficult in fabrication of magnetic material with current CMOS technology • Challenge in minimizing a size of devices
Piezoelectric	• Higher switching speed • Low power consumption	• Small displacement range • High actuation voltage
Electrothermal	• Easy fabrication • Low actuation voltage	• High power consumption • Slow response time • Thermal fatigue due to thermal cycle
Electrostatic	• Low power consumption • Fast response time • Easy to integrate and implement with CMOS technology • Compatible with most fabrication methods	• High actuation voltage • Limited operation range due to the pull-in

2.6 Literature review

With the use of MEMS in every field, there has been a lot of development and novelty in the RF MEMS switches. Mechanism for tuning capacitive switches using warped bimetallic beams was introduced. Simple and flexible, warped beams don't require thin dielectrics, tuned circuits, or larger sizes. The electrical isolation performance was promising as well. Measured results demonstrated that the inclusion of these beams into the structure allows a high capacitance ratio to be achieved without the use of large switch gaps or high-dielectric-constant materials. For lower actuation voltages and higher inductance, a serpentine spring structure can be designed. By using dual tuning, the switch performance can be adjusted without drastically modifying switch performance. This capacitive switch required a pull-in voltage of 27 V, had an insertion loss of less than 0.2 dB, and an OFF-state isolation of 41 dB at 10.5 GHz [41]. A new class of capacitor-type RF MEMS switches based on a standard CMOS process was presented for the first time. Utilizing the dielectric and interconnect metal layers of a CMOS process, the switches were fabricated using the TSMC 2P4M 0.35-MM CMOS process. Through the use of warped-plate structures, the capacitance ratio can be improved. Switches made based on the fabricated device have a capacitance ratio of 91:1. At 20 GHz, I/O switch 1, with an insertion loss of more than 0.98 dB, a return loss of 13 dB, and an isolation of 17.9 dB, exhibited a very good performance. The second cascaded switch fabricated using the -match circuit method, has a lower return loss and improved isolation performance. Over the frequency range from 10 to 20 GHz, the switch demonstrated insertion loss less than 1.41 dB, return loss better than 19 dB, and isolation better than 19 dB. MEMS capacitive switches are suitable for implementing multiband, reconfigurable RF front ends. It is possible to fabricate these RF MEMS switches with standard CMOS processes therefore this fully integrated silicon solution has been realized [48]. According to the bridge length, another switch was introduced with relatively low actuation voltages of 15–20 V, insertion loss around -0.8 dB up to 30 GHz, and isolation around -40 dB at the resonant frequency of 15–30 GHz. [50]. There was a finding that the fixed anchors of switches which are spring-type were less susceptible to residual stress or tensile stress. Electrical stress was applied for a certain time to the devices both in air and under vacuum. Due to a fast polarization and higher dielectric conductivity, AlN switches reduce residual charges better than Si_3N_4 switches. The charge distribution in AlN dielectric materials follows a square root time law, which seems to be beneficial for their reliability

[52]. The beam shape and the RF performance of the actuator were studied by researchers. Serpentine spring beams were used to lower the switch spring constant and to increase capacitive area. This enhanced switch RF performance because the capacitance ratio was higher. CAD finite element analysis software CoventorWare was used to analyze the pull-in voltage. In their design, the actuation voltage was as low as 1.5V and the actuation area was 110*100*m2. The design of serpentine beams was able to produce pull-in voltages between 1.5 and 4.75V. It provided better than 25 dB isolation in off state with a capacitance ratio of 94-96; the switch had a return loss of 42 to 12 dB and an insertion loss of 0.47% from 2-40GHz. An important factor influencing spring stiffness and actuation voltage is optimizing the number of meanders and the width of meanders [61].

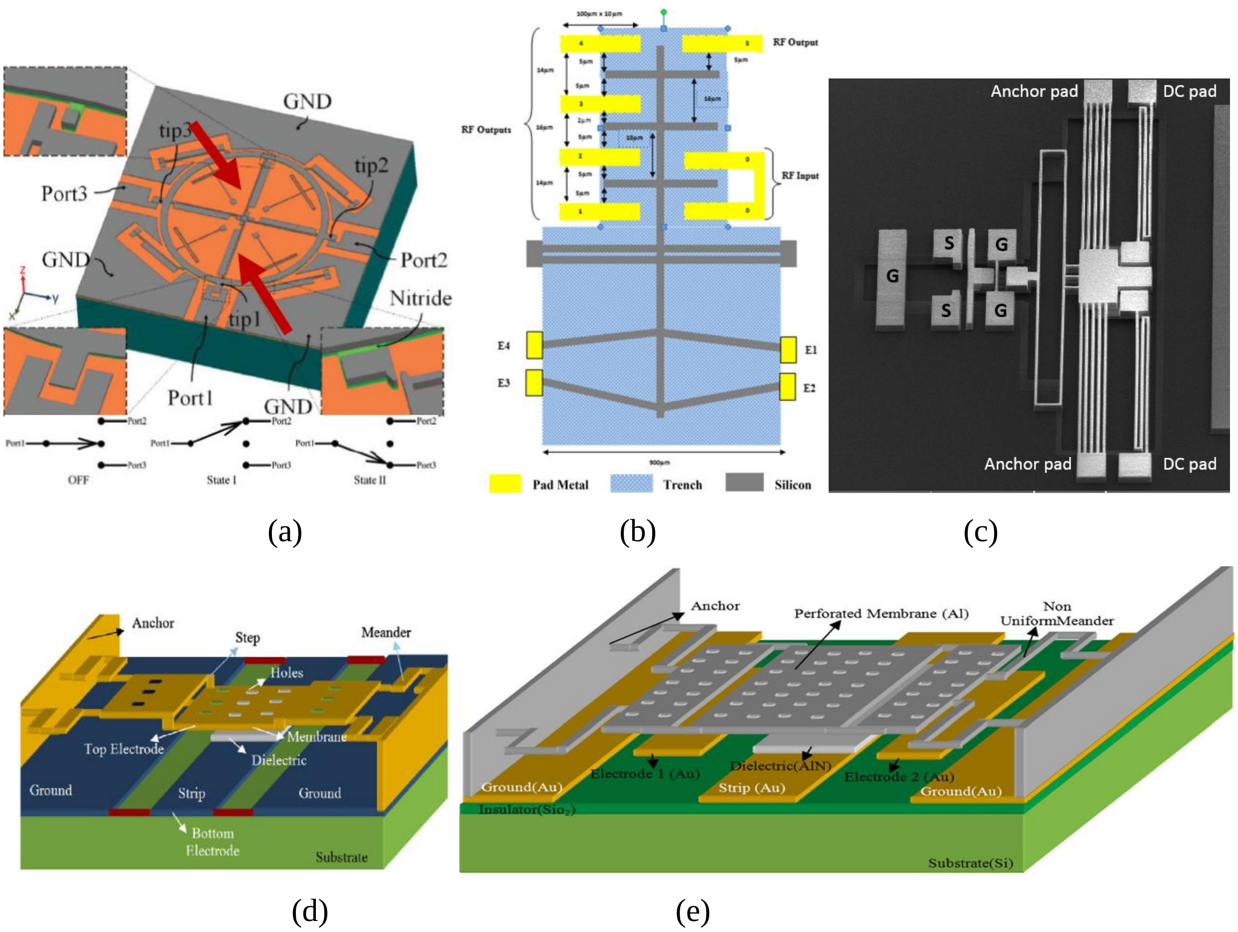

Figure 4: In plane and Out of plane switches a) Ilkhechi et al.2015 [106] b) Bala et al.2017 [101] c) Asanjan et al.2019 [15] d) Narayana et al.2017 [34] e) Sravani et al.2018 [83]

RF-MEMS multi-responding switch of 3.04 V pull-in voltage can be achieved and compatible with most CMOS power supply requirements. The mimicked response time of the MEMS switch is 13.5 us and the capacitance ratio were 52. As the frequency of 40 GHz increases, so will the isolation and the insertion loss. This optimization methodology can be applied not only to the statistical constraints of the RF-MEMS switch, but also be applied to the optimization process of other RF-MEMS devices, especially those with multiple objectives or responses [66]. RF MEMS switches with novel actuation structures have been developed. Unlike conventional switches, this new switch does not use an actuation voltage on the signal line to operate. In such a structure, the RF signals and DC voltage are decoupled from the ground planes when the actuation electrodes are biased with an appropriate bias voltage. Because the actuation voltage is insulated from the RF system, the switch is fit to work for commercial uses. As well as reducing the capacitance area, the actuation voltage does not need to be increased. Due to the reduced capacitance area, the up-state capacitance is also reduced, and the insertion loss is also reduced. A 35GHz switch fabricated using the proposed approach exhibits insertion losses of 0.29dB and isolations of 20.5dB. A voltage of 18.3V is used for actuation. In addition to being simple to implement, the switch has low insertion loss, low actuation voltage, and easy integration into radio frequency systems [71].

