Modeling and Optimisation of Multi-Port Compact RF MEMS Switch Matrices

Dissertation – II

Submitted in partial fulfilment of the requirement for the award of the

Degree of
Master of Technology
in
VLSI Design

by

SUKHDEEP SINGH
Regd. # 11310578

Under the Guidance of
MR. TEJINDER SINGH

School of Electrical and Electronics Engineering
Lovely Professional University
PB, India

April 2015

LOVELY PROFESSIONAL UNIVERSITY

Transforming Education, Transforming India

School of: Electronics & Electrical Engg.

DISSERTATION TOPIC APPROVAL PERFORMA

Name of the Student: Sukhdeep Singh

Registration No: ~~11301750~~ 11310578

Batch: 2013

Roll No. ~~A05~~ A19

Session: 2014-2015

Parent Section: E2310

Details of Supervisor:

Designation: Asst. Prof.

Name: Tejinder Singh

Qualification: M. Tech

U.ID 18700

Research Experience: 2 Yrs.

SPECIALIZATION AREA: ______________________ **(pick from list of provided specialization areas by DAA)**

PROPOSED TOPICS

1. Modeling and Optimization of Multi-Port Compact RF MEMS Switch Matrices
2. Design, Modeling & Analysis of Compact Multi-Port RF MEMS Switch Matrices.
3. Optimization of RF MEMS Switches for Switch Matrices.

18700

Signature of Supervisor

PAC Remarks:

Approved

APPROVAL OF PAC CHAIRPERSON: Signature: Date: 30/10/14

*Supervisor should finally encircle one topic out of three proposed topics and put up for approval before Project Approval Committee (PAC)

*Original copy of this format after PAC approval will be retained by the student and must be attached in the Project/Dissertation final report.

*One copy to be submitted to Supervisor.

Modeling and Optimisation of Multi-Port Compact RF MEMS Switch Matrices

A Dissertation Submitted
in partial fulfillment of the
requirement for the award of the
Degree of
MASTER OF TECHNOLOGY
By
Sukhdeep Singh

Under the Guidance of
Tejinder Singh

April 2015

Abstract

Co-planar waveguide (CPW) lines are the crucial components for the designing of any RF system. RF signal propagates in CPW lines. There are many circuit components for CPW like bends, junctions, air bridges and crossovers that should have proper impedance matching to propagate the signal without any loss. We have designed the required CPW components for the integration of RF MEMS switches for switch matrices. We have optimized the CPW bends, air bridges, crossovers and junctions to match the impedance with rest of the circuit to avoid any excess loss in signal. We have optimized the dimensions of these components for characteristic impedance of 50 Ω. A comprehensive idea is presented that how the propagation of RF signal varies with dimensions and how to avoid that. For any RF system, high RF performance is the most importanct factor and this is applicable for RF MEMS switches also. We have simulated the designed structures and achieved better performance with maximum magnitude of reflection coefficient less than 0.02, 0.055 and 0.015 till 60 GHz for bend, crossover and T-junction respectively. In the present satellite communication systems, there is a wide scope to replace many of the radio frequency components with the Microelectromechanical Systems (MEMS) technology. MEMS switches are essentially miniature devices that use a mechanical movement to achieve a short circuit or an open circuit in a transmission line. MEMS switches for low-frequency applications have also been demonstrated in the earlier times. Since the RF MEMS components have the potential to substantially reduce weight, size, and the power consumption. One of the major application of RF MEMS switching networks is in communication systems. Switching networks are used in virtually every communication system and include SPNT (single-pole N-throw) switches for filter or amplifier selection, NxN switching matrices, and general SPDT (single-pole double-throw) and DPDT (double-pole double-throw) routing switches. In present satellite systems, most of the switching networks are built using coaxial switches, while PIN diodes

are used in the base-station systems except after the power amplifiers. Although, PIN diode switches are much less expensive than coaxial switches, but require input and output amplifiers to compensate for the loss introduced by the switching network. Outstanding result in terms of isolation and insertion loss are key features of the coaxial switches. The coaxial switches generate very low intermodulation products and these can handle a lot of RF power. Due to these advantages, they are the preferred switches for high-performance or high-power applications. Generally, a typical satellite system has 100-300 switches depending on the configuration, and the switching networks can easily cost in the millions of dollars per satellite. RF MEMS switches can easily provide the isolation requirement of N×N switching matrices, but it shows slightly higher loss due to their contact resistance. However, they result in much lighter and smaller systems which is essential for satellite applications. Moreover, the performance of the RF MEMS is also superior as compared to that of the current technologies. Switching networks are used as basic building blocks in network payloads. Apart of functionality to provide Connections, switching networks also enhance the performance of network. Building block is fundamental part of network on which whole performance of the network depends, so all building blocks should be optimized such that we can get better performance from whole network. Various building blocks have been designed to generate a final interconnect network. Various simulations show insertion loss better than 0.5 dB. All simulations shows isolation and return loss better than 30 dB and 20 dB respectively at worst.

Acknowledgements

I would like to offer my heartiest salutation to the Almighty God for unbroken health and courage bestowed upon me in all the adversities at every step and at every moment throughout the entire span of my studies and in every aspect of my life. It is matter of great pleasure for me to submit Dissertation-I on Modeling and Optimisation of Multi-Port Compact RF MEMS Switch Matrices, as a part of curriculum for award of Master of Technology (VLSI Design) degree of Lovely Professional University (Punjab). I am highly indebted to my thesis advisor Mr. Tejinder Singh for his constant encouragement and able guidance without which this work was not possible. It is my pleasure to be thankful to various people, who directly or indirectly contributed in various ways in preparing this Dissertation. Lastly, I would like to thank my parents for their moral support and my friends from whom I received lots of suggestions that improved my quality of work.

Certificate

This is to certify that the Dissertation-Il titled *"Modeling and Optimisation of Multi-Port Compact RF MEMS Switch Matrices"* that is being submitted by "SUKHDEEP SINGH" is in partial fulfillment of the requirements for the award of degree, *Master of Technology in Very Large Scale Integration*, is a record of bonafide work done under my/our guidance. The contents of this thesis, in full or in parts, have neither been taken from any other source nor have been submitted to any other institute or university unless otherwise cited for award of any degree or diploma and the same is certified.

Dissertation Supervisor

MR.TEJINDER SINGH

Asst. professor

Dept. of Electron. Elect. Engg.

Lovely Professional University

Phagwara, 144 402, PB, India

Email: tejinder.18700@lpu.co.in

Objective of the dissertation [   ] SATISFACTORY / [   ] UNSATISFACTORY

Examiner I **Examiner II**

Certificate

This is to certify that Mr. Sukhdeep Singh, bearing registration no. 11310578 has completed objective formulation of thesis titled, *"Modeling and Optimisation of Multi-Port Compact RF MEMS Switch Matrices"* under my guidance and supervision. To the best of my knowledge, the present work is the result of his original investigation and study. No part of the thesis has ever been submitted for any other degree at any University.

Dissertation Supervisor

MR.TEJINDER SINGH

Asst. professor

Dept. of Electron. Elect. Engg.

Lovely Professional University

Phagwara, 144 402, PB, India

Email: tejinder.18700@lpu.co.in

April 25, 2015

Declaration

I, Sukhdeep Singh, student of *Master of Technology* under *Department of Electronics and Communication Engineering* of Lovely Professional University, PB hereby declare that this thesis titled, Modeling and Optimisation of Multi-Port Compact RF MEMS Switch Matrices and the work presented in it are my own. I confirm that:

- This work was done wholly while in candidature for a masters degree at this University.
- Where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated/cited.
- Where I have consulted the published work of others, this is always clearly attributed.
- Where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work.
- I have acknowledged all main sources of help.
- Where the thesis is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself.

SUKHDEEP SINGH

Grad. Research Student,

Dept. of Electron. Elect. Engg.

Lovely Professional University

Phagwara, 144 402, PB, India

Email: mr.sukhdeep.saini@ieee.org

To my parents.

Contents

List of Tables

List of Figures

Chapter 1

INTRODUCTION

Microelectromechanical systems (MEMS) technology can be considered to have a potential to replace many of radio frequency (RF) components as a part of present satellite communication systems [5, 6]. The RF MEMS components have the potential to substantially reduce weight, size, and the power consumption. The RF MEMS also show superior performance as compared to that of the current technologies [7, 8]. The MEMS technology shows commendable benefit for switch matrices. The switch matrices comprise of a large number of switching elements, therefore any small reduction in size and mass would have large overall impact. Moreover, RF MEMS switches with billions of switching cycles have been demonstrated .In recent decades, there is a massive evolution of Microelectromechanical systems (MEMS). The MEMS are extensively exploited in several fields such as redundant and broadcast systems. In the RF/microwave field, RF MEMS switches are the most burgeoning MEMS. These include both types of configurations: contact and capacitive. RF MEMS switches show the advantages of both semi-conductor switches and mechanical switches which leads to make RF MEMS as an emerging field. Good RF performance posses a low inter- modulation distortion [8] is demonstrated by small sized RF MEMS switches. There are several designs available in the literature for the construction of MEMS switches. This design of switch showed an excellent isolation of 75dB and noticeably a low insertion loss of 0.13 dB at 28 GHz [?]. The switch matrix provides all possible combinations of routes between N input signals to N output signals. Sophisticated redundancy switches are required on much priority for the satellite applications. These switches are providing sophisticated redundancy as these are being used as microwave switches. The decision on the integration pattern of redundancy switch matrix with a large size arises a major problem while integration [9]. This problem is being overshot by using SPNT switches. However, the use of multiport R-type, T-type and C-type of switches considerably simplifies the integration problem of such redundancy switch matrix [10, 11]. An intensive literature survey presents the following key points to be considered while designing several building blocks so as to improve system performance: 1) CPW circuits can be made even denser and these circuits present a facility to design wideband components. 2) RF MEMS switches provide advantages of both mechanical and semi-conductor switches. 3) The integration problem of redundancy switch matrix is considerably simplified by using multiport R-type, T-type and C-type. In order to utilize these advantageous features explained above, there is a need to design various building blocks with due care. In this paper, various building blocks are optimized. These building blocks are further used together to form switches namely R-type, T-type and C-type [12],[10].

Switching networks are essential components that are used in modern communication applications. It provides full flexibility to enhance the capacity of satellite. Interconnect network provides routing of signal from N input ports to N output ports. Satellite beam linking systems vastly rely on switch matrix functionality to manage traffic routing and for optimum utilization of system bandwidth. Microwave switch matrices are used as building blocks in satellite communication systems [5, 6]. More importantly, they enable the ability to optimize bandwidth usage for beam linking systems [13]. Semiconductor and MEMS switches are two prominent candidates for

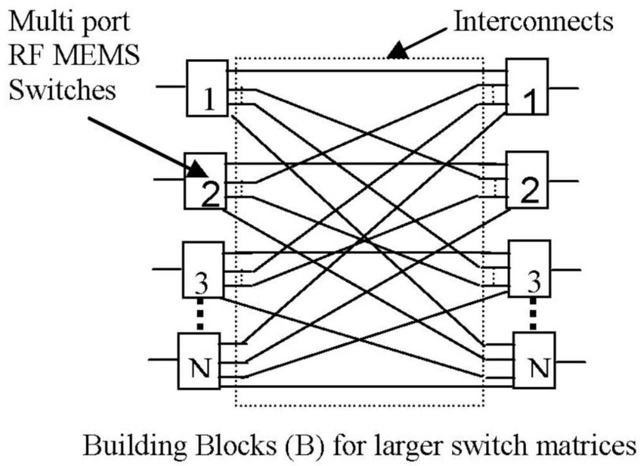

Figure 1.1: Schematic of N*N switch matrix.

realizing such type of switch matrices. Therefore, the interconnect network bas to be amenable to integration with these switching elements. In addition, signal transmission and isolation of the interconnect lines are key factors for successful design of the switch matrix.

