

# **PERFORMANCE OPTIMIZATION OF TUNABLE RF MEMS BASED DEVICES**

**VISHAL KUMAR**



**CENTRE FOR APPLIED RESEARCH IN ELECTRONICS**

**INDIAN INSTITUTE OF TECHNOLOGY, DELHI**

**FEBRUARY 2023**

**©Indian Institute of Technology Delhi (IITD), New Delhi, 2023**

**PERFORMANCE OPTIMIZATION OF TUNABLE  
RF MEMS BASED DEVICES**

*by*

**VISHAL KUMAR**

**CENTRE FOR APPLIED RESEARCH IN ELECTRONICS**

*Submitted*

**in fulfillment of the requirements of the degree of Doctor of Philosophy**

*to the*



**Indian Institute of Technology, Delhi**

**FEBRUARY 2023**

# **DEDICATION**

**To my family**

# Certificate

This is to certify that the thesis entitled, "**Performance Optimization of Tunable RF MEMS Based Devices**", being the submitted by **Shri. Vishal Kumar** for the award of the degree of Doctor of Philosophy (Ph. D.) to the Indian Institute of Technology, Delhi, is a record of original bonafide research work carried out by him under our guidance and supervision.

In our opinion, the thesis has reached the standard of fulfilling the requirements of all the regulations related to the degree. The results contained in this thesis have not been submitted in part or full, to any other university or institute for the award of any degree or diploma.

We certify that he has pursued the prescribed course of research.

**Prof. A. Basu**

*Centre for Applied Research  
in Electronics (CARE)  
Indian Institute of Technology, Delhi  
New Delhi-110016, INDIA*

**Prof. Shibani K. Koul**

*Centre for Applied Research  
in Electronics (CARE)  
Indian Institute of Technology, Delhi  
New Delhi-110016, INDIA*

## EPIGRAPH

*If there is a will, there is a way.*

- Shakespere

# ACKNOWLEDGMENT

I would like to express my sincere appreciation and gratitude to my supervisors Prof. Shibhan Kishen Koul and Prof. Ananjan Basu for their valuable guidance, constant motivation, and much needed suggestion throughout this research work. With immense expertise of our supervisors in the field of RF/Microwave technology & engineering, RF components modelling, Passive and Active circuits, Reconfigurable microwave circuits and RF MEMS technology motivated me to work in this fascinating but challenging field. I gained a lot of academic knowledge from the invaluable discussion held with both the supervisors. I am indeed blessed and honored to be their student.

I am also grateful to Prof. Mahesh P. Abegaonkar and Prof. Bhaskar Mitra for their valued suggestions which helped me to solve the challenges faced during my research. I am also thankful to Prof. Arun kumar as SRC committee chairman whose well-timed advices helped me to shape my thesis nicely.

I would like to recognize the company of my companion researchers at CARE, Dr. Saurabh Pegwal, Dr. Rajesh Kumar Singh, Dr. Robin Kalyan, Dr. Ayushi Barthwal, Dr. Deepika Sibal, Dr. Amit Kumar, Ms.Somia Sharma, Mr. Shakti Singh Chauhan, Mr. Pranav KumarShrivastava, and Ms. Rakhi Kumari who made useful contribution during discussions and gave suggestions from time to time to prepare my thesis. I am also thankful to Dr. Sandeep Chaturvedi, GAETEC for his timely help in characterization of few of the MEMS devices at GAETEC characterization facility.

I am indebted to thank the entire CARE faculty and staff members who helped me directly or indirectly during my research and towards successful completion of my research work. I would like to thank Mr. S P Chakraborty, Mr. Ashok Pramanik who helped me to understand the basics of device fabrication which helped me to make an efficient process flow of MEMS devices.

Finally, I have to express my everlasting gratitude to my parents who have inspired me to complete the research with full dedication and hard work. I am also thankful to my sister Manisha, brother Vikas, wife Alka and son Pratyush who remained with me throughout the arduous past years and made me to believe in self.

# ABSTRACT

Comprehensive studies on Radio Frequency Micro Electro Mechanical Systems (RF MEMS) based devices followed by implementation of novel design and fabrication process to optimize the performances of these devices are presented in this thesis. The work aimed at development of RF MEMS shunt switches, switch based MEMS phase shifter, tunable capacitor and bulk-micromachined inductors to be implemented in the futuristic next generation systems for airborne applications.

To start with Tri-layer (nitride-metal-nitride) membrane rather than all metal membrane have been investigated to enhance the membrane properties and to realize the stress free, thermally stable, and stictionless structure. The process flow was optimized as per the established MEMS process of the Indian foundry named Semiconductor Technology & Applied Research Centre, STAR-C (formerly known as Society for Integrated Circuit and Applied Research, SITAR), Bangalore. All these structures are fabricated on high resistivity Silicon substrate to ensure low RF loss as well as low parasitic capacitance.