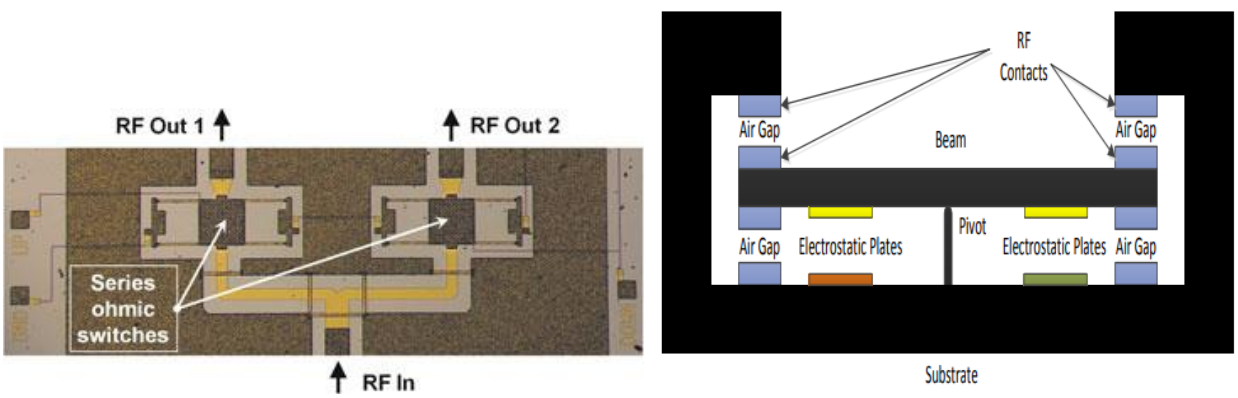

Figure 5: a)SPDT switch **b)** DPDT switch [73]

The K band applications of a new RF MEMS capacitive shunt switch were presented, which had low actuation voltage, high isolation, and low loss. For the switch to have minimal actuation voltage, a slight air gap must be present, resulting in its design as a step membrane. To increase the down-state capacitance and improve the isolation of the switch, aluminium nitride (AlN) was used instead of conventional dielectrics such as silicon dioxide and silicon nitride as a dielectric. As a result of serpentine beam design, the resonant frequency has been shifted to the desired band and increased isolation has been achieved. From 1 to 40 GHZ, the actuation voltage was reduced to 2.9 V, and S11 was less than -10 dB and S21 exceeded -0.72 dB. At the frequency range of K-band, the switch has excellent isolation in downstate. With a resonance frequency of 27 GHz, the maximum isolation is 58 dB [73]. Capacitive shunt MEMS switches with different meanders were designed and simulated. A great deal of interest is being expressed in RF MEMS switches in the communications industry. So far, many switches have been designed with various structures that mainly concentrate on the pull-in voltage. RF MEMS capacitive shunt switches with uniform and non-uniform meanders are analyzed for their electromechanical, switching timing, and performance. Using MEMS switches, membranes are moved over coplanar waveguides. Gold is used as a material and Si_3N_4 or HfO_2 is used as a dielectric in the electromechanical analysis of movable beams. Simulated results indicate that a non-uniform single meander has a return loss of -60 dB, an insertion loss of -0.2 dB, and an isolation loss of -14 dB at 20 GHz. Compared with the uniform 3 meander switch, its return loss is -55 dB. Consequently, the typical time for three-meander beams is 0.12 ms, and the average time for one-meander beams is 0.7 ms [5]. A novel RF MEMS shunt capacitive switch was introduced that contains a unique spring design. A key characteristic of the proposed switch was low actuation voltage, as well as good RF performance, such as low insertion loss, low return loss and considerably high isolation. Ka-band performance is ensured by the design of the proposed switch. Voltage was reduced by combining two methods. A step structure has been employed to reduce air gaps by using a reduction of air gap. Another technique for reducing k involves using a helical spring that has been developed recently. Aluminium is selected as the switch material because of its low weight and good electrical conductivity. Since SiO_2 has high insulation and low conductivity, it was used for the dielectric layer. Switching cycles with a high degree of vulnerability. At 30.5 GHz, the isolation measured at 2.2 V is -71 dB. There is a loss of more than - 0.85 dB for insertion and a loss of 11.5 dB for reflection between 1 and 40 GHz [32, 88].

Bala [101] introduced a new design of MEMS in-plane RF switch which was actuated using chevron actuators. This was a SPDT switch which showed promising results from the previous designs in the literature. Satellite payload applications can benefit from RF MEMS switches with a single input multiple output topology. Depending on the configuration of an electrothermal actuator, the actuator's electrode pads are alternately electrically charged with voltage to trigger motion forward or backward in plane. A significant reduction in reflection and insertion losses has been achieved. Based on the measurements, the input reflection coefficient (S11) is less than -50 dB, and the forward transmission coefficient (S21) is better than -2 dB in the dual-mode position. A positive flat-mode transmission (S21) is better than +3.5 dB at 0–15 GHz when the input reflection coefficient (S11) is less than -55 dB. In both modes of operation, there is a greater than 50 dB isolation achieved between 0 and 15 GHz, ensuring information is not lost when operating in dual and quad modes. A 4.5 V actuation voltage enabled the switch to handle power up to 35 dBm while only consuming 50 mW. With low insertion loss, good isolation, low power consumption, and capability to handle high power, this compact RF MEMS capacitive switch delivers excellent performance [101]. The literature review is summarized in table 1.

Table 2: Comparison of different RF MEMS switches

Reference	**Switch type**	**Pull-in voltage (V)**	**Operating frequency (GHz)**	**Insertion loss (dB)**	**Isolation (dB)**	**Return loss (dB)**	**Metal material**
Ansari et al.2018 [87]	Out-of-plane	2.2	1-40	-0.65 @ 30.5 GHz	-70 @ 30.5 GHz	-11.47 @ 40 GHz	Al
Shekhar et al.2017 [82]	Out-of-plane	6.3	Up to 60	0.25 @ 20 GHz; 0.7 @ 50 GHz	30-40 @17 GHz; 30 @ 40 GHz	12 @ 50 GHz	Au
Bala et al.2017 [101]	In-plane	4.5	0-15	-2 to -4	-50	-50 to -55	Au
Ravirala et al.2017 [79]	Out-of-plane	2.45	1-40	-0.07 @ 1-40 GHz	-61 @ 28 GHz	-60 @ 1-40 GHz	Poly-tetra-fluoro-ethylene (PTFE)
Samaali et al.2017 [80]	Out-of-plane	3.01	0.1-50	-0.31 @ 10 GHz	<-23 @ 10-50 GHz	-12.41 @ 10 GHz	- (Conductive polyethylene)
Narayana et al.2017 [34]	Out-of-plane	4.2	0.6-40	-0.01-0.45	-20 @ 21 GHz	-42 to -16	Au
Ma et al.2017 [65]	Out of plane	2.9	20	-0.5665 @ 20 GHz	-22.12 @ 20 GHz	-7.783 @ 20 GHz	Al
Sravani et al.2017 [78]	Out-of-plane	2.3	20	-0.2 @ 20 GHz	-14 @ 20 GHz	-55 @ 20 GHz	Au
Molaei et al.2016 [72]	Out-of-plane	2.9	1-40	- 0.8 @ 25 GHz	- 58 @ 27 GHz	- 10 @ 40 GHz	Al

Li et al.2016 [71]	Out-of-plane	18.3	0-40	0.29 @ 35 GHz	20.5 @ 35 GHz	-25 @ 35 GHz	Au
Angira et al.2016 [43]	Out-of-plane	6	3.2-19.8	0.10 @ 25 GHz	48.80 @ 4.5 GHz; 54.56 @ 9.7 GHz	36.80 dB @ 25 GHz	Au
Ilkhechi et al.2015 [106]	In-plane	5	30	-0.37 @ 30 GHz	-45.48 @ 30 GHz	-11.74 @ 30 GHz	Polysilicon
Kaur et al.2014 [60]	Out-of-plane	1.5	2-40	0.9 @ 40 GHz	25 @ 40 GHz	12 @ 40 GHz	Au
Angira et al.2014 [58]	Out-of-plane	11.75	1-25	<0.11 @ 25 GHz	20 @ 25 GHz	26.27 @ 25 GHz	Au
Buitrago et al.2012 [51]	Out-of-plane	12	0-40	0.2 @ 40 GHz	38.5 @ 40 GHz	9.23 @ 40 GHz	Au
Persano et al.2011 [49]	Out-of-plane	15-20	0-40	-0.8 @ 30 GHz	-40 @ 15-30 GHz	-10 @ 28 GHz	Au
Fouladi et al.2010 [47]	Out-of-plane	12	10-20 GHz	1.41 @20 GHz	19 @20 GHz	19 @ 20 GHz	Al
Aldahleh et al.2010 [41]	Out-of-plane	27	0-40	0.2 @ 10.5 GHz	-41 @ 10.5 GHz	-20 @ 10 GHz	Au