1.1 MEMS and conventional technologies

The mechanical switches (coaxial and waveguide) and the semiconductor switches (p-i-n diode and FET) are the most common RF switches used in microwave industry now a days. Mechanical switches (coaxial and waveguide) leads to the benefits of large off-state isolation, low insertion loss, and the high power handling capabilities. Moreover, these are highly linear. However, they are heavy, bulky, and slow [8]. The semiconductor switches provide a much faster switching speed, and are smaller in size and weight. But semiconductor switches are inferior in terms of the isolation, dc power consumption, insertion loss, intermodulation and power handling. MEMS switches facilitate the combined advantageous properties of both the semiconductor and mechanical switches. MEMS switches offer the low weight and small size features of semiconductor switches along with low DC power consumption and better RF performance and of mechanical switches [14, 15, 16].

	FET	p-i-n diode	Mechenical	MEMS
dc Power	0	10 mW	0	0
Isolation	Low	Medium	High	High
Size(mm^2)	small	Small	Large	Small

Table 1.1: Comparison between conventional switches and MEMS.

Most of the MEMS switches are actuated by the electrostatic forces which leads to the near-zero power consumption, since there is no current flow. MEMS switches result in excellent isolation by using air gaps for OFF state. MEMS also offer an advantage of being a very linear devices with very low intermodulation products. Table 1.1 gives a comparison between MEMS and its other counterparts highlighting the benefits.

RF MEMS technology is also having some shortcomings. Earlier life time was one of the concerns, but nowadays it has been widely addressed by researchers indicating millions of switching cycles. MEMS can be used in applications to a few watts, as MEMS switches can handle low to medium power levels. In order to widen use of MEMS technology in the satellite payloads, their power handling level needs to be increased [17]. Packaging is also another topic of study for MEMS switches, in concern with switch matrices having large number of moving elements and RF ports. RF performance deteriorated by the conventional hybrid packaging techniques, overshadows the benefits of MEMS technology. Monolithic packages showing better performance would result in more benefits [18]. The matrix is formed by the integration of the solid-state SP2T switches and a multilayer printed circuit board (PCB) interconnect network.This switch matrix results in a smaller and lighter alternative but it exhibits a very high insertion loss, hindering its use in the appearing satellite switching applications.

1.2 RF MEMS switch matrix applications in the satellite industry

There are two switch matrix applications serving the opposite extremes of the switch market. The spacecraft applications need the highest switching performance and MEMS technology can provide commendable benefit in the area of reducing mass and volume. On the other hand, the wireless handheld devices need low-cost devices and the MEMS technology can provide benefits in the area of DC power and insertion loss reduction. During the signal processing, the signal passes through four sets of the switch matrices, out of which, three sets operate at a low power and can be replaced by RF MEMS technology. The RF switch matrices result in the system redundancy for the payload against receiver or high power amplifier failures. If there is any failure, the signal is rerouted by the switch matrices, to spare component located in the system and hence maintain full functionality of the system. Satellite communication systems also rely on switch matrices to provide system redundancy and to enhance the satellite capacity by providing full and flexible interconnectivity between the received and transmitted signals. The switch matrices also provide system redundancy for satellite communication systems. It also provide full and flexible interconnectivity between received signals and transmitted signals, and hence enhance satellite capacity [19].

1.3 General design consideration

RF MEMS switches are the basic building blocks in RF MEMS switch matrices. On applying voltage between beam and electrode, an electrostatic force is applied and beam is pulled down. The following equation is used to estimate the actuation voltage of such design [19]:

$$V_p = \sqrt{\frac{8K}{27\epsilon_o W w} g_o^3} \tag{1.1}$$

where k represents the spring constant of beam, A represents the common area between beam and electrode, and d^3 is the distance between beam and electrode. For a typical cantilever beam with a large electrode, the spring constant due to a uniform force applied over the entire beam can be approximated by:

$$K = \frac{2Ew}{3}(\frac{t}{l})^3 \tag{1.2}$$

where E is the Young's modulus o beam material, t is thickness of beam, w is width of beam, and l is length of electrode. The actuation voltage should be reduced while maintaining reasonable restoring force. These equations are a good starting point and the designing should continue with the optimization of the individual switch basic building blocks, the interconnects and entire matrix integration. During designing the various stages of RF MEMS switch matrices, advanced design and simulation tools are used for optimization of the RF performance and the mechanical behaviour simultaneously. In multi-port configurations, such as RF MEMS switch matrices with multiple mechanical actuators and several multi-port switches, this issue is very noticeable. Nowadays, vastly used software package is ANSYS for mechanical optimization of individual MEMS beams and High Frequency Structure Simulator (HFSS) for RF performance. Micro-fabrication compatibility is another important issue which should be kept in mind while designing. The RF requirements such as low loss and high conductivity must be satisfied. Fabrication process using Gold and based on low-loss substrate would be considered as a good candidate for switch matrix development.

1.4 Switching time

In single MEMS switches, the switching time is mostly dependent on the mechanical response of actuating beams. In switch matrices, it is also highly dependent on the material biasing line. This is because of the long and complex DC bias routing which is required to actuate the individual beam and also its effect on increase of RC delay. It is noticeable that while selecting the material for bias network, a tradeoff occurs between the switching speed and RF performance of the matrix. The selection of high resistivity material for bias lines generally results in improving the RF response while at the same time the speed is deteriorated. Although these RF MEMS switches have relatively slow switching time, still such switching speeds could meet several redundancy applications.

1.5 RF MEMS redundancy switch matrices

As shown in Fig. 1.2, the SPDT and switch cells are divided into subsections, in order to achieve effective RF performance and wideband operation. The sub circuits are: RF MEMS single-pole single-throw (SPST) switch, an RF crossover, a 90°bend, and t-junction. In order to attain the desired characteristics each of these sub circuits is designed in an optimized way. Coplanar waveguide technology provides an approach of scalable designing pattern, hence it is suitable for miniaturisation purposes. It provides low dispersion, thus a suitable technology to be used for broadband applications. For minimising loading effect, a single double ended switch consisting of two SPST switches connected back to back. A 90°bend is employed between two SPST switches. C type,R type and T type switches are basically used in various configurations of switch matrices. Several states of switches and their operations are as presented below in fig.1.3, 1.4 and 1.5. The SPST switch shows an effective performance in the development of switch matrix. In [8], Rebeiz presented a number

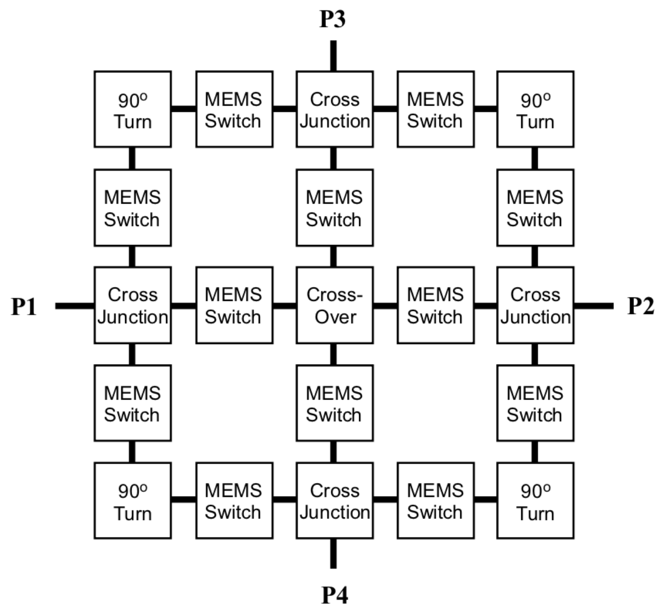

Figure 1.2: Various building blocks having T-junction, 90°bend, RF switch and a crossover.

of contact type configurations. Among these configurations, the cantilever contact type has proven to provide the broadband operational bandwidth. High performance cantilever contact type switches are employed as the switch matrix [20], however multiple beams with the requirement of similar characteristics and simultaneous operations are used. While designing a switch matrix, it is highly important to provide isolation between the various ports used for the wideband operations. The isolation in the several states of switches occurs because of coupling in the crossovers. In switch matrix designing operating bandwidth needs to be broadband since it is a crucial parameter. Although a broadband capability is provided by using RF crossover and MEMS switch, T-junction leads to be the most challenging circuit in determining the operational frequency. In the past decade, the major portion of the published work in the field of RF MEMS switches has been done for designing the SPST switches [21, 8] . More recently, research work has been carried out for T-type, R-type and C-type of RF MEMS switches [10, 11].

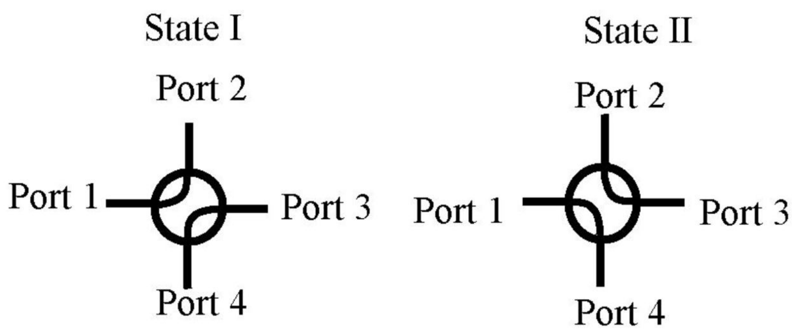

Figure 1.3: States of C type switch. State 1; Port 1 and port 2, port 3 and port 4 are connected and state 2; Port 1 and port 4, port 2 and port 3 are connected.

1.5.1 C type switch

For satellite applications, there is a requirement of switch matrices which are sophisticated redundancy switches. C type switches are also known as transfer switch. These switches are used as microwave switches hence providing sophisticated redundancy. There are two type of operational states for these switches. These are as shown in fig.1.3. In state l, ports 1 and 2; port 3 and 4 are connected with each other. To maintain the proper system functionality there is an arrangement to modify the switching state 1 to change the signal path towards the spare components during any failure.

1.5.2 R type switch

As shown in fig.1.4 there are three operational states for r-type switch. The advantage of one more state then c-type switch makes the r-type switches more superior as compared to c-type as there is a considerable reduction in the number of building blocks for switch matrix. Hence, the overall topology is simplified to a large extent.

1.5.3 T type switch

There are four ports and three signal paths in t-type switches. There are three operational states possible based on the connectivity of the ports as demonstrated in

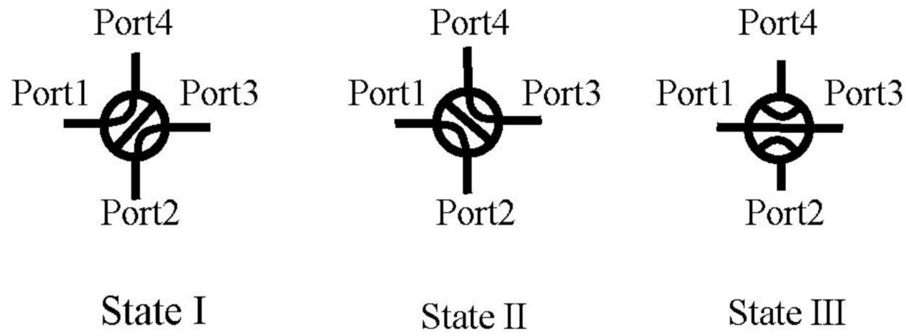

Figure 1.4: States of R type switch. State 1; Port 1 and port 4, port 2 and port 3 are connected, state 2; Port 1 and port 2, port 4 and port 3 are connected and state 3; Only port 1 is connected to port 3.

fig.1.5. In each state two pairs of ports are connected simultaneously, hence providing two conducting paths. In state l, the connectivity is established between the pairs of 1, 3 and 2, 4 ports. In second state, ports 1, 4 and 2, 3 get connected with each other in respective pairs.In state lll, the RF signal crossover occurs and ports 1, 2 and 3, 4 are connected. The switches close in each state based on the state definition in state l; the SPST switch between port 2, 4 and 1, 3 gets closed. The various states are named based on the connectivity of ports. It is noticeable that none of these states can be used interchangeably. One of the major problem faced in integration of large sized redundancy switch matrix is deciding its integration pattern [9]. The use of SPNT switches overshoots this problem. However, the integration problem of such redundancy switch matrix is considerably simplified by using multiport r-type and c-type of switches [10]. Although t-type switches provide an appreciable degree of flexibility in the view of redundancy network. This is considered to be the major benefit of t-type switches. Another advantages of t-type switches are: good isolation for a broad band width operation and simple switch matrix design. Moreover, t-type switch provides even more and unique path combinations in case the path failures happen. But t-type switch has a drawback of asymmetry while switching operation which badly affects the operational bandwidth.