Chapter 2 presents an electrostatic RF MEMS shunt switch using the novel tri-layer membrane which results low actuation voltage less than 15V, high isolation better than 35 dB and has stictionless operation. Inductance tuning is implemented by creating the narrow trench in the CPW ground to lower the resonant frequency and enhance the isolation.

Chapter 3 presents the MEMS shunt switch based low actuation voltage, wideband Distributed MEMS Transmission Line (DMTL) phase shifter which exhibit a highly linear phase shift through the entire band. The phase shifter uses the same switch developed during the research. This 1-bit phase shifter can be cascaded with the other bits and can be used in phased array based systems.

Keeping the requirements of tunable devices in futuristic wireless communication architecture in view, two basic components such as tunable capacitor and inductors are developed with enhanced linearity and improved Q factor respectively as mentioned in chapter 4 and chapter 5. The same tri-layer membranes were used to realize capacitor plate and the inductor coil. The thesis concludes by suggesting the room for improvement of these devices as well as the future task directions in this field.

## सार

रेडियो फ्रीक्वेंसी माइक्रो इलेक्ट्रो मैकेनिकल सिस्टम्स (आरएफ एमईएमएस) आधारित उपकरणों पर व्यापक अध्ययन, इन उपकरणों के प्रदर्शन को अनुकूलित करने के लिए नोवेल डिजाइन और निर्माण प्रक्रिया के कार्यान्वयन के बाद इस थीसिस में प्रस्तुत किया गया है। आरएफ एमईएमएस शंट स्विच, स्विच आधारित एमईएमएस फेज शिफ्टर, ट्यून करने योग्य कैपेसिटर और बल्क-माइक्रोमशीन इंडक्टर्स के विकास के उद्देश्य से किए गए कार्य को हवाई अनुप्रयोगों के लिए भविष्य की अगली पीढ़ी की प्रणालियों में लागू किया जाएगा।

सभी धातु झिल्ली के बजाय त्रि-परत (नाइट्राइड-मेटल-नाइट्राइड) झिल्ली के साथ शुरू करने के लिए झिल्ली गुणों को बढ़ाने और तनाव मुक्त, तापीय रूप से स्थिर और कठोर संरचना का एहसास करने के लिए जांच की गई है। सेमीकंडक्टर टेक्नोलॉजी एंड एप्लाइड रिसर्च सेंटर, STAR-C (पूर्व में सोसाइटी फॉर इंटीग्रेटेड सर्किट एंड एप्लाइड रिसर्च, SITAR), बेंगलूर के नाम से भारतीय फाउंड्री की स्थापित एमईएमएस प्रक्रिया के अनुसार प्रक्रिया प्रवाह को अनुकूलित किया गया था। इन सभी संरचनाओं को कम आरएफ नुकसान के साथ-साथ कम परजीवी कैपेसिटर सुनिश्चित करने के लिए उच्च प्रतिरोधकता वाले सिलिकॉन सबस्ट्रेट पर गढ़ा गया है।

अध्याय 2 नई त्रि-परत झिल्ली का उपयोग करके एक इलेक्ट्रोस्टैटिक आरएफ एमईएमएस शंट स्विच प्रस्तुत करता है, जिसके परिणामस्वरूप 15V से कम एकचुएशन वोल्टेज, 35 डीबी से बेहतर उच्च आइसोलेशन और स्टिकशनलेस ऑपरेशन होता है। गुंजयमान आवृत्ति को कम करने और अलगाव को बढ़ाने के लिए CPW ग्राउंड में संकीर्ण खाई बनाकर इंडक्शन ट्यूनिंग को लागू किया जाता है।

अध्याय 3 एमईएमएस शंट स्विच आधारित कम एकचुएशन वोल्टेज, वाइडबैंड वितरित एमईएमएस ट्रांसमिशन लाइन (डीएमटीएल) चरण शिफ्टर प्रस्तुत करता है जो पूरे बैंड के माध्यम से एक अत्यधिक रैखिक चरण बदलाव प्रदर्शित करता है। चरण शिफ्टर अनुसंधान के दौरान विकसित उसी स्विच का उपयोग करता है। यह 1-बिट चरण शिफ्टर अन्य बिट्स के साथ कैस्केड किया जा सकता है और चरणबद्ध सरणी आधारित सिस्टम में उपयोग किया जा सकता है।