2.7 Displacement amplification mechanism

The purpose of MEMS actuators is primarily to perform substantial translational movement. In this case, an intermediate mechanism can be implanted that magnifies the outpu in form of displacement actuation. MEMS fabrication techniques can easily be used to fabricate several of these reduced amplification systems that use less power, are lightweight and can be easily manufactured. Mechanisms that are compliant are a common element of many machineries that require ultra-high precision motion generation. Examples are scanning probe microscopes, lithography mechanisms, nano-imprint lithography mechanisms, precision manufacturing, cell manipulation mechanisms, and optical steering mechanisms. Prismatic-spherical-spherical parallel mechanisms have been combined in a monolithic altering mechanism proposed in 2016. The deep ultraviolet lithography objective lens requires mechanisms with micrometer strokes, nanometer accuracy, high load capacities, and compact structures, which this mechanism provided. Using the thinned fillet flexure hinge as the spherical joint of the parallel 6-PSS mechanism, authors proposed improving mechanical accuracy, simplifying alignment, and achieving monolithic configuration [102]. It was shown in 2016 that a five axis nano positioner based on flexures could be used for tip-based nanofabrication. The prototyping process of the mechanism was accelerated using pseudo rigid body modeling (PRBM) and finite element analysis (FEA). By combining the flexure hinge and cantilever beam structures, a hybrid compliant mechanism concept has been introduced towards improving the microgripper's grasping behavior for high precision and fidelity manipulation.

Micro-flexion and micro-hinges are arranged in a bridge-type mechanism so that input displacement is amplified multiple times, irrespective of dimensional parameters, angles and hinge types used for the micro-flexure. Around the world, researchers have been studying bridge type displacement amplification mechanisms extensively. Different types of hinges and geometric properties are used in this mechanism. The combination of circular and single axis flexure hinges can enhance displacement amplification. In micro actuators, a bridge type mechanism is a useful mechanism for gaining a high voltage stroke ratio due to its small size and high amplification. When used with comb drives as sensing mechanisms, bridge type displacement amplification mechanisms increase capacitive signals with a changing signal-to-noise ratio when used with microdevices. It is an inherent limitation of bridge type displacement amplification mechanisms that they de-amplify forces. As a result, the flexure hinges can become brittle and eventually crack the whole device due to a concentration of stress. In addition, MEMS safety-and-arming (SA) devices that utilize cascaded V-beam amplification were proposed. A cascaded V-beam amplification was used along with two mechanical sliders and two V-shape electrothermal actuators. V-beam amplifications had a much larger vertical anti-acceleration stiffness to meet the requirements of high-acceleration weapons [104]. To guarantee the MEMS SA device was armed, the two symmetric mechanical sliders doubled the displacement. In-plane displacements are induced by most of the designed amplifiers. Mechanically amplifying signals can be beneficial for acceleration dynamos, piezoelectric devices, and electrostatic devices. Displacement amplifiers have the disadvantage of being stiff overall which affects the modal operable frequencies. Micro devices become larger as these amplifiers are incorporated. If an amplifier is used for electrostatic sensing or actuation, the output deflection can be increased without having an impact on noise levels. Lai proposes a system that consists of two L-shaped levers and bridge equipment. Flexible hinges in the hardware carry both tensile and bending loads, which can solve potential overturning problems [103]. The symmetrical distribution of the L-shaped lifting gear can avoid the turning moment and lateral force of the driver, thereby protecting the rotary motor gear. An arithmetic and analysis model for the displacement of the expansion, input stiffness and natural frequency of the system based on the rigidity of the matrix method has been established and optimal design is carried out under certain constraints. The final element analysis results are then given to verify the design model and a prototype of the expansion device is made to test the results. Stable and powerful test results show that the range of the hardware is 288.3 μm, the motion resolution is 50 nm and the operating frequency of the system without and with the operating system is 155 Hz and 178 Hz, respectively. Hu proposes a piezoelectric linear operating system driven by lateral motion. The designed operating system only needs a piezoelectric stack that is nestled in a special parallel-grade flexible parachute system to achieve a big stroke of linear motion. The experimental results show that at 100 V operating voltage and 2000 Hz driving frequency, the maximum engine speed designed is about 14.25 mm s-1; when the operating voltage is 10 V, the minimum step is 0.04 μm, Maximum output is 3.43 N [105].

Micro-transfer amplification equipment is becoming increasingly important in MEMS applications that require motion accuracy, reliability, precision, and density. These displacement amplification methods improve the sensitivity of the micro-sensor and the voltage-to-voltage ratio of the microarray. These features open the door to new and improved small devices with unprecedented results. In this article, Iqbal et al reviewed the flexible displacement amplification equipment, including bridge equipment, location level measuring equipment, Scott-Russell hardware, micro-motorized microcontroller hardware, multi-stage power amplification equipment, hydraulic transmission equipment and thermal propulsion equipment [99]. The displacement actuation mechanism used in this research (figure 6) shows a level of novelty as it gives more control over getting specific degree of actuation amplification. The various parameters effecting the amplification can be optimized to give particular result.

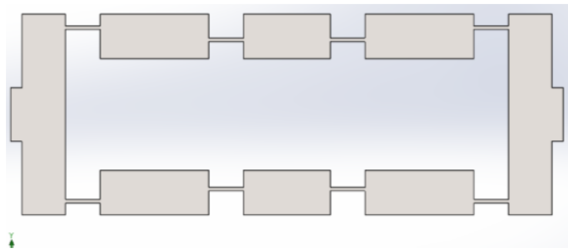

Figure 6: Displacement amplification mechanism modeled in this research

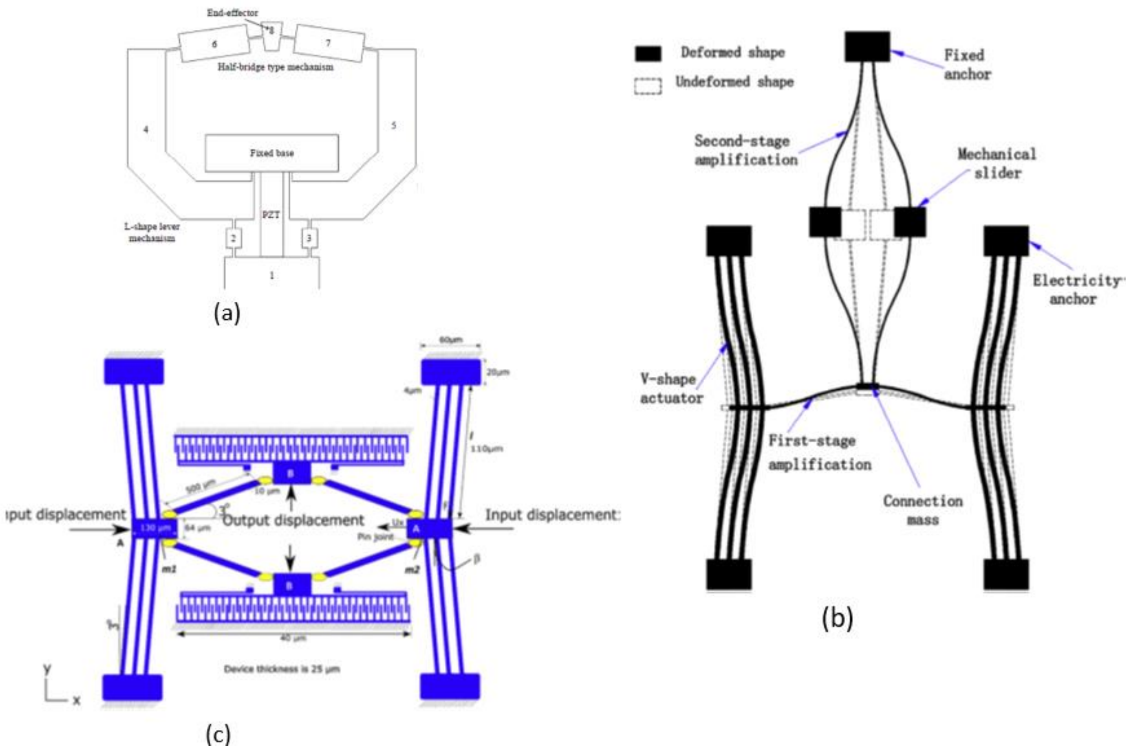

Figure 7: Different DA mechanisms a) Lai et al.2017 [103] b) Hu et al.2018 [105] c) Iqbal et al.2019 [102]

CHAPTER 3: PROPOSED RF MEMS SWITCH DESIGN

Design, analysis, and mathematical modeling of a new RF MEMS switch is presented in this research. A single pole dual throw switch is proposed which is modeled by combining displacement actuation mechanism and chevron actuators. Chevron actuators are used because of low actuation voltage. Despite the drawbacks of electrothermal actuators, the trade-off aspect gives us greater benefit for low actuation voltage of electrothermal actuators. The design has two modes of operation. RF MEMS actuator with dual and quad outputs, electro-thermally actuated, has been developed which allows for connectivity to two outputs for one setting as well as to four outputs for another. Three RF input–output pads move in plane between the central beam and 3 cross beams to one end. Dual mode provides signal routing to two outputs while quad mode provides signal to four outputs. The central beam is anchored using fixed-fixed beams.