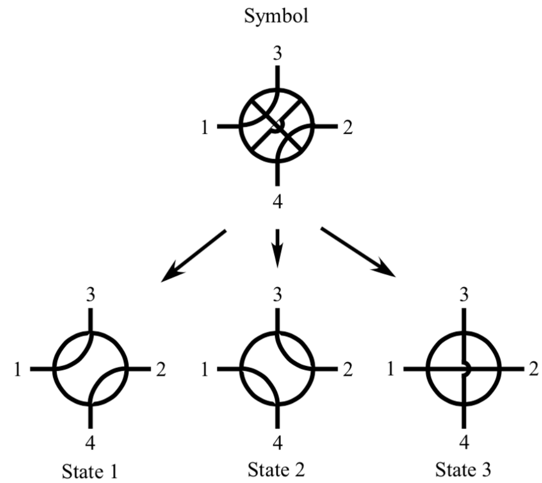

Figure 1.5: States of T type switch. State 1; Port 1 and port 3, port 2 and port 4 are connected, state 2; Port 1 and port 4, port 2 and port 3 are connected and in state 3; Port 1 and port 2, port 3 and port 4 are connected.

Varied open path lengths will be seen for an RF signal while it traverses from one port to another and hence four open paths are followed. Thus, it leads to a significantly different capacitive loading. The overall value of characteristic impedance varies from 50 Ω due to the capacitive loading experienced at the cross junction of the four ports. Therefore, the performance starts degrading with an increase in the operational frequency, as this leads to a degradation of insertion loss and thus, the deviation of overall impedance from 50 Ω continues. Hence the losses keep on increasing.

Conclusively, there is a need to develop such a schematic that at 4 port cross junctions, any RF signal can have symmetric open paths. As reported in [11], we can achieve this schematic by employing 2 individual SPST switches in each of the path. Hence, it shows that total 12 switches are needed to make six signal paths operational as per the state configuration described in the system in Fig. 1.2 [22].

Fig. 1.2 shows a schematic realization of a T-type switch. It constitutes of 4 four-port cross junctions, 1 RF crossover, 12 single ended SPSTs, 4 90°bends in the turn paths. In each arm, SPST switches are placed in a symmetrical manner in order to achieve open stub length symmetry for all switches in off states. [11]

Chapter 2

LITERATURE REVIEW

2.1 Crossbar Switch Matrix Topology

A flexible switch matrix design is provided by using switch matrix having switch cells. This approach is similar to memory array designs used conventionally. In Fig. 2.1, a crossbar topology is shown. The size of matrix is easily adjustable by addition of columns and rows in the matrix. A switch matrix with dimensions 4×4 can be expanded to dimensions 5×5. The idea behind expansion of dimensions is to simply add extra rows and columns. Hence, the advantage of using crossbar switch matrix relies on the expansion of dimensions. There is similarity in the operation sequence of RF crossbar microwave switch and the traditional DC counterparts. However broadband and high frequency circuit are designed. The two operational states of switch cell are needed for proper crossbar functionality. These states are Turn and Thru, as shown in Fig. 2.1. A 90 °rotation for input is provided in Turn state operation. However, in Thru state, in the same cell, two input signals are cross over. In Turn state, ports 2 and 3 are kept floating, while only ports 1 and 4 are having connections, while in Thru state, ports 1, 2 and 3, 4 are connected in pairs. An array of switching units connecting horizontal and vertical input and output ports

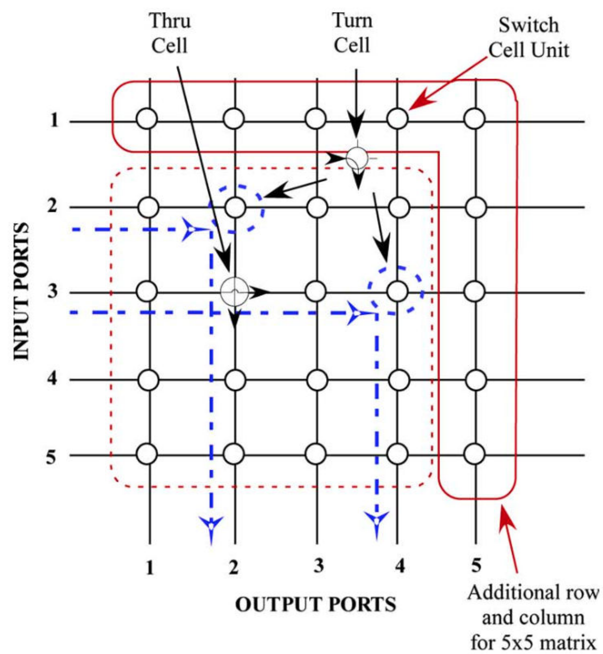

Figure 2.1: RF MEMS crossbar switch matrix topology [1].

are used in the circuit. The purpose of each unit is to either connecting input with output or connecting them to ports designated in the adjacent units. The major advantage of this method is the feature of expanding matrix dimensions by easily adding extra rows and columns. Secondly, simple planar transmission lines are used to make interconnection network. Hence there is no need of multilayer complex interconnection network. In fig. **??**, configuration of switching unit is depicted. The component structure employs 3 SPST switches and a crossbar switch. During one state, switch S2 is in ON state while switches S2 and S3 are in OFF state. Thus the connection and isolation of input and output states are provided. During second state, Switches S1 and S3 are in ON state and provide transition of input as well as output ports to intended adjacent unit cells.The isolation switch S1 or S3 at the last column or row are removed to further simplify the structure [23, 24].

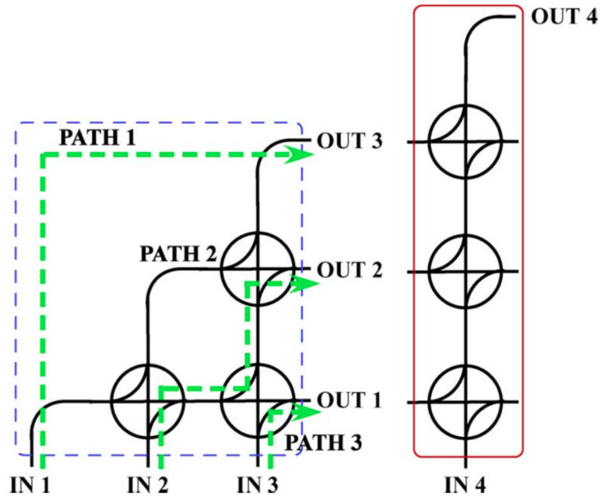

Figure 2.2: RF MEMS staircase switch matrix topology [2, 3].

2.2 Staircase Switch Matrix Topology

The operational bandwidth of Staircase Switch matrix design is smaller in comparison to crossbar. The physical size of matrix is relatively larger and it shows limited RF performance. However, in [25, 24], crossbar designs offered good RF performance, wideband operation and matrix size expansion capability. However, many control signals are needed due to limitations of crossbar design. In [25, 24], a single unit requires two control signals. As per citechan2009scalable, the total number of control signals is

$$2(N^2 - 1)$$

in case of N × N switch matrices. Hence it is less practical or the cases where N ¿ 5. A staircase matrix topology is solution for such problems. It is as illustrated in Fig. 2.2. In [2], mathematical prove for this proposed topology is illustrated. Similar to crossbar matrix, this topology presents the expandable characteristics and hence it can provide any number of connections between the input and output ports. A semi-T switch is used to develop an RF microwave staircase switch matrix.

2.3 L Matrix Topology

Although design flexibility and efficient RF performance is offered by crossbar switch matrix, the longest and shortest path are out of phase with a huge difference. For various applications, e.g. beam forming networks, problems may arise due to large insertion loss and phase difference between different paths. Thus it results in increasing the complexity of the system. An L-matrix topology is a solution for such problems. This topology was introduced by Yeow cite997361 in switch matrix. Then, K. Y. Chan [1] also showed the use of L-matrix topology. In order to attain more uniform phases and path losses for all paths, the original idea presented the use of double-sided MEMS mirrors as well as single sided MEMS mirrors in conjunction with each other. L-matrix topology is almost similar to crossbar, as said by Yeow et. al., as its expansion is done by addition of extra cells in switch matrices. It is noticeable that L-matrix topology introduces even order dimensions only.

The RF microwave applications employ the L-matrices concept. In Fig. 2.3, an example of L-matrix proposed in microwave form, is shown. Larger matrix dimensions are easily achieved by addition of extra cells around the output as well as inputs of L matrix topology. An example in shown in Fig. 2.3, it presents the expansion of 4×4 Matrix to 6×6 Matrix versions. Previously proposed and designed SPDT and switch cell are being used. The research shows that there is a need of additional cell which has 2 turn states. This additionally introduced cell is labeled as semi T switch [2].

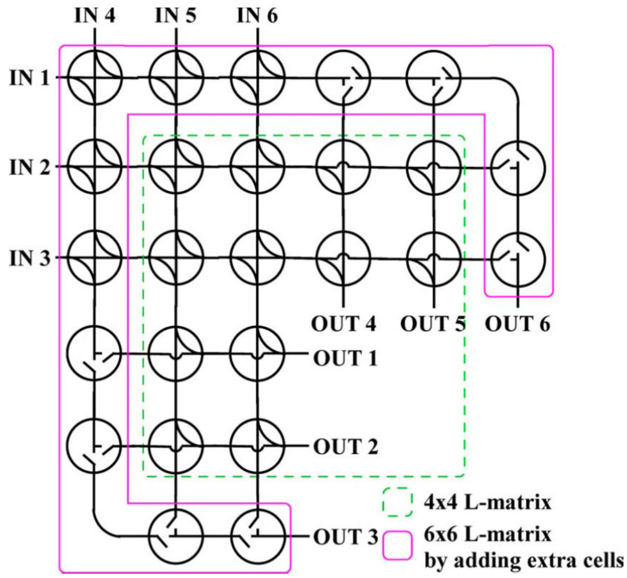

Figure 2.3: RF MEMS L matrix topology [4, 1].

2.4 Review summary

2.4.1 A Novel Integrated Interconnect Network for RF Switch Matrix Applications

M. Daneshmand et. al. presented a new integrated RF interconnect network. The circuit was printed on a double sided alumina substrate, hence eliminating the need to use the multilayer manufacturing technology. Finite Ground Coplanar (FGC) lines and vertical 3-via transitions are employed in the interconnect network. These interconnect network can be easily integrated with MEMS switches and semiconductor in order to form switch matrix. They also presented simulation and experimental results for a 3x3 interconnect network. An isolation of better than 40 dB up to 30 GHz and a return loss of -20 dB are shown [26].

2.4.2 Design and Optimization of RF MEMS T -Type Switch for Redundancy Switch Matrix Applications

Soumendu Sinha et. al. presented a novel approach to monolithically implement a planar multiport RF MEMS T -type switch. T-type switches are used as building blocks for redundancy switch matrix applications in space telecommunication. In space telecommunication redundancy switch matrix applications, the basic building blocks are are T-type switches. There are three operational states to perform signal routing with T-type switch. One of them is a crossover state and other two are turning states. They proposed a design using a series metal contact clamped-clamped beam SPST switches, a RF crossover and four port cross junctions. A return loss of better than -l5.50dB, an isolation better than 17.73dB for all states across frequency range 0-30GHz and an insertion loss of -0.46dB was demonstrated for the entire T-type switch. An excellent RF performance is shown by the switch near Ku-band and X band of frequencies [27].

2.4.3 Design of a RF NEMS Switch Matrix

Eugene Siew et. al. presented the development of a monolithic RF NEMS switch matrix for the first time. They designed and simulated a prototype 3X3 monolithic switch matrix at the nano-scale level using Ansoft HFSS and Agilent ADS. The results obtained from simulation show that the proposed NEMS switch matrices are capable of functioning up to 60GHz with good RF performance. It presented isolation of at least 78dB, return loss of at least 20dB and insertion loss of 0.58dB (at most). The proposed design proved to be at least 10, 000 times more compact than the RF switch matrices reported previously. Larger matrices can be made by expanding 3X3 NEMS switch matrix using Clos network [28].