फ्यूचरिस्टिक वायरलेस कम्युनिकेशन आर्किटेक्चर में ट्यून करने योग्य उपकरणों की आवश्यकताओं को ध्यान में रखते हुए, ट्यून करने योग्य कैपेसिटर और इंडक्टर्स जैसे दो बुनियादी घटकों को क्रमशः बढ़ी हुई रैखिकता और बेहतर क्यू फैक्टर के साथ विकसित किया गया है जैसा कि अध्याय 4 और अध्याय 5 में उल्लेख किया गया है। यह वही त्रि-परत झिल्ली है जिसका उपयोग कैपेसिटर प्लेट और इंडक्टर्स के विकास के लिए किया गया। इस क्षेत्र में इन उपकरणों के सुधार के साथ-साथ भविष्य की कार्य दिशाओं के लिए सुझाव देकर थीसिस समाप्त होती है।

# TABLE OF CONTENTS

ACKNOWLEDGEMENTS	i
ABSTRACT	ii
संर	
TABLE OF CONTENTS	iii
LIST OF FIGURES	ix
LIST OF TABLES	xiv
LIST OF ABBREVIATIONS	xv
LIST OF SYMBOLS	xxi
Chapter1: Introduction	
1. Introduction	1
1.1. MEMS and Microsystem	1
1.2. Need for miniaturization	2
1.3. MEMS Fabrication: An Interdisciplinary nature	2
1.3.1. Bulk Micromachining	3
1.3.2. Surface Micromachining	3
1.3.3. LIGA process	4
1.4. Evolution of MEMS	5
1.5. Application areas of MEMS technology	6
1.6. RF MEMS technology	10
1.7. Application of RF MEMS technology	11
1.8. RF MEMS Switch technology	12
1.8.1. RF MEMS Switch configuration	14
1.8.2. Actuation mechanisms	15
1.8.3. Advantages of MEMS Shunt switch over Series switch	17
1.9. Application of RF MEMS Shunt switch	17
1.9.1. Phased array system	18
1.9.2. RF front end receiver	19

1.9.3. Reconfigurable antenna	20
1.9.4. Switch matrix	21
1.9.5. Digitized capacitor banks	22
1.10. Evolution of RF MEMS Shunt switch technology	23
1.11. Reliability consideration of capacitive switches	29
1.11.1. Stiction	29
1.11.2. Mechanical failure	31
1.11.3. Thermal failure	31
1.11.4. Creep failure	31
1.11.5. Self-pull-in failure	32
1.11.6. Pull-in voltage variation	32
1.11.7. Packaging	33
1.12. Challenges	33
1.13. Proposed plan of research	35
1.14. Dissertation scope	35
Chapter 2: Stictionless RF MEMS Shunt switch based on Tri-layer membrane topology	38
2.1. Introduction	38
2.2. Switch parameters	38
2.3. Electromagnetic design consideration of MEMS shunt switch	41
2.3.1. Physical description and working principle of MEMS shunt capacitive switch	41
2.3.2. Circuit model of MEMS capacitive shunt Switch	42
2.3.3. Loss in the MEMS switch	46
a. Substrate loss	46
b. Transmission line loss	46
2.4. Mechanical design consideration of MEMS shunt switch	47
2.4.1. Determination of spring constant of the membrane	47
2.4.2. Determination of pull-in voltage	49
2.4.3. Analysis of Multilayer membrane	51

2.4.4. Design consideration for Low spring constant MEMS shunt switch	51
2.4.5. Incorporation of holes in the membrane	53
2.4.6. Switching time calculation	54
2.5.Design, Fabrication and Characterization of fixed-fixed flexure based stictionless low actuation voltage RF MEMS switch based on tri-layer membrane	55
2.5.1. Implementation of tri-layer	55
2.5.2. Device structure	56
2.5.2.1.Selection of substrate	56
2.5.2.2.CPW design	57
2.5.2.3.Dielectric layer	57
2.5.2.4.Membrane design	57
2.5.3. Fabrication of RF MEMS switch	64
2.5.4. Characterization of MEMS Switch	65
2.5.5. CLR parameter extraction	69
2.5.6. Fitting of CLR parameter	71
2.5.7. Switching time measurement	75
2.5.8. Reliability measurement	76
2.6.Summary	77
2.7.Conclusions	80
Chapter 3:Low actuation voltage MEMS Phase Shifter using tri-layer Membrane based Shunt Switch	81
3.1 Introduction	81
3.2 Types of Phase Shifter	82
3.3 Development of Phase Shifter	83
3.4 Literature Survey	86
3.5 Design of MEMS Phase Shifter	94
3.5.1 Equivalent circuit modeling of Phase Shifter	96
3.5.2 Phase shift	98
3.5.3 Effect of Bragg frequency	98

3.5.4	Design of CPW line	100
3.6	Development of MEMS switch for Phase Shifter	100
3.6.1	MEMS Switch Simulation	101
a.	Mechanical simulation	101
b.	EM simulation	103
3.6.2.	MEMS switch fabrication	