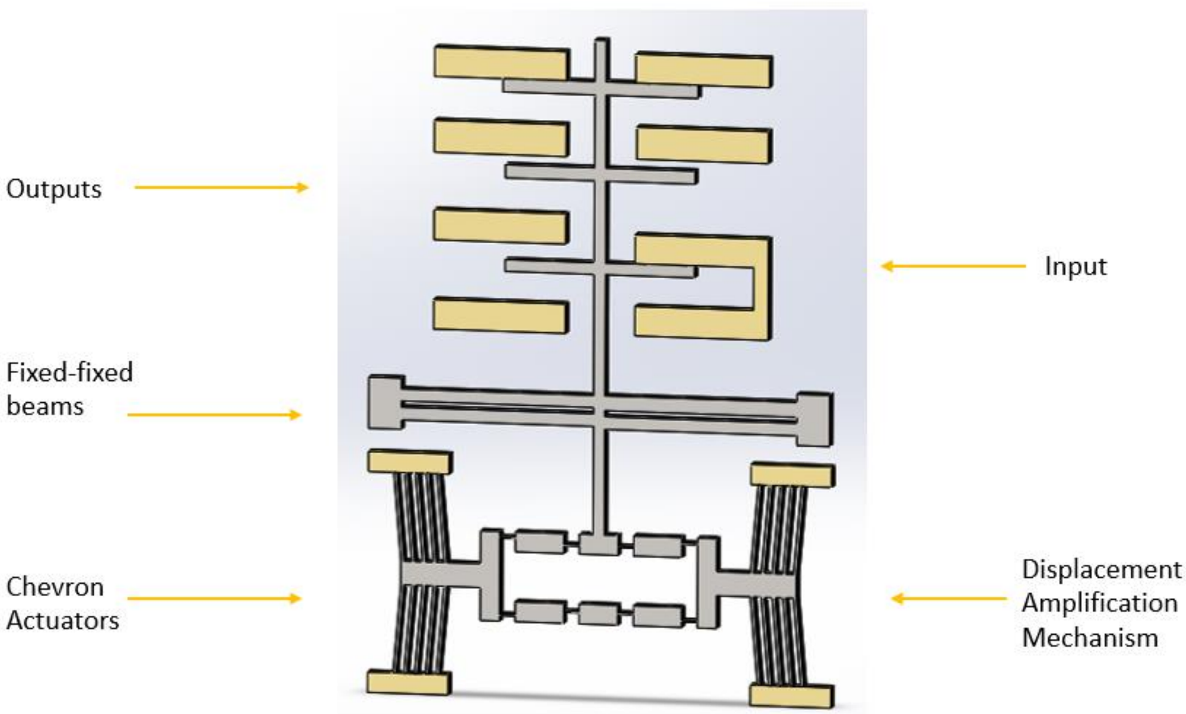

Figure 8: Proposed design

The beam is then connected with the displacement amplification mechanism which takes its input displacement from a pair of chevron actuators. The lower side of the DA mechanism is anchored, and the upper portion gives amplification to the displacement provided by the chevron actuators on the sides. A thermo-electric actuator provides greater displacement while using fewer complex mechanisms than an electrostatic actuator. It has a spring-complaint middle section that improves device stability. Each spring beam is fixed with an anchor at each end. The whole system is modeled keeping in mind the SOIMUMPS (Silicon-On-Insulator Multi Users Micromachining Process). This implies that the devise is pure silicon with a thin layer of gold etched on it. The substrate is silicon with silicon dioxide layer separating it from the structure. A negative space is created to ease the movement of actuator and actuation beam.

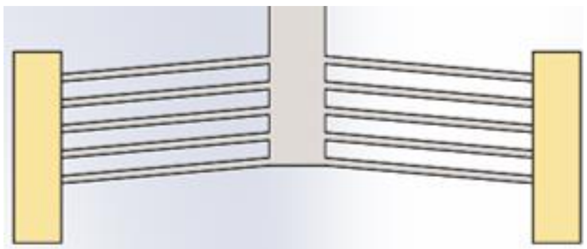

Figure 9: Chevron Actuator

3.1 Modes of operation

Chevron actuators operate on the principle of Joule heating and thermal expansion. When voltage is applied across the legs of the Chevron actuators, the central beam is lifted to provide actuation to the system attached. The switch is in dual mode in resting position such as the top two beams are connected to the actuator beam which connects to the input beam while the other electrodes are grounded, and the signal is only being routed to two outputs. This is the forward actuated mode. The backward actuation is achieved by applying voltage to the electrothermal actuators. This moves the actuators in backward actuation such that the central beam is connected to four output electrodes and one input electrode to route the signal successfully to four outputs. A trench is designed to assist smooth movement of the in plane actuator and actuation amplification mechanism. This trench creates a negative space for free movement of the actuation system. Hence in OFF state, dual mode is active and in ON state quad mode is active. The working of the displacement amplification mechanism is of great significance here since electrothermal actuators provide large displacements at considerably small voltage, the displacement amplification mechanism enhances this movement by a certain factor which is determined by parameterizing the design. Design dimensions are given in table 3.

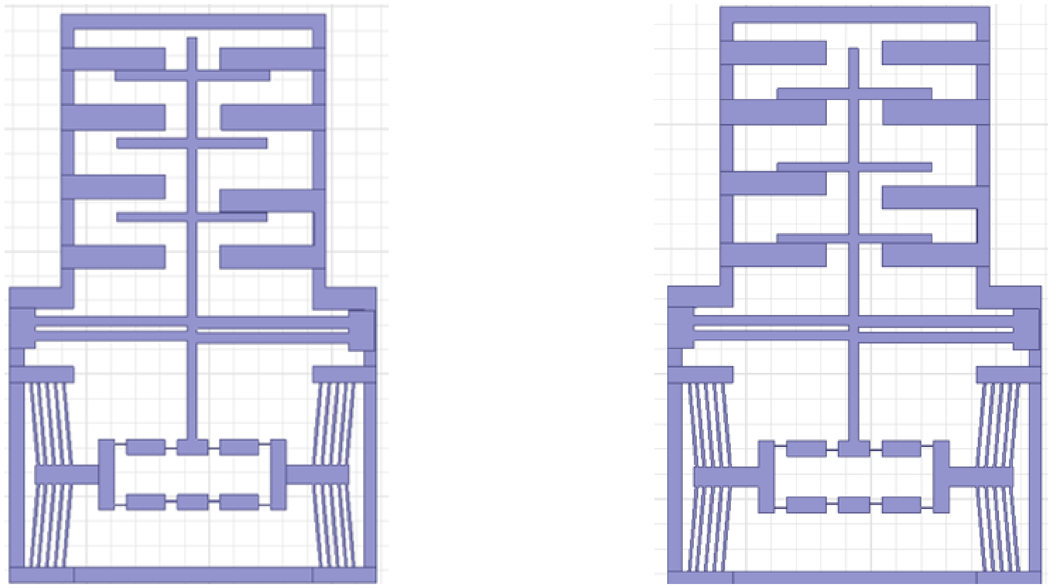

Figure 10: Modes of operation of switch a) Dual mode b) Quad mode

Table 3: Dimensional details of proposed device

Parameter	**Value (μm)**
Span of device	1500
Height of device	1000
Thickness of device	10
Actuator beam length	400
Actuator beam thickness	5
Contact pad length	150
Contact pad width	150
Anchor width	50
Anchor length	100
DA mechanism length	800
DA mechanism width	300

3.2 Mathematical modeling

The proposed switch is mathematically modeled to give significantly better results than previous designs mentioned in the literature. The mathematical modeling mainly includes optimization of displacement amplification mechanism parameters, modeling chevron actuators to match the actuation required along with DA and the correlation of force produces by actuators and displacement input for amplification mechanisms. This is critical for analysis of the switch which shows the temperature rise in the switch and operating voltage. Parameters optimized by mathematically modeling the switch are then tested in Ansys workbench and optimized more using analytical analysis.