2.4.4 Integrated Interconnect Networks for RF Switch Matrix Applications

Mojgan Daneshmand et. al. presented two new types of integrated RF interconnect networks. The circuit was printed on a double sided alumina substrate, hence eliminating the need to use the multilayer manufacturing technology. Finite Ground Coplanar (FGC) lines and vertical transitions are employed in the interconnect network. These interconnect network can be easily integrated with MEMS switches and semiconductor in order to form switch matrix. Theoretical and experimental investigation of a wide-band 3x3 interconnect network utilizing single and double three-via vertical transitions was done. The measured results show an isolation of better than 40 dB up to 30 GHz and a return loss of 20 dB. A via less double-sided interconnect network for satellite band applications is also studied and optimized. A process using only the front and the back pattern metallization is used for this type of network. The measured results indicated an isolation of better than 45 dB and a return loss of better than 17 dB [29].

2.4.5 Investigation and Optimization of Transitions in an LTCC based RF MEMS Switching Matrix for Space Applications

Taeyoung Kim et. al. introduced optimized and compensated transitions for use in an LTCC circuit combining it with RF MEMS switches for frequencies up to 20 GHz. New designs and improvements were introduced and the sensitivity performance of whole circuit with these components was investigated. Big switching matrices for communication purposes in space applications are used to combine several inputs with corresponding outputs. Mechanical switches, which are reliable, but heavy and bulky are used in the switch matrix approach. RF MEMS switches are employed in new approaches as these are small, lightweight and extremely linear and also do not need much power. Much more flexibility together with compact elements is given by a modular approach [30].

2.4.6 Miniature RF MEMS Switch Matrices

A. A. Fomani et. al. reported a novel miniature-size switching unit as the building block application of multiport switch matrices. The constituent of the cell are 3 cantilever-beam contact type MEMS devices coupled to CPW transmission lines. In the path of signal, there was a single MEMS switch inducing a similar loss in all switching states. A six-mask fabrication process was used for constructing the entire system. A 4X4 switch matrix measuring 1.45 X 1.45 mm2 dimensions was build by using the switching unit. The system presented an excellent RF performance with the worst-case return loss, insertion loss and isolation of -17dB, -1.8dB and 26dB up to 40GHz, respectively [31].

2.4.7 Miniaturized RF MEMS Switch Cells for Crossbar Switch Matrices

King Yuk (Eric) Chan et. al. proposed a miniaturized RF MEMS switch cell units for the wideband scalable switch matrices. Two switch cells: type 1 and type 2, each having four and three MEMS switches respectively, were presented. Both of the cells were miniaturized in physical dimensions upto 340 um and 340 um. These were reported to be the smallest cell units for RF MEMS switch matrices ever reported. For the proposed switch cell units, RF performance was presented. Both of the designs showed excellent RF performance. The measured results have shown return loss (S11 and S44) better than 20 dB in both cases, while maintaining isolation (S41) better than 20 dB in state 1, across DC to 40 GHz bandwidth for both types. At state 2, 20 dB isolation was recorded across the bandwidth under consideration. They also demonstrated better than 20 dB return loss (S11) [32].

2.4.8 Scalable RF MEMS Switch Matrices: Methodology and Design

King Yuk (Eric) Chan et. al. proposed new solutions for the implemention wideband large switch matrices. These solutions were based on L-shaped and crossbar topologies. In order to build up scalable switch matrices, high-performance wideband switch cell was introduced. Designing, fabrication and characteristics of the switch cell and 3x3 crossbar switch matrix were introduced. They also presented an RF MEMS systems L-shaped switch matrix indicating less variation of characteristics for certain types of connectivity. It also demonstrated that for a 4x4 switch matrix, there was an improvement in insertion loss and phase-shift variation of upto 50 % [1].

2.4.9 Monolithic RF MEMS Switch Matrix Integration

M. Daneshmand et. al. presented monolithic integration of an RF MEMS switch matrix for the first time. They designed novel SP3T RF MEMS switches and also monolithically integrated with an electromagnetically coupled interconnect network. For this purpose, a thin film fabrication process was developed and fine tuned exclusively. Further fabrication and testing of a prototype unit of a 3x3 monolithic switch matrix was done. A good RF performance was shown for the frequency range of 9.5GHz to 13.5GHz. Using Close networks, the proposed monolithic 3X3 switch matrix can be easily expanded to a larger matrices [33].

Chapter 3

SCOPE OF STUDY

The performance of RF MEMS Switches have been demonstrated by number of researchers in last decade. Coaxial switches in the field of mechanical switches and pin diodes or Field effect transistors (FET) in the field of semiconductors switches are used frequently in RF applications but both switches have their disadvantages that mechanical switches are bulky and semiconductor switches have poor RF performance. A switch was required with low cost and better performance so RF MEMS switch was introduced. RF MEMS switches offers very high isolation, low insertion loss and low power consumption [34]. With advantage of these parameters MEMS switches also suffers from some drawbacks like low power handling and high electrostatic voltage requirement. These Switches has made a large growth in RF applications and becomes essential component to handle RF signal.

MEMS devices are mechanical components which are surface micro-machined to achieve a short circuit and open circuit in RF transmission lines. Various types of actuation mechanisms and different types of contact with membrane are there in MEMS Switches. Depending on these mechanisms different configurations are designed for MEMS Switches. Various switching circuits ranging from 0.1 to 120

GHz are designed due to near ideal response and near zero power consumption of MEMS switches. MEMS switch can also be cost effective through low unit pricing.

Further these switches can be used to make interconnections between N*N ports. All other conventional switches used in satellite payloads and others switch matrix applications does not offer good performance, but they are used due to high reliability of those switches. As discussed earlier MEMS switches shows very good performance so they can be replaced by conventional switch matrices. Although, these switches are having better performance but they still need improvement. Intense research has been made since last decade in the field of MEMS. Increasing the reliability of switch, Increasing the isolation between various paths in switch matrices interconnect network, increasing the return loss, decreasing the insertion loss of path are the key parameters which are still under research.

Chapter 4

OBJECTIVE OF STUDY

- Increasing the reliability of switches used in switch matrices.
- Increasing the return loss of design.
- Increasing the isolation between various signal paths of design.
- Decreasing the insertion loss of signal paths.
- As it is not a easy task to achieve all these parameters because these parameters are in trade off with each other. So we can optimise these parameters.
- Building blocks should be designed in such a manner so that the performance of overall system should gets increased.
- Multi-port switches can be used to design various building blocks. Problems which may occur due to non functionality of any single switch should be kept in mind.
- Variation in phase of the signal should be equal in all paths of the switch matrices.
- Power handling is a major drawback of these switches which should be improved.

Chapter 5

RESEARCH METHODOLOGY

- By intensive literature review of various papers we come to know that MEMS technology is replacing all those conventional technologies which are bulky and having poor performance. Despite the fact MEMS switches are not much reliable as compared to those conventional switches but they are used in RF application due to their excellent RF performance and very wide band of operation.

- Theoretical work is the first step to calculate various parameters of switches. These parameters include actuation voltage, Spring constant of flexure, Capacitances related to the switches and switching time of switches.

- Various parameters are calculated using EM solver. Electric and magnetic fields are plotted there. Graphs of insertion loss,isolation loss and return loss are plotted.

- FEM (Finite element modeller) is used to design flexures. Graphs of parameters like force required to actuate the switch and spring constant are extracted using FEM simulators. Parameters like stress analysis at various corners and maximum stress at any flexure is analysed in FEM simulator. Pressure distribution at various parts of flexures is extractracted.

- At last comparing simulated results and analytical results we conclude that simulated results shows good performance.

Chapter 6

BUILDING BLOCK DESIGN

The switch cell and SPDT switches are sub divided into sections in order to achieve the wideband operation and effective RF performance as shown in Fig. 1.2. Both of the cell units can be easily constructed by using few of the following sub-circuits: a T-junction, an RF MEMS single-pole single- throw (SPST) switch, an RF crossover, and a 90° bend. In order to obtain the desired characteristics, the designing and optimization of each of the sub-circuits is done [35]. Coplanar wave guide (CPW) technology is used as the basic design technology for the miniaturization purposes as it provides the possibility for scalable design with lower dispersion suitable for the broadband applications. Two SPSTs connected back-to-back in conjunction with a 90 bend have been employed to minimize loading effect and to emulate a single double-ended SPST for the switch cell turn path.

A new approach of designing the various building blocks is presented in this section. Moreover the optimization of key parameters shows an improved system performance.

6.0.10 90 °bend

In order to design an overall good performance system, each individual block should be designed with optimized values. The losses can be positively reduced by avoiding sharp bends in turn paths. The degradation of RF performance of bend happens due to the sharp bends causing radiations because of cut ground planes. Most of the times, the bridges also leads to performance degradation by introducing resonance and hence, should be avoided. In order to compensate for the parasitic capacitance and reactance, chamfering the corner is preferred instead of using air bridges [28, 27]. In [36] Daneshmand has shown a way to suppress the parasitic slot line mode by presenting design with air bridges. Radiation losses can be reduced by opting for an optimal chamfering of both strip and slot. Maximum chamfer allowed in air bridges may be the optimal value for chamfering [37]. Using a dielectric overlay and a step change in strip line width may be another alternate to chamfering the corners [**?**].

There is a need for reduction of the unwanted slot-line mode as it tends to radiate. This can be achieved by placing air-bridges near the CPW discontinuities. The cause of generation of slot-line mode in CPW bends is the occurrence of path length difference for slots. However, air-bridges add unwanted capacitance which further results in degrading the performance of the bend. Fig.6.3 shows a basic pictorial view of chamfering in a bend. Chamfering provides compensation for reactance arising in bend, as well as it partially compensates the effects of air bridge. For different bend structures, the optimal chamfering values are being determined. On the basis of results the optimal chamfered value for CPW bend structure shows current density as shown in Fig 6.2. It should be noted that all parameters for air-bridge are having the same value as in the case of an optimally chamfered CPW bend. Fig. 6.3 shows the effects of chamfering on S_{11} for CPW 90° bends. Fig. 6.3 and 6.4 shows a comparison between optimally chamfered conventional bend and conventional bend chamfered at various possible values with design parameters W= 50 μm and G= 25 μm, cor-

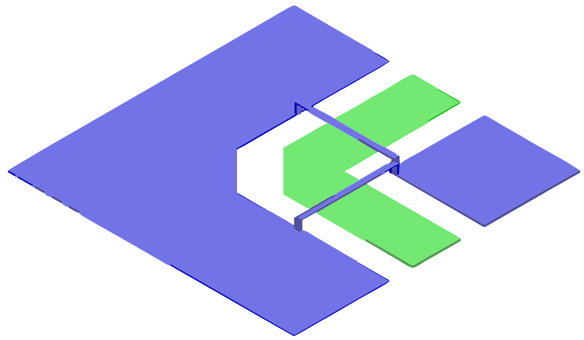

Figure 6.1: Coplanar waveguide 90°bend with air bridges and chamfered corners for low loss design.

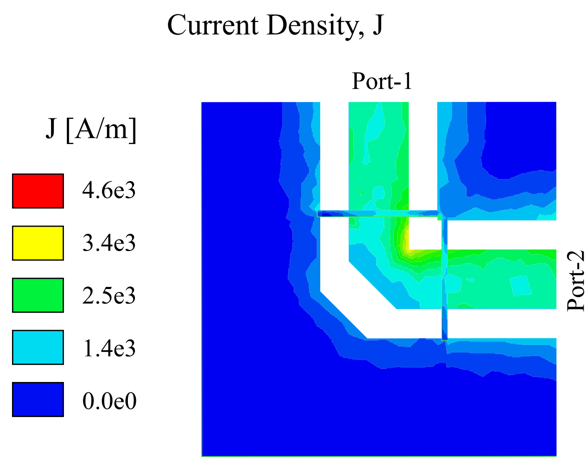

Figure 6.2: Coplanar waveguide 90°bend with current density at various parts of design.

responding to $Z_0 = 50\ \Omega$. Comparison of optimally chamfered bend with the over chamfered bend and under chamfered bend also shows improvements. The results show that an optimally small value of magnitude lying between 0.02-0.03 is obtained for chamfer size = 40 μm at frequency of 60 GHz. In the case of over chamfering, i.e. chamfer size is above 40 μm, the value of magnitude increases and hence leads to poor performance. On the other hand, in the case of under chamfering, i.e. chamfer size is lower than 40 μ m, the magnitude increases drastically and hence degrade the performance to a large extent. The corresponding values of the phase calculated for the respective optimally chamfered, over chamfered and under chamfered bends is as shown in Fig. 6.2.

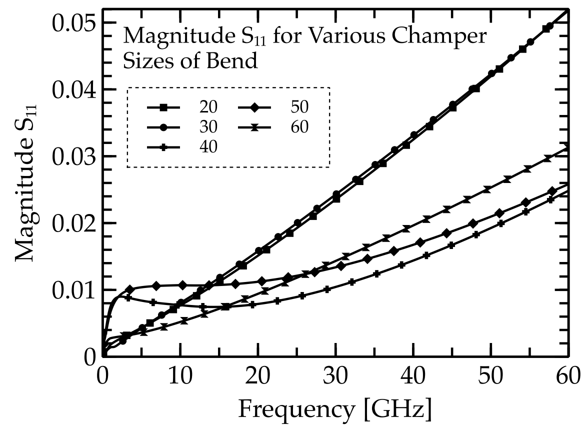

Figure 6.3: Computed reflection coefficient (Magnitude) as a function of frequency with chamfer value as parameter.

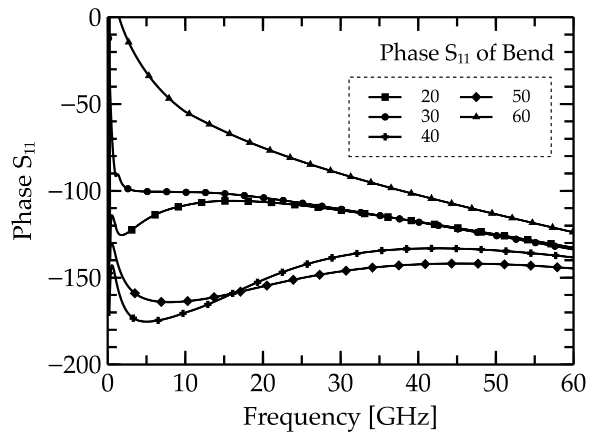

Figure 6.4: Computed reflection coefficient (Phase) as a function of frequency with chamfer value as parameter.

6.0.11 RF crossover

In SPNT applications, the extreme importance is given to the design isolation between all ports during a wideband operation. The major reason behind design isolation between all the ports in various connection states of the R-type, T-type and C-type is coupling arising in the crossovers. Thus, in order to attain reduction in the coupling occurring in 3-D model of RF crossover, the researchers have presented various efforts. Somehow, in the design, they have utilized the scalability of the CPW line. A major achievement is in terms of the reduction in the overlapping area by using possibly

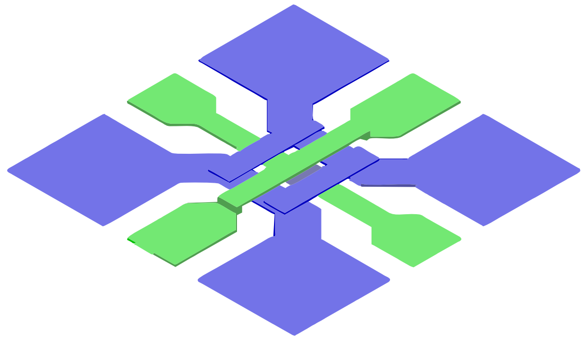

Figure 6.5: Coplanar waveguide Crossover design with air bridges for centre strip and ground planes.

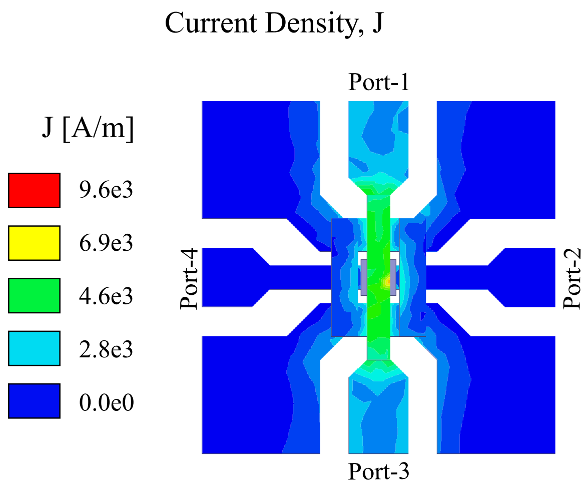

Figure 6.6: Coplanar waveguide Crossover design with current density at various parts of design while signal flows through path between Port1 and Port3.

the smallest dimensions of fabrication for CPW lines center conductor i.e. 10m. This is done in order to considerably reduce coupling effect between two perpendicular transmission lines crossing each other. While retaining small gap size, a good match characteristics impedance is also sustained [36]. The idea of perpendicular lines are an additional cause in reducing the coupling [38]. Fig. 6.14 shows a pictorial sectional view of the bridge. The connectivity of the ports is depicted in the Fig. 6.6 and 6.7. Fig. 6.6 and 6.7 shows the current density during the connection between port-1, port-3 and port-2, port-4 respectively.

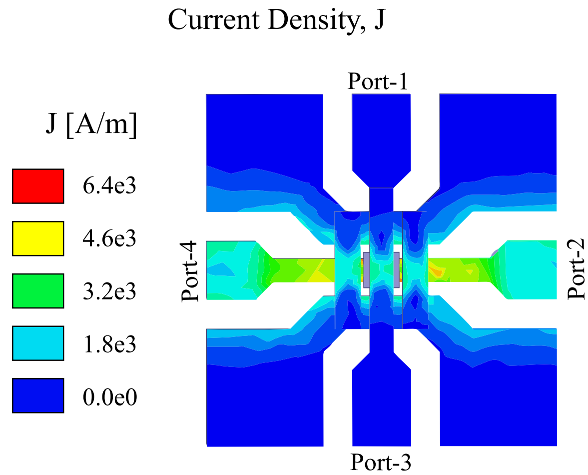

Figure 6.7: Coplanar waveguide Crossover design with current density at various parts of design while signal flows through path between Port2 and Port4.

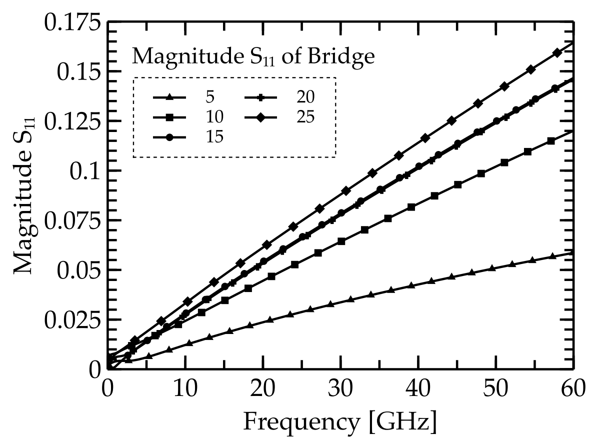

Figure 6.8: Computed reflection coefficient S_{11} (Magnitude) as a function of frequency with bridge height as parameter.

As evident from the above description, the optimized value of height of bridge proves to play a critical role in system performance. Fig. 6.8 and present the variation of return losses and isolation respectively, with the varying height of the bridge.

It can be clearly observed from the above figures, that the value obtained for return losses is noticeably low at lower bridge heights. A very good performance in terms of return loss is achieved at bridge height$=5$. If the height of bridge is increased beyond 5 μm, it leads to a drastic increase in return loss. However, on the other hand, at bridge height $= 5$ μm the isolation is very poor. In order to obtain better

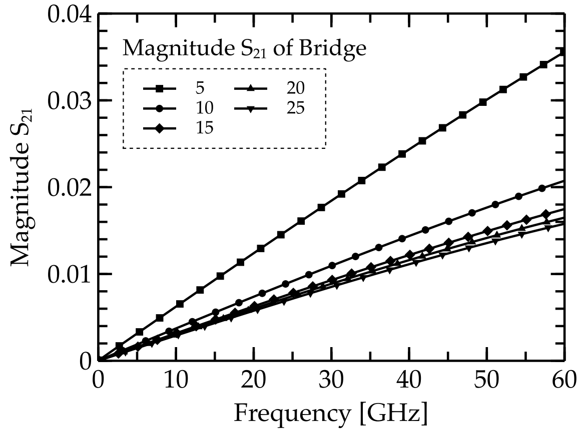

Figure 6.9: Computed isolation S_{21} (Magnitude) as a function of frequency with bridge height as parameter.

isolation, the bridge height should be increased slightly. Conclusively, it is observed that there occurs a trade-off between the return loss and isolation value. Since both return losses and isolation are critical performance parameters, so there is a need to select the height of bridge in such a way that we obtain optimal performance. Hence, the bridge height should be selected lying in the range of 5-10 μm. By choosing an optimal bridge height, we can progressively improve the system performance.

6.0.12 T junction design

T-junctions are necessary in the design of coplanar waveguide components such as, branch-line couplers, power dividers and stub filters. Several discontinuities included in a T-junction leads to mode conversion taking place within the circuit. Thus the power conversion happens resulting into parasitic coupled slotline mode from the desired CPW mode. However, maintaining electrical continuity between the ground planes of the circuit proves to be a simple method for suppressing the conversion to coupled slotline mode. Normally this can be attained by air-bridges or bond wires.

A CPW conventional T-junction is as shown in Fig. 6.10. In this figure, the structure comprises of three CPW center strip conductors. These conductors meet to form the junction while either the air-bridges or the bond wires maintain the

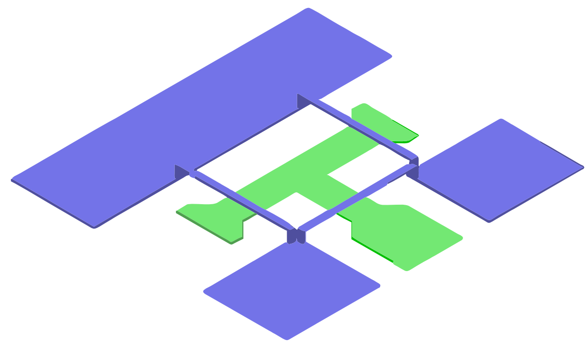

Figure 6.10: Coplanar waveguide T-junction design with air bridges and reduced strip width for low loss design.

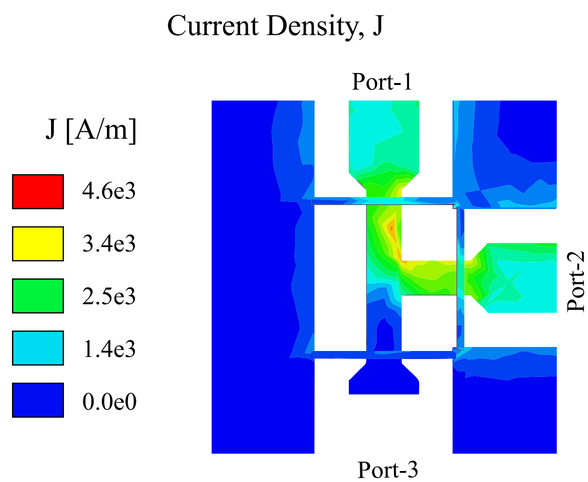

Figure 6.11: Coplanar waveguide T-junction design with current density at various parts of design.

continuity between ground planes at the junction. The current density across the 3 ports in T-junction is as shown in Fig.6.10 .