3.2.1 Parameters of DA mechanism

From kinematics theories it is possible to calculate the ideal displacement amplification ratio during deformation. The parameters affecting performance of the displacement amplification mechanism are the geometric dimensions of the structure. The mechanism is made of silicon similar to the rest of the structure. Intrinsic properties of the structure may affect working of the mechanism, but these intrinsic properties do not target displacement amplification individually but affects the whole structure hence these properties can be ignored in individually modelling the mechanism. Materials and thickness of the structure do not affect the displacement amplification ratio of bridge-type mechanisms. The planar dimension of the structure is the only factor. The amplification device works such as displacement is provided as an input to the side beams of the device which is then enhanced to a certain factor due to the incorporation of different sized beams in the mechanism. The ratio of these beams is selected after optimization. Length and thickness of few beams affect the output more than the others. Bridge-type mechanisms are most sensitive to the vertical distance between hinge centers. It increased fairly quickly when it increased from zero, until it reached a peak, and then decreased slowly. As the hinge width increases, the threshold rises, and the peak arrives. During displacement amplification, the lengths of the rigid link and flexure hinges are added up instead of their respective lengths as in displacement amplification ratio bridge-type mechanisms. In other words, as the distance between them grows, the displacement amplification ratio grows as well.

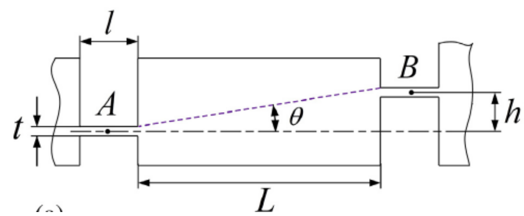

Figure 11: Parameters of displacement amplification mechanism

The output displacement is calculated using the following formula

$$R_{amp} = \frac{3h(l + L)}{t^2 + 3h^2}$$

where h=gap between notches

l=length of notch

L=length of link

t= thickness of notch

These parameters were analyzed using design of experiments approach. Values were then optimized after mathematical and analytical modeling keeping in mind the constraints of the design. Table 4 give the parametric values and the corresponding output. It is evident that the notch thickness and gap between notches affect the output displacement the most. Length of notch and length of link have a linear relation with output so any value can be selected as long as it complies with the other parametric values. The values thus selected are

L=250um

l=100um

t=10um

h=25um

3.2.2 Chevron Actuators

Thermoelectric actuators (ETAs) operate without the need for high voltages and electrolytes, as they are powered by electricity. Based on the principle of using thermal expansion gradients with electricity input, ETA is a powerful technology. Temperature, spiraling, and the skin effect are all factors that can affect the resistance, and therefore the loss, of conductors. Conductors increase their resistance as temperature rises. Elevator temperatures can significantly affect power losses on electric power lines. Conductor resistance increases as a result of spiraling, marked by the way stranded conductors spiral about the center. Conductors that are exposed to higher alternating current frequencies gain a greater effective resistance due to the skin effect. A mathematical model can estimate the loss of capacitance and resistivity.

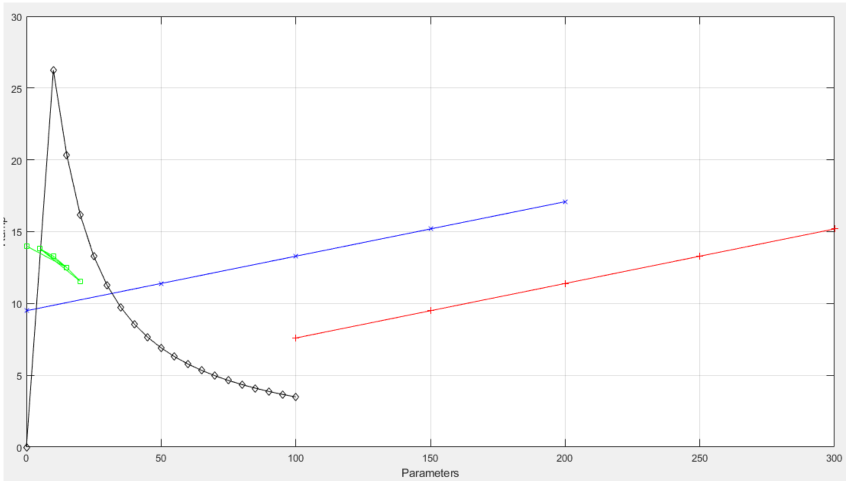

Figure 12: Parameters of DA mechanism vs output displacement

Chevron actuators are a type electrothermal actuators which consist of an angled beams that provide actuation when voltage is applied across it. The output force depends on a number of factors that can be calculated using formula

$$F = N\alpha TEA \frac{\cos\theta}{\frac{\sin^2\theta}{\varphi} + \cos^2\theta}$$

where N=number of actuator beams

α=thermal expansion coefficient of silicon

T=temperature

E=young's modulus

A=area of beam

θ=pre-bending angle of beam

$\varphi = \frac{AL^2}{12I}$ where I is moment of inertia

All these factors affect the working of a chevron actuator, but the most effective parameter is the pre-bending angle of the beams. Force becomes a function of the angle, θ, and varies periodically. All the other factors affect the output linearly so any value can be chosen keeping in mind the design constraints. Figure 13 shows the value of force as a function of θ. Although the maximum value of theta (5 degrees) was chosen due to max output, it was then changed to 7 degrees due to design requirements modeled analytically and in Ansys.

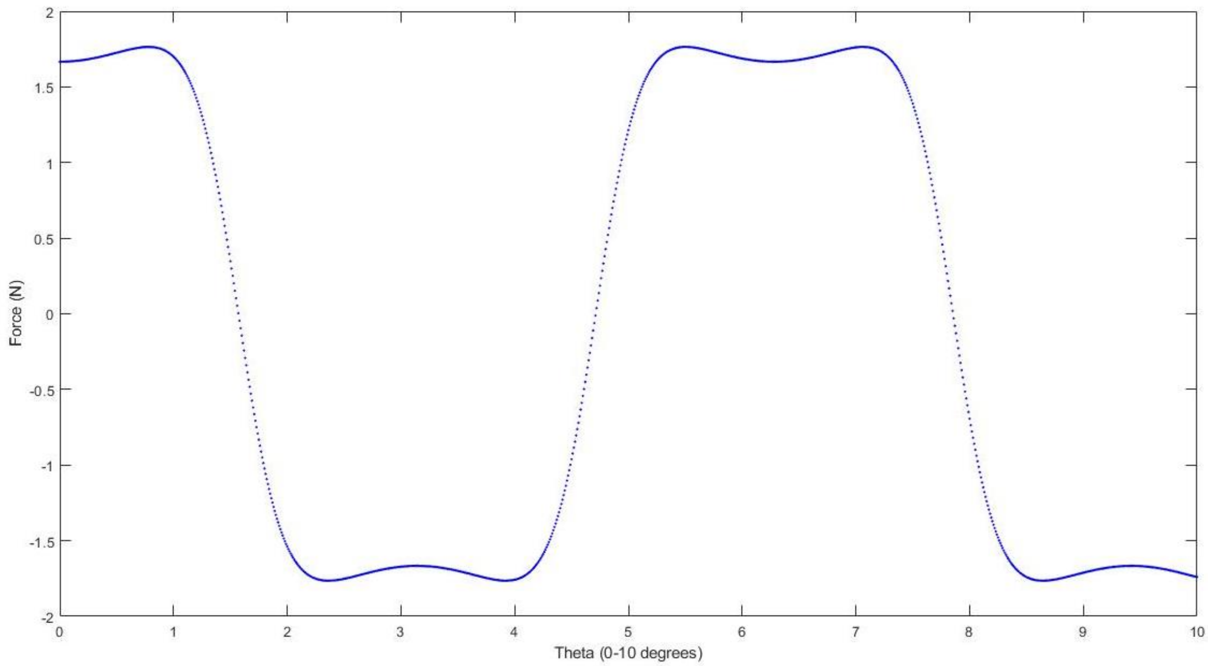

Figure 13: Force as a function of theta

3.2.3 Relation between Chevron actuators and DA mechanism

A simple relation between output of chevron actuators and input of displacement amplification mechanism can be established. This relation gives us the input required by the DA mechanism which gets amplified into R_{amp}. This relation is given by the equation

$$F = kx$$

where k = spring constant of the material used and

$$x = \frac{Final\ displacement\ required}{R_{amp}}$$

CHAPTER 4: RESULTS AND CONCLUSION

The switch was designed keeping in mind the requirements for 5G communication. Before these requirements get fulfilled, it is critical to test all the factors that modelled mathematically. These factors are assessed under a microscope so that the final product is structurally stable and capable of handling temperature and deformation variations. If these parameters fail to produce such design, the process of mathematical modelling is repeated to get desired results. Analysis of a switch is done in more than one steps. First step is analyzing the switch mathematically which is also a part of design process. Once this is done, a geometry is created and reviewed on Ansys with added loads, temperature, and boundary conditions. The outputs to be considered usually are the temperature rise and deformity that the structure might suffer from since the device in question is extremely small. Once the structural analysis is done, the actuation is tested so that voltage and power issue can be solved. Then we move on to the RF analysis of the structure done on HFSS. This test the RF characteristics in a certain frequency band. This lets us know if the switch will transmit a signal of that particular frequency band.