A major concern arising in RF system designs is broad bandwidth required for operating smoothly. Although a broad bandwidth capability is provided by both RF MEMS and crossover switches, still T-junction is the most critical circuit considered in determining the operational band of frequencies. In the switch cell and SPDT, only one input and one output is present as the T-junction has only one path in ON state at a time. Hence, in other words, always one path is in OFF state. So it behaves as a capacitive loading. The capacitive loading effect can be minimized by designing MEMS switch location properly and carefully. It should be in such a way

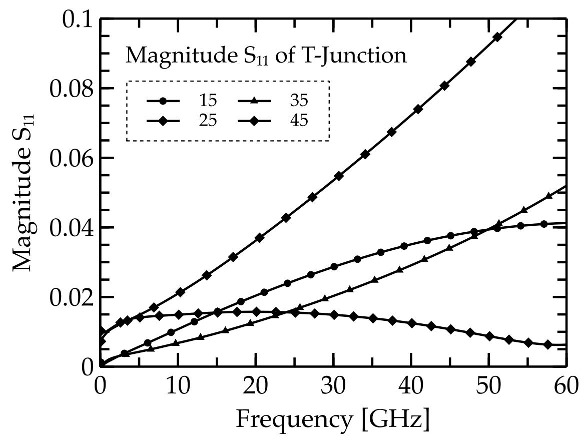

Figure 6.12: Computed reflection coefficient S_{11} (Magnitude) as a function of frequency with centre strip width as parameter.

that the switch opens with a minimum possible transmission line length towards the T-junction. In order to achieve further reduction of capacitive loading, the ground bridges are attached to a single point. After successfully establishing the T-junction loadings, major concern is attaining a wideband operation. T-junction should be designed in such a way that it leads to input and output path matching in all connecting conditions to around 50Ω [39, 40]. By employing T-junction with cantilever beam switches, the overall characteristic impedance is approximately 50 Ω for all the states for frequency band under consideration [36]. In order to enhance the performance of T-junction, the strip width should be decided carefully as it has a major impact on the return losses [34]. The return losses and respective phase obtained at various values of strip width are as shown in fig.6.12 and 6.13 respectively.

The results depicted in fig. 6.12 show that an acceptable and low value of return loss is obtained with strip width = 25 μm. However, if we try increasing or decreasing the width, it results in considerably raising the value of return losses and hence degrade the system performance. Thus, the optimal value of strip width is 25 μm. The respective values of phase can be observed from fig. 6.13. As mentioned above, the T-junction is always having one path in on-state and another in off-state. The open path length is an important parameter under consideration while designing

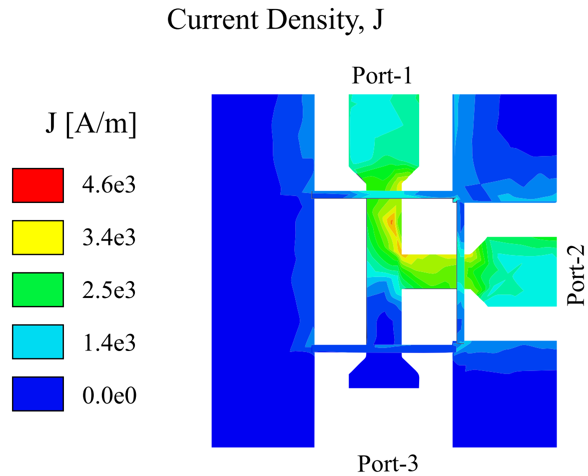

Figure 6.13: Computed reflection coefficient S_{11} (Phase) as a function of frequency with centre strip width as parameter.

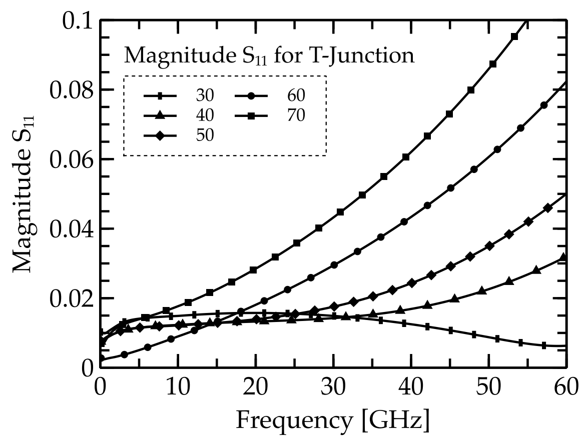

Figure 6.14: Computed reflection coefficient S_{11} (Magnitude) as a function of frequency with length of open path as parameter.

T-junction, since its value directly impacts the system performance by introducing return losses. As shown in Fig. 6.14, there is a noticeable variation in return loss by varying open path length.

It should be noticed that the minimum return losses are obtained at path length $= 30$ μm. In all other cases with longer path length, the magnitude of return losses becomes very high. It should be noticed that there is a restriction on the lower limit of open path length, hence we cannot take the values lower than 30 μm because we need some external switches to turn path from OFF state to ON state. The plot

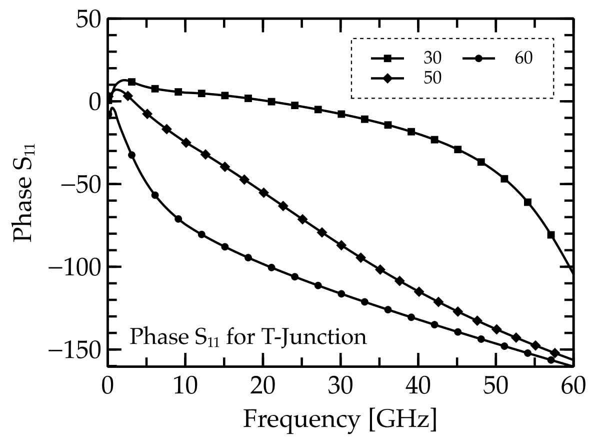

Figure 6.15: Computed reflection coefficient S_{11} (Phase) as a function of frequency with length of open path as parameter.

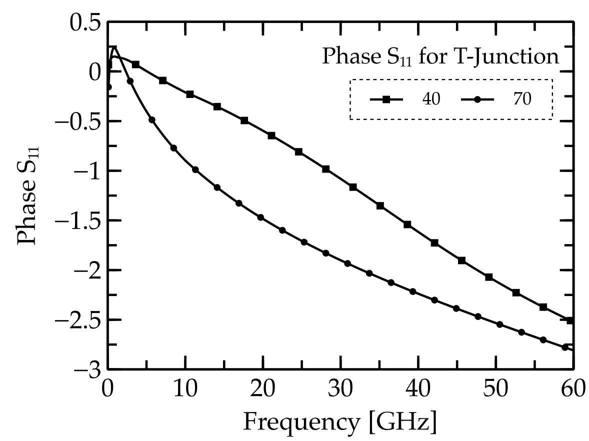

Figure 6.16: Computed reflection coefficient S_{11} (Phase) as a function of frequency with length of open path as parameter.

of phase for the respective cases is as shown in fig. 6.12 and 6.16. Thus, it can be concluded that, the open path length should be kept at the minimum possible value in order to lower the value of return losses.

Chapter 7

PROPOSED SWITCH MATRIX TOPOLOGY

Proposed switch matrix topology consists of a 2×2 building block design. The design in easily scalable to large interconnect networks. The 2×2 matrix is used repeatedly for scalable designs as shown in fig. 7.2 a 2×2 design is used 6 times to form a 4×4 interconnect network. A basic 2×2 design consists of a crossover, eight switches and six bends. All of these components are optimised to achieve better RF performance

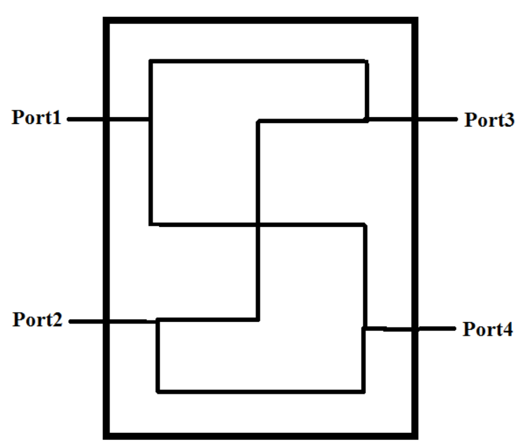

Figure 7.1: Proposed 2X2 switch matrix architecture.

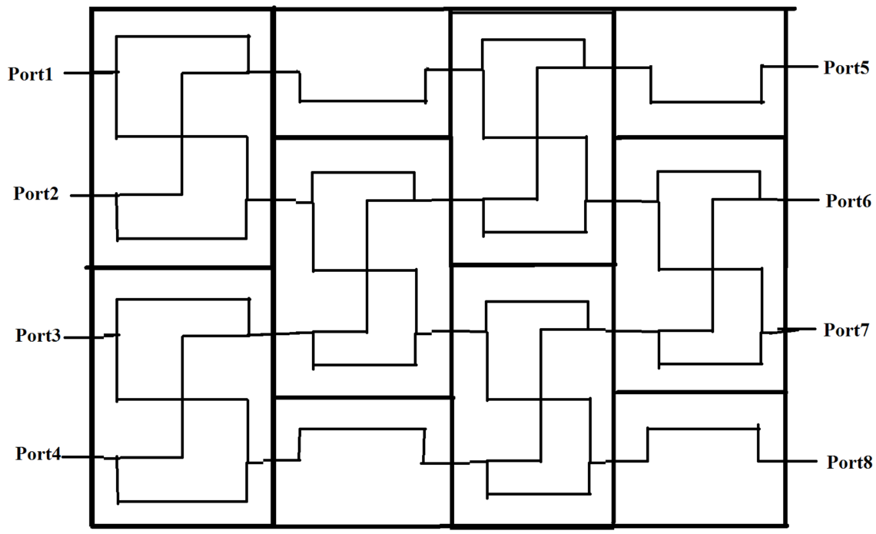

Figure 7.2: Proposed 4X4 switch matrix architecture.

of overall system. Characteristic impedance is kept 50 Ω while designing. Traditional topologies like crossbar switch matrix and staircase switch matrix were having a major drawback that phase variation between different signal paths was found.

The purpose of L-matrix topology was only to achieve minimum phase variation between various signal paths. The design is made symmetric so that in both states of operation phase difference is achieved equal. In fig. 7.2 it is shown that in support of six 2×2 blocks four additional blocks are also attached in which CPW length is increased using bends. The length is increased in order to compensate the phase variation caused by 2×2 design attached parallel to the block with CPW connector only. This design is having least number of switches and crossovers used as compared to other traditional switch matrix topologies. Similarly further using 4×4 blocks as building block we can scale the network upto 8×8 and so on. As every component like crossover switches and t junctions introduce some loss in network, using the minimum number of crossovers and switches in proposed topology further leads to the increase in RF performance of the system. All these components are attached on a single substrate and gold is used for CPW as well as ground planes in whole design.

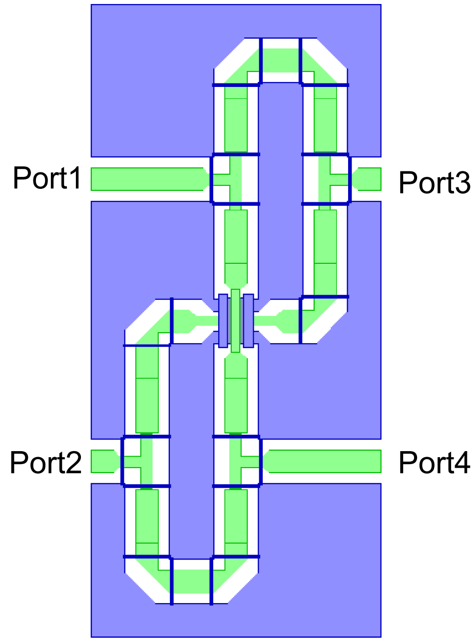

Figure 7.3: Proposed 2X2 switch matrix topology.

7.0.13 Operation principle

A 2×2 architecture is shown in fig. 7.3. The design is having two different states of operation. In state one Port1 is connected to Port4 and Port2 is connected to Port3 through crossover whereas in state two Port1 is connected to Port3 and Port2 is connected to Port4. At any time instance the design is in one of the two states of operation. Here in state one either input ports are straight away connected to output paths or both inputs ports are inverted through crossover to feed the output ports.

Chapter 8

RESULT AND DISCUSSION

For proposed switch matrix topology the results of various building blocks have been optimised and shown in chapter 6. To support the proposed design the results of complete integration of 2×2 system are shown in fig. 8.1, 8.2 and 8.3. Fig. 8.1 shows the insertion loss offered by complete 2×2 design which is less than 0.5 dB in both states. Fig. 8.2 shows isolation between both signal paths which is above 30 dB in both states of operation. Fig. 8.3 shows reflection coefficient S_{11} which is at worst 20 dB in both states of operation. Results have been simulated from dc to 40 GHz. The architecture proposed in chapter 7 can be used instead of using

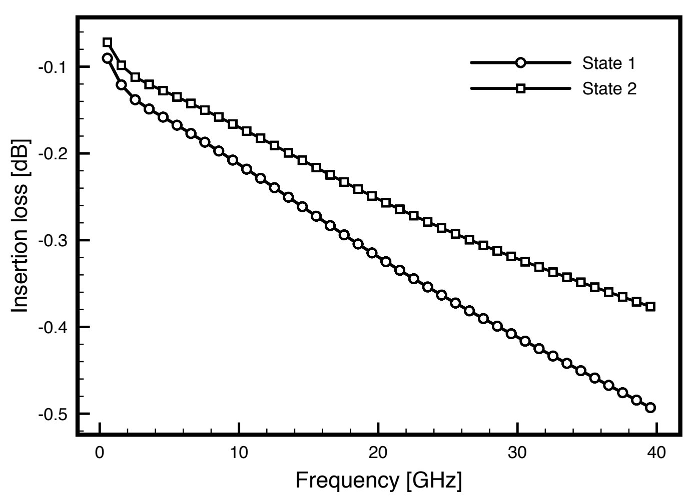

Figure 8.1: Computed insertion loss as a function of frequency.

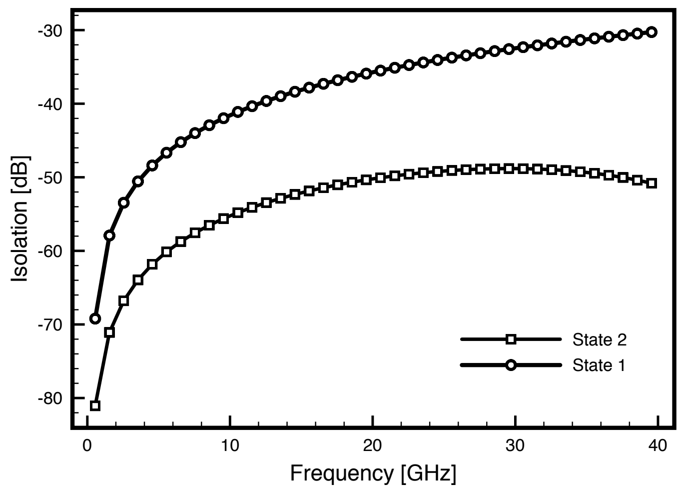

Figure 8.2: Computed isolation between two different signal paths as function of frequency.

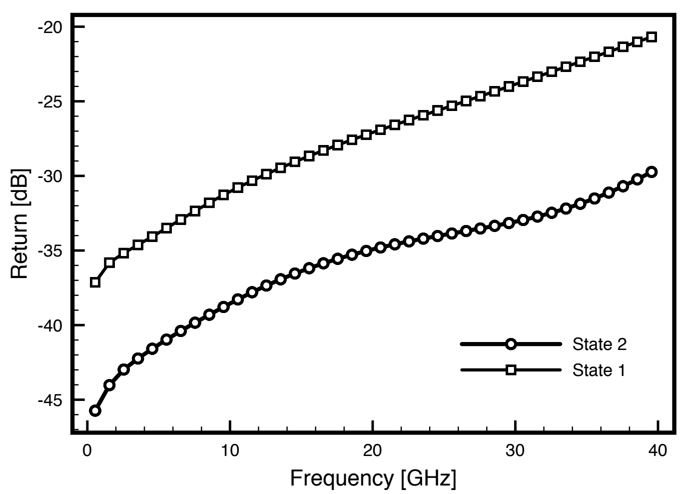

Figure 8.3: Computed reflection coefficient S_{11} as function of frequency.

conventional techniques. It can be seen in every results graph that state 2 shows better RF performance as compared to that of state 1. It is due to the crossover involved in state 1. These result graphs of insertion loss, isolation loss and return loss itself are proof that reducing the number of switches and crossers in overall system will leads to better RF performance. Simulation results proves that design is capable of producing good RF performance which is acceptable for system design.

Chapter 9

CONCLUSION

A new switch matrix topology for switch matrix interconnections is proposed and 2×2 interconnect system is designed. Comparison table 9 clearly shows the reduction in number of overall MEMS switches/crossovers than crossbar switch matrix and L-matrix topology. Whereas, it is noticeable that all values are equal to Staircase switch matrix topology.

	Crossbar Matrix	Staircase Matrix	L matrix	Proposed switch matrix
2X2	32/4	8/1	12/1	8/1
4X4	128/16	48/6	52/6	48/6
8X8	512/64	224/28	260/34	224/28

Table 9.1: Switches/Crossovers used in various topologies.

Advantages of using L-matrix topology over staircase and crossbar switch matrix topology was improved phase difference. Proposed design shows the advantage of improved phase difference between all possible paths with reduced number of components required for system design. It is also noticeable here that reduced components will potentially avoid loss as well as reduce system complexity and actuation mechanism complexity. As the number of components like crossovers and switches are reduced improvement is observed in complete design integration.

Bibliography

[1] K. Y. Chan, M. Daneshmand, R. Mansour, and R. Ramer, "Scalable rf mems switch matrices: Methodology and design," *Microwave Theory and Techniques, IEEE Transactions on*, vol. 57, no. 6, pp. 1612–1621, June 2009.

[2] J. T. Yeow and S. S. Abdallah, "Novel mems l-switching matrix optical cross-connect architecture: Design and analysis-optimal and staircase-switching algorithms," *Lightwave Technology, Journal of*, vol. 23, no. 10, pp. 2877–2892, 2005.

[3] K. Y. Chan, R. Ramer, and R. Mansour, "Novel miniaturized rf mems staircase switch matrix," *Microwave and Wireless Components Letters, IEEE*, vol. 22, no. 3, pp. 117–119, March 2012.

[4] T. Yeow, K. Law, and A. Goldenberg, "Micromachined l-switching matrix," in *Communications, 2002. ICC 2002. IEEE International Conference on*, vol. 5, 2002, pp. 2848–2854 vol.5.

[5] H. De Los Santos, G. Fischer, H. Tilmans, and J. Van Beek, "Rf mems for ubiquitous wireless connectivity. part i. fabrication," *Microwave Magazine, IEEE*, vol. 5, no. 4, pp. 36–49, 2004.

[6] H. J. De Los Santos, G. Fischer, H. Tilmans, and J. Van Beek, "Rf mems for ubiquitous wireless connectivity. part ii. application," *Microwave Magazine, IEEE*, vol. 5, no. 4, pp. 50–65, 2004.

[7] V. K. Varadan, K. J. Vinoy, and K. A. Jose, *RF MEMS and their applications*. John Wiley & Sons, 2003.

[8] G. Rebeiz, *RF MEMS: Theory, Design, and Technology*. Wiley, 2004. [Online]. Available: http://books.google.co.in/books?id=A7728XHtmzAC

[9] M. Daneshmand and R. R. Mansour, "Redundancy rf mems multiport switches and switch matrices," *Microelectromechanical Systems, Journal of*, vol. 16, no. 2, pp. 296–303, 2007.

[10] M. Daneshmand and R. Mansour, "C-type and r-type rf mems switches for redundancy switch matrix applications," in *Microwave Symposium Digest, 2006. IEEE MTT-S International*. IEEE, 2006, pp. 144–147.

[11] E. Chan, M. Daneshmand, A. A. Fomani, R. R. Mansour, and R. Ramer, “Monolithic mems t-type switch for redundancy switch matrix applications,” in *Microwave Conference, 2008. EuMC 2008. 38th European.* IEEE, 2008, pp. 1513–1516.

[12] M. Daneshmand and R. Mansour, “Rf mems satellite switch matrices,” *Microwave Magazine, IEEE*, vol. 12, no. 5, pp. 92–109, Aug 2011.

[13] F. Assal, R. Gupta, K. Betaharon, A. Zaghloul, and J. Apple, “A wide-band satellite microwave switch matrix for ss/tdma communications,” *Selected Areas in Communications, IEEE Journal on*, vol. 1, no. 1, pp. 223–231, January 1983.

[14] E. McErlean, J.-S. Hong, S. Tan, L. Wang, Z. Cui, R. Greed, and D. Voyce, “2× 2 rf mems switch matrix,” *IEE Proceedings-Microwaves, Antennas and Propagation*, vol. 152, no. 6, pp. 449–454, 2005.

[15] P. Grant, M. Denhoff, and R. Mansour, “A comparison between rf mems switches and semiconductor switches,” in *MEMS, NANO and Smart Systems, 2004. ICMENS 2004. Proceedings. 2004 International Conference on.* IEEE, 2004, pp. 515–521.

[16] H. Y. Lee, F. K. Hwang, and J. D. Carpinelli, “A new decomposition algorithm for rearrangeable clos interconnection networks,” *Communications, IEEE Transactions on*, vol. 44, no. 11, pp. 1572–1578, 1996.

[17] M. Daneshmand, R. R. Mansour, and N. Sarkar, “Rf mems waveguide switch,” *Microwave Theory and Techniques, IEEE Transactions on*, vol. 52, no. 12, pp. 2651–2657, 2004.

[18] N. Vahabisani and M. Daneshmand, “Thick thb sacrificial layer and metal encapsulation process,” in *Microsystems and Nanoelectronics Research Conference, 2009. MNRC 2009. 2nd.* IET, 2009, pp. 144–147.

[19] J. Héctor, *RF MEMS circuit design for wireless communications.* Artech House, 2002.

[20] E. Chan, M. Daneshmand, R. Mansour, and R. Ramer, “Novel beam design for compact rf mems series switches,” in *Microwave Conference, 2007. APMC 2007. Asia-Pacific.* IEEE, 2007, pp. 1–4.

[21] M. Daneshmand, “Multi-port rf mems switches and switch matrices,” 2006.

[22] K. Beilenhoff, W. Heinrich, and H. L. Hartnagel, “Analysis of t-junctions for coplanar mmics,” in *Microwave Symposium Digest, 1994., IEEE MTT-S International*, May 1994, pp. 1301–1304 vol.2.

[23] A. Fomani and R. Mansour, “Miniature rf mems switch matrices,” in *Microwave Symposium Digest, 2009. MTT’09. IEEE MTT-S International.* IEEE, 2009, pp. 1221–1224.

[24] A. A. Fomani and R. R. Mansour, “Monolithically integrated multiport rf mems switch matrices,” *Microwave Theory and Techniques, IEEE Transactions on*, vol. 57, no. 12, pp. 3434–3441, 2009.

[25] E. Chan, M. Daneshmand, R. Mansour, and R. Ramer, “Monolithic crossbar mems switch matrix,” in *Microwave Symposium Digest, 2008 IEEE MTT-S International*, June 2008, pp. 129–132.

[26] M. Daneshmand, R. Mansour, P. Mousavi, S. Choi, B. Yassini, A. Zybura, and M. Yu, “A novel integrated interconnect network for rf switch matrix applications,” in *Microwave Symposium Digest, 2004 IEEE MTT-S International*, vol. 2. IEEE, 2004, pp. 1213–1216.

[27] S. Sinha, D. Bansal, and K. Rangra, “Design and optimization of rf mems t-type switch for redundancy switch matrix applications,” in *Computing, Electronics and Electrical Technologies (ICCEET), 2012 International Conference on*, March 2012, pp. 501–508.

[28] E. Siew, K. Y. Chan, R. Ramer, and A. Dzurak, “Design of a rf nems switch matrix,” in *Antennas and Propagation (APSURSI), 2011 IEEE International Symposium on*, July 2011, pp. 12–15.

[29] M. Daneshmand, R. Mansour, P. Mousavi, S. Choi, B. Yassini, A. Zybura, and M. Yu, “Integrated interconnect networks for rf switch matrix applications,” *Microwave Theory and Techniques, IEEE Transactions on*, vol. 53, no. 1, pp. 12–21, Jan 2005.

[30] T. Kim, M. Faz, and L. Vietzorreck, “Investigation and optimization of transitions in an ltcc based rf mems switching matrix for space applications,” in *Microwave Conference, 2009. APMC 2009. Asia Pacific*, Dec 2009, pp. 988–991.

[31] A. Fomani and R. Mansour, “Miniature rf mems switch matrices,” in *Microwave Symposium Digest, 2009. MTT ’09. IEEE MTT-S International*, June 2009, pp. 1221–1224.