The results derived from the analysis of this switch are quite promising and are discussed below.

4.1 Electrothermal analysis

The electrothermal analysis is done on Ansys workbench. The first part of analysis was to design the switch on Solidworks. All the parts of the switch were designed separately and combined into a single assembly. The individual parts designed for assembly are actuator (silicon), actuation amplifier (silicon), pad metal (silicon), layer on pad metal; actuator and amplification mechanism (gold), substrate (silicon), layer on substrate (silicon dioxide), trench (via cut extrude) and radiation box around design (air). Only the actuator part and voltage inputs were required for this analysis, rest of the assembly parts were suppressed. Solidworks assembly was saved in a parasolid file. The file was imported in the Ansys workbench Geometry. It was then linked to geometry in Thermal Electric analysis and Static Structural analysis. Engineering data was setup, Gold and Silicon were added in the analysis as materials. In thermal-electric model, materials were assigned to designated parts under Geometry. In Analysis setting, 5V voltage was given to one input, while other three inputs were grounded. An ambient temperature on 22 degrees Celsius was set up for the inputs Convection was setup in the silicon part. Units were set in um. For analysis results, voltage and temperature was monitored. For structural analysis, fixed support was added to the parts fixed in geometry and deformation was recorded.

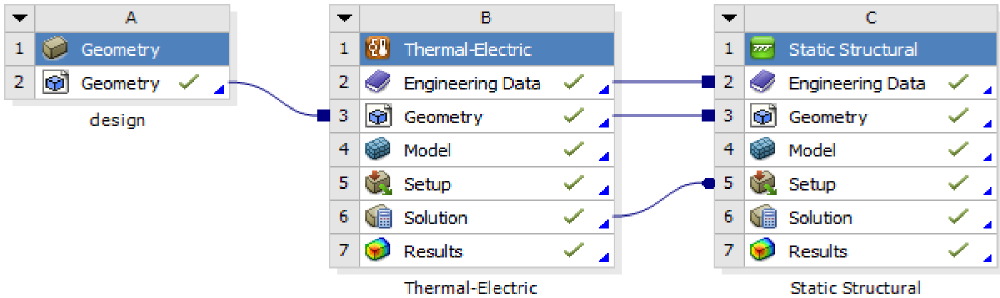

Figure 14: Electrothermal Analysis

Results obtained from this analysis give very promising values. The main reason for performing this analysis was to monitor the actuation voltage and the temperature rise in the device. The operating voltage came out to be as low as 400 mV. Maximum displacement of 637um can be achieved with 4.5 volts. The actuation and displacement were also recorded for the displacement amplification mechanism and the whole device.

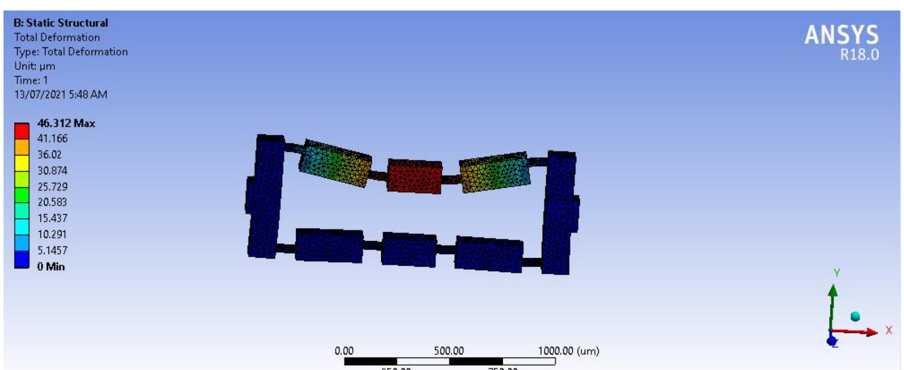

Figure 15: Displacement in amplification mechanism

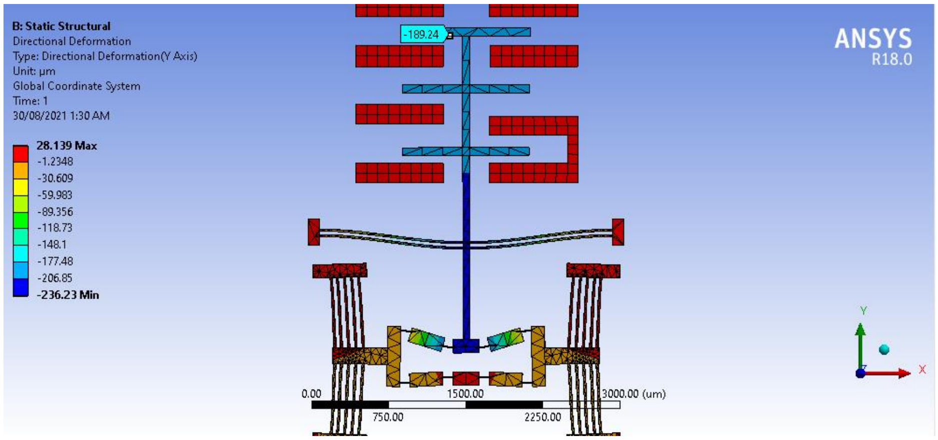

Figure 16: Displacement in whole device

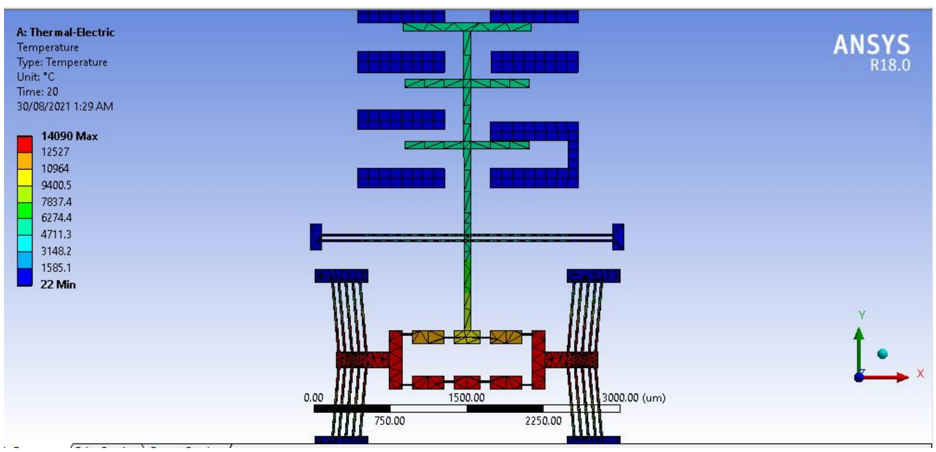

Figure 17: Temperature profile of the whole structure

4.2 Electromagnetic analysis

The electromagnetic analysis is done on Ansys workbench. Similar to electrothermal analysis, the geometry was created on Solidworks and exported as a parasolid file. Geometry of Solidworks design was modified to fit the Ansys HFSS model. Airbox was added along with silicon dioxide layer, substrate, trench and gold layer on pad metal. Actuation mechanism was suppressed since it had no functionality in Ansys HFSS model. After importing geometry into the project, materials were assigned to all the elements. Radiation was assigned to air box. Wave port excitation was assigned to inputs and outputs. Frequency sweep was added for 5G frequency band to check if this switch is capable of communications for higher 5G band or mmWave frequency regime. It was found that the operation frequency band of this device is 20-50Ghz. In dual mode, insertion loss is - 1.9 dB @30 GHz, isolation is - 87.7 dB @ 30 GHz while return loss is -2.07 @ 30 GHz. Whereas in quad mode insertion loss is - 5.3 dB @30 GHz, isolation is - 92.9 dB @ 30 GHz and return loss comes out to be -1.93 dB @ 30 GHz.

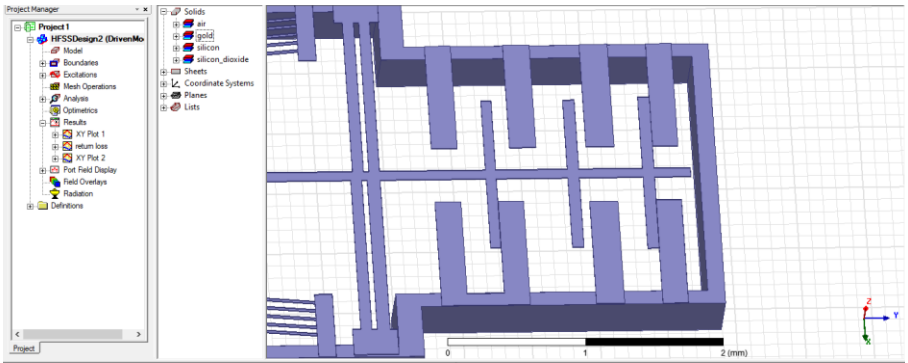

Figure 18: Electromagnetic analysis

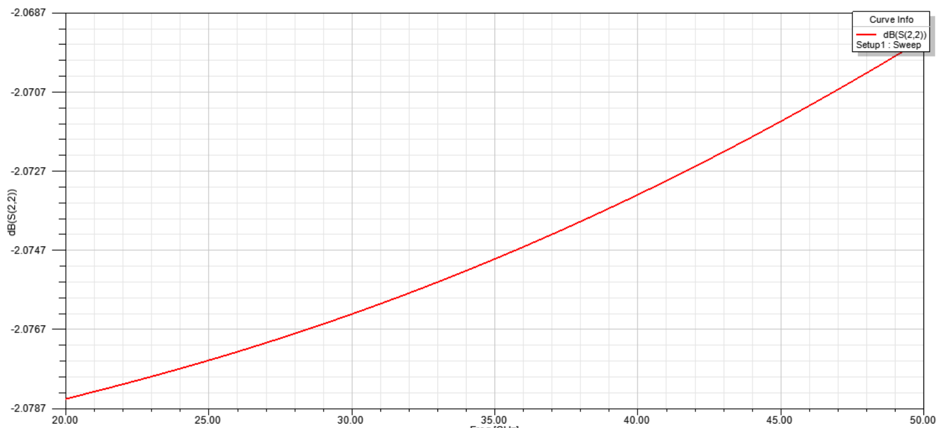

Figure 19: S11 dual mode

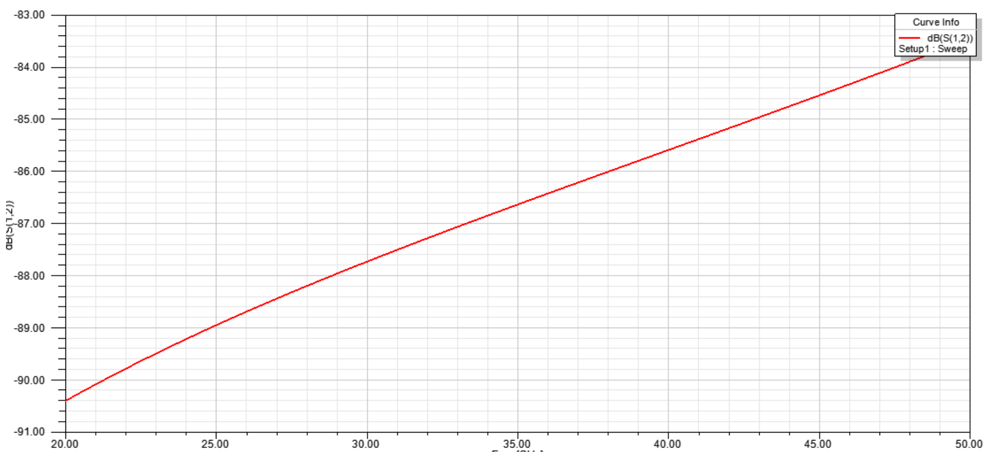

Figure 20: S21 dual mode

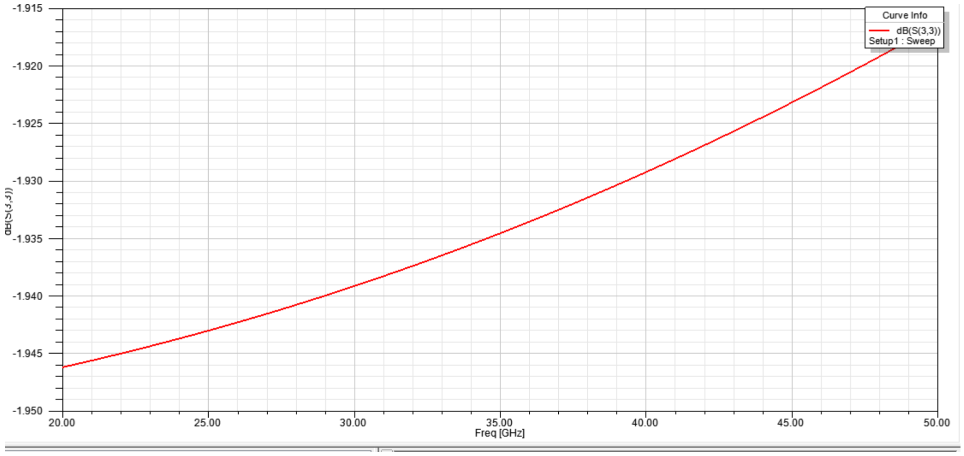

Figure 21: S11 Quad mode

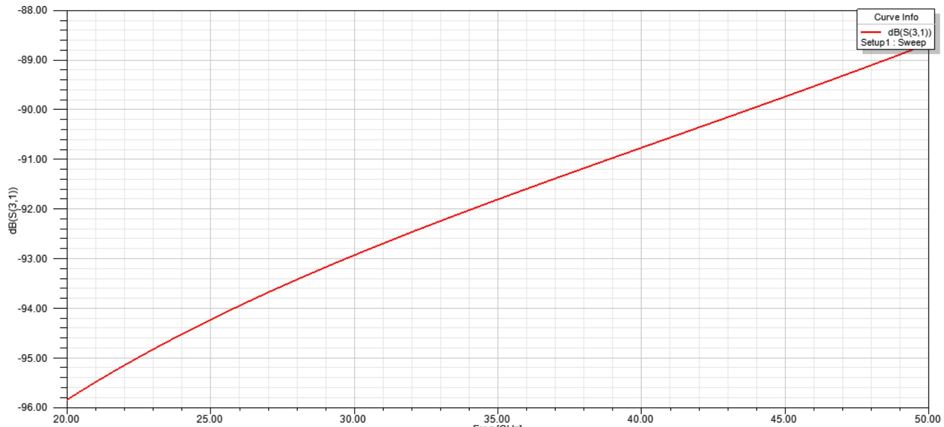

Figure 22: S22 Quad mode

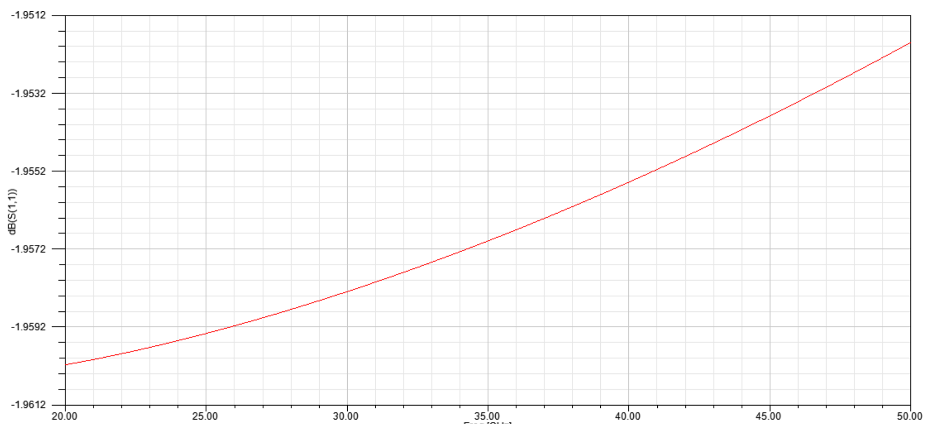

Figure 23: Insertion loss dual mode

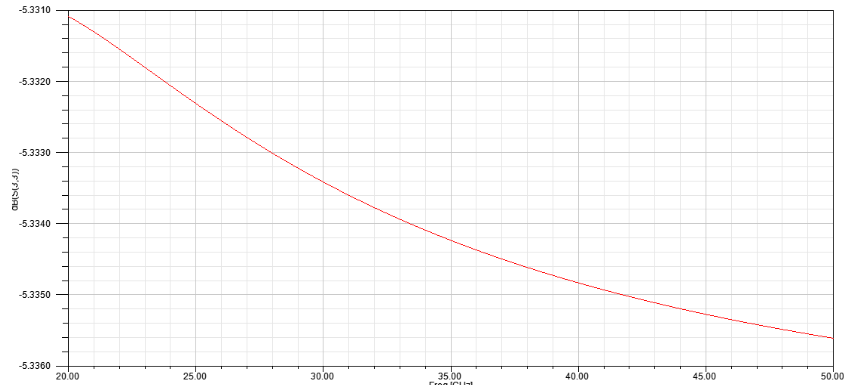

Figure 24: Insertion loss dual mode

4.3 Discussion and Conclusion

After carefully analyzing and reviewing the findings, the proposed design shows better results than any of the designs discussed in the literature. The displacement actuation mechanism shows drastically viable results and can be modeled into any design easily.