[32] K. Y. Chan, R. Mansour, and R. Ramer, “Miniaturized rf mems switch cells for crossbar switch matrices,” in *Microwave Conference Proceedings (APMC), 2010 Asia-Pacific*, Dec 2010, pp. 1829–1832.

[33] M. Daneshmand and R. Mansour, “Monolithic rf mems switch matrix integration,” in *Microwave Symposium Digest, 2006. IEEE MTT-S International*, June 2006, pp. 140–143.

[34] G. M. Rebeiz and J. B. Muldavin, “Rf mems switches and switch circuits,” *Microwave Magazine, IEEE*, vol. 2, no. 4, pp. 59–71, 2001.

[35] R. L. Borwick III, P. A. Stupar, J. F. DeNatale, R. Anderson, and R. Erlandson, “Variable mems capacitors implemented into rf filter systems,” *Microwave Theory and Techniques, IEEE Transactions on*, vol. 51, no. 1, pp. 315–319, 2003.

[36] M. Daneshmand and R. Mansour, "Monolithic rf mems switch matrix integration," in *Microwave Symposium Digest, 2006. IEEE MTT-S International*. IEEE, 2006, pp. 140–143.

[37] P. Watson and K. Gupta, "Em-ann modelling and optimal chamfering of 90/spl deg/cpw bends with air-bridges," in *Microwave Symposium Digest, 1997., IEEE MTT-S International*, vol. 3. IEEE, 1997, pp. 1603–1606.

[38] R. N. Simons, *Coplanar Waveguide Circuits, Components, and Systems*, ser. Wiley Series in Microwave and Optical Engineering. Newark, NJ: Wiley, 2001.

[39] Z. Peng, C. Palego, S. Halder, J. Hwang, C. V. Jahnes, K. Etzold, J. M. Cotte, and J. H. Magerlein, "Dielectric charging in electrostatically actuated mems ohmic switches," *Device and Materials Reliability, IEEE Transactions on*, vol. 8, no. 4, pp. 642–646, 2008.

[40] Z. Peng, X. Yuan, J. Hwang, D. I. Forehand, and C. L. Goldsmith, "Dielectric charging of rf mems capacitive switches under bipolar control-voltage waveforms," in *Microwave Symposium, 2007. IEEE/MTT-S International*. IEEE, 2007, pp. 1817–1820.

[41] R. W. Jackson and D. W. Matolak, "Surface-to-surface transition via electromagnetic coupling of coplanar waveguides," *IEEE Transactions on Microwave Theory Techniques*, vol. 35, pp. 1027–1032, 1987.

[42] J.-P. Raskin, G. Gauthier, L. P. Katehi, and G. M. Rebeiz, "W-band single-layer vertical transitions," *Microwave Theory and Techniques, IEEE Transactions on*, vol. 48, no. 1, pp. 161–164, 2000.

[43] R. Chan, R. Lesnick, D. Becher, and M. Feng, "Low-actuation voltage rf mems shunt switch with cold switching lifetime of seven billion cycles," *Microelectromechanical Systems, Journal of*, vol. 12, no. 5, pp. 713–719, 2003.

[44] P. Blondy, A. Crunteanu, A. Pothier, P. Tristant, A. Catherinot, and C. Champeaux, "Effects of atmosphere on the reliability of rf-mems capacitive switches," in *Microwave Conference, 2007. European*. IEEE, 2007, pp. 1346–1348.

[45] X. Yuan, Z. Peng, J. Hwang, D. Forehand, and C. L. Goldsmith, "A transient spice model for dielectric-charging effects in rf mems capacitive switches," *Electron Devices, IEEE Transactions on*, vol. 53, no. 10, pp. 2640–2648, 2006.

[46] K. Grenier, D. Dubuc, B. Ducarouge, V. Conedera, D. Bourrier, E. Ongareau, P. Derderian, and R. Plana, "High power handling rf mems design and technology," in *Micro Electro Mechanical Systems, 2005. MEMS 2005. 18th IEEE International Conference on*. IEEE, 2005, pp. 155–158.

[47] R. Kwiatkowski, "Bi-planar microwave switches and switch matrices," Oct. 4 2005, uS Patent 6,951,941.

[48] S. DiNardo, P. Farinelli, F. Giacomozi, G. Mannocchi, R. Marcelli, B. Margesin, P. Mezzanotte, V. Mulloni, P. Russer, R. Sorrentino *et al.*, "Rf mems based switch matrices for complex switching networks," *Proc. IEEE Microwave Theory and Techniques and 5th ESA Round Table on Micro/Nano Technologies for Space, Netherlands*, pp. 3–5, 2005.

[49] K. J. Herrick, J.-G. Yook, and L. P. Katehi, "Microtechnology in the development of three-dimensional circuits," *Microwave Theory and Techniques, IEEE Transactions on*, vol. 46, no. 11, pp. 1832–1844, 1998.

[50] R. N. Simons, R. Lee, K. Shalkhausere, J. Owens, J. Demarco, J. Leen, and D. Sturzebecher, "Finite width coplanar waveguide patch antenna with vertical fed through interconnect," in *Antennas and Propagation Society International Symposium, 1996. AP-S. Digest*, vol. 2. IEEE, 1996, pp. 1338–1341.

[51] A. Margomenos, K. J. Herrick, M. I. Herman, S. Valas, and L. P. Katehi, "Isolation in three-dimensional integrated circuits," *Microwave Theory and Techniques, IEEE Transactions on*, vol. 51, no. 1, pp. 25–32, 2003.

[52] M. Tsuji, H. Shigesawa, and A. A. Oliner, "New interesting leakage behavior on coplanar waveguides of finite and infinite widths," *Microwave Theory and Techniques, IEEE Transactions on*, vol. 39, no. 12, pp. 2130–2137, 1991.

[53] B. Yassini, S. Choi, A. Zybura, M. Yu, R. E. Mihailovich, and J. F. DeNatale, "A novel mems ltcc switch matrix," in *Microwave Symposium Digest, 2004 IEEE MTT-S International*, vol. 2. IEEE, 2004, pp. 721–724.

[54] N. McGruer, *RF and current handling performance of electrostatically actuated microswitches.* Northeastern Univ., 1999.

[55] D. Peroulis, S. P. Pacheco, and L. P. Katehi, "Rf mems switches with enhanced power-handling capabilities," *Microwave Theory and Techniques, IEEE Transactions on*, vol. 52, no. 1, pp. 59–68, 2004.

[56] H. J. De Los Santos, "Introduction to micorelectromechanical(mem) microwave systems(book)," *Norwood, MA: Artech House, 1999.*, 1999.

[57] C.-C. Nguyen, "Transceiver front-end architectures using vibrating micromechanical signal processors," in *Silicon Monolithic Integrated Circuits in RF Systems, 2001. Digest of Papers. 2001 Topical Meeting on.* IEEE, 2001, pp. 23–32.

[58] X.-j. He, Q. Wu, B.-s. Jin, M.-X. Song, and J.-H. Yin, "Influence of wafer level packaging modes on rf performance of mems phase shifters," in *Electronic Packaging Technology, 2006. ICEPT'06. 7th International Conference on.* IEEE, 2006, pp. 1–4.

[59] C. Tsai, P. A. Stupar, R. L. Borwick III, M. Pai, and J. DeNatale, "An isolated tunable capacitor with a linear capacitance-voltage behavior," in *TRANSDUCERS, Solid-State Sensors, Actuators and Microsystems, 12th International Conference on, 2003*, vol. 1. IEEE, 2003, pp. 833–836.

[60] H. S. Hinton, J. Erickson, T. Cloonan, F. Tooley, F. McCormick, and A. Lentine, "An introduction to photonic switching fabrics," 1993.

[61] M. Moraja and M. Amiotti, "Advanced getter solutions at wafer level to assure high reliability to the last generations mems," in *Reliability Physics Symposium Proceedings, 2003. 41st Annual. 2003 IEEE International*. IEEE, 2003, pp. 458–459.

[62] C. T.-C. Nguyen, "Rf mems in wireless architectures," in *Proceedings of the 42nd annual Design Automation Conference*. ACM, 2005, pp. 416–420.

[63] R. C. Allison and J. J. Lee, "Micro electro-mechanical system (mems) transfer switch for wideband device," Sep. 23 2003, uS Patent 6,624,720.

[64] T. Oogarah, M. Daneshmand, R. Mansour, and S. Chang, "Low temperature variable inductor using porous anodic alumina," in *Microwave Symposium Digest, 2008 IEEE MTT-S International*. IEEE, 2008, pp. 1055–1058.

[65] M. Daneshmand, S. Fouladi, R. R. Mansour, M. Lisi, and T. Stajcer, "Thermally actuated latching rf mems switch and its characteristics," *Microwave Theory and Techniques, IEEE Transactions on*, vol. 57, no. 12, pp. 3229–3238, 2009.

[66] M. Daneshmand and R. R. Mansour, "Fabrication and modeling of an sp3t rf mems switch," in *Antennas and Propagation Society International Symposium, 2003. IEEE*, vol. 1. IEEE, 2003, pp. 391–394.

[67] K. Y. Chan, M. Daneshmand, R. R. Mansour, and R. Ramer, "Scalable rf mems switch matrices: Methodology and design," *Microwave Theory and Techniques, IEEE Transactions on*, vol. 57, no. 6, pp. 1612–1621, 2009.

[68] M. Daneshmand, R. R. Mansour, P. Mousavi, S. Choi, B. Yassini, A. Zybura, and M. Yu, "Integrated interconnect networks for rf switch matrix applications," *Microwave Theory and Techniques, IEEE Transactions on*, vol. 53, no. 1, pp. 12–21, 2005.

[69] J. Schaffner, A. E. Schmitz, T.-Y. Hsu, D. Chang, R. Loo, and D. Sievenpiper, "Metal contact rf mems switch elements for ultra wideband rf front-end systems," in *Ultra Wideband Systems and Technologies, 2003 IEEE Conference on*. IEEE, 2003, pp. 32–36.

[70] G. M. Rebeiz, G.-L. Tan, and J. S. Hayden, "Rf mems phase shifters: design and applications," *Microwave Magazine, IEEE*, vol. 3, no. 2, pp. 72–81, 2002.

[71] S. Gong, H. Shen, and N. S. Barker, “A 60-ghz 2-bit switched-line phase shifter using sp4t rf-mems switches,” *Microwave Theory and Techniques, IEEE Transactions on*, vol. 59, no. 4, pp. 894–900, 2011.

[72] J.-G. Guo, L.-J. Zhou, and Y.-P. Zhao, “Instability analysis of torsional mems/nems actuators under capillary force,” *Journal of colloid and interface science*, vol. 331, no. 2, pp. 458–462, 2009.

[73] Y. Xu and N. Aluru, “Pull-in/out analysis of nano/microelectromechanical switches with defective oxide layers,” *Applied Physics Letters*, vol. 95, no. 7, p. 073112, 2009.

[74] S. Demoustier, E. Minoux, M. Le Baillif, M. Charles, and A. Ziaei, “Review of two microwave applications of carbon nanotubes: nano-antennas and nano-switches,” *Comptes Rendus Physique*, vol. 9, no. 1, pp. 53–66, 2008.

[75] B. A. Cetiner, N. Biyikli, B. S. Yildirim, and Y. Damgaci, “Nanoelectromechanical switches for reconfigurable antennas,” *Microwave and Optical Technology Letters*, vol. 52, no. 1, pp. 64–69, 2010.

[76] H. Rahman and R. Ramer, “Experimental considerations and fabrication analysis of surface micromachined rf nems switch,” *Microsystem Technologies*, pp. 1–11, 2014.

[77] F. T. Assal, R. Gupta, K. Betaharon, A. Zaghloul, and J. Apple, “A wide-band satellite microwave switch matrix for ss/tdma communications,” *Selected Areas in Communications, IEEE Journal on*, vol. 1, no. 1, pp. 223–231, 1983.

[78] W. ge Yu, K. qu Zhou, Z. zhong Wu, and T.-H. Yang, “Analysis of nems switch using changeable space domain,” in *Electrical and Control Engineering (ICECE), 2010 International Conference on*, June 2010, pp. 3339–3342.