This design was modelled after the design presented by Bala et al.2017 [101]. this work discussed the fabrication of an electro-thermally actuated in-plane multiport novel RF MEMS switch, which operates in two modes. The device showed isolation loss - 50 dB @ 10.5 GHz in dual mode and around - 50 dB to - 60 dB @ 15 GHz in quad mode. The insertion loss came out to be - 2.5 dB @10.5 GHz for dual mode and - 4 dB to - 5 dB for quad mode. The operational voltage was 4.5 V. The main goal of this research was to design a switch that not only required less actuation voltage to function but also showed promising RF parameter results for the applications in the 5G frequency band. The results have been in favor of this design. A comparison of outputs for both the switches is shown in table 5.

Table 4: Comparison of proposed design with the Bala et al.2017

Bala et al.2017	**Proposed design**
Actuation voltage: 4.5 volts Maximum displacement: 2.5um Frequency band: 0-20Ghz Dual mode Insertion loss: - 2.5 dB @10.5 GHz	Actuation voltage: 0.4 volts Maximum displacement: 637um (4.5 volts) Frequency band: 20-50Ghz Dual mode

Isolation: - 50 dB @ 10.5 GHz. Quad mode Insertion loss: - 4 dB @15 GHz Isolation: - 50 dB @ 15 GHz	Insertion loss: - 1.9 dB @30 GHz Isolation: - 87.7 dB @ 30 GHz. Return los: -2.07 @ 30 GHz Quad mode Insertion loss: - 5.3 dB @30 GHz Isolation: - 92.9 dB @ 30 GHz Return loss: -1.93 dB @ 30 GHz

It is evident that the proposed design operates on a voltage as low as 400 mV as compared to 4.5 volts. While only 2.5um displacement is achieved with this actuation voltage, in the design presented in this research, the actuation achieved with 4.5 volts is 637um. This is due to the incorporation with displacement actuation mechanism. It is determined that the temperature and displacement increase with an increase in voltage. These results can be further improved by using different electrothermal actuators other than chevron actuators e.g., z-type or kink shaped. Designing and handling this switch will require a tradeoff between the displacement achieved and temperature rise due to electrothermal actuator. However more research can be done on electrothermal actuators and how they can be used in design of switches without the risk of overheating thus affecting reliability of device. Chevron actuators are characterized by an out-of-plane buckling effect, which limits their operating temperatures. Due to insufficient mask resolution and stiction problems, the fabrication of chevron actuators can be more challenging compared to other electrothermal types. The electromagnetic analysis is important to find out the RF parameters of the switch. RF parameters of any switch are the measure of its performance according to application. The analysis shows that in dual mode insertion loss and isolation of proposed design is - 1.9 dB and - 87.7 dB @ 30 GHz with return loss of -2.07 @ 30 GHz. While in quad mode return loss is -1.93 dB @ 30 GHz with insertion loss of - 5.3 dB @30 GHz and isolation of - 92.9 dB @ 30 GHz. This has improved as compared to the reference design. The RF characteristics depend greatly on the manufacturing process and subsequently on the size of electrodes, substrate, oxide and handle layers, materials used and their intrinsic properties. These parameters can be improved with a few changes in design specific to application. The results obtained cater for 5G communications requirements. Insertion loss is a bit high but that can be considered a tradeoff for low actuation voltage, good return loss and insertion loss. Results shown and discussed in chapter 9 prove that this switch is perfectly suitable for application in 5G frequency band regime. In conclusion, a novel design was proposed and analyzed. The switch utilizes low actuation voltage for electrothermal actuator used and produces increased actuation. This is achieved by combining a displacement amplification mechanism and modeling it, so it gives maximum amplification within the constraints of the device geometry. The device was designed according to SOIMUMPS. The RF characteristics were modeled so that the device is fit for application in the 5G frequency regime. Despite few drawbacks like using chevron actuators, greater size due to in plane actuation, far from ideal insertion loss; the switch shows favorable performance in terms of actuation voltage and displacement produced, the successful incorporation of an amplification mechanism within an in plane switch and its likely use in 5G applications. With this being said, further research and exploring new options has always been the most positive approach. This design like any other can be improved with extended work on actuation, 5G and technology advancement.

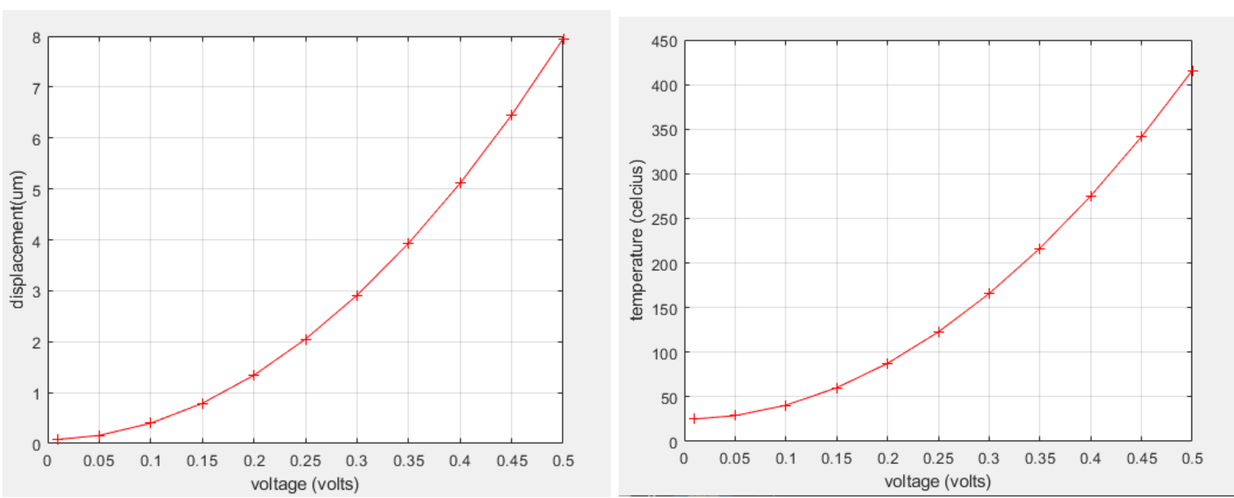

Figure 25: Increasing voltage vs a) output displacement b) temperature

APPENDIX A

Optimization of Displacement Amplification mechanism

Using design of experiments, the parameters of the displacement amplification mechanism were optimized in MATLAB using the following code

```
length=[150 200 250 200 250 200 200 100 150 200 200 200 200 300 200 ...
   200 150 200 150 250 150 250 250 150 200 250 150 250 250 200 150];
l=[50 100 150 0 150 100 200 100 50 100 100 100 100 100 100 100 150 ...
   100 50 150 50 50 50 150 100 50 150 50 150 100 150];
h=[25 50 25 50 75 50 50 50 75 50 50 50 50 50 100 0 75 50 75 25 25 75 ...
   75 75 50 25 25 25 75 50 25];
t=[5 20 15 10 5 10 10 10 15 10 10 10 10 10 10 10 5 10 5 5 15 15 5 15 0 ...
   15 5 5 15 10 15];
l1=length+l;
h1=3*h;
up=h1.*l1;
t1=t.*t;
h2=h.*h;
h2=3*h2;
down=t1+h2;
Ramp=up./down;
T = table(length.',l.',h.',t.',Ramp.');
f = figure;
data= [length.' ,l.' ,t.' ,h.' ,Ramp.'];
colnames = {'L', 'l', 't' , 'h' , 'Ramp'};
t = uitable(f, 'Data', data, 'ColumnName', colnames);
```

Optimization of Chevron Actuator

Chevron actuator was modelled by creating a function of force in terms of theta. The relation was analyzed in MATLAB with the following script.

```
k=1.6665;
for x=0:0.01:10
    si=sin(x).^2;
    co=cos(x).^2;
    f=(k*cos(x))/((si/2.978)+co);
  plot(x, f, 'bo-', ...
  'LineWidth', 1, 'MarkerSize', 1, ...
  'MarkerFaceColor', 'r')  hold on
end
```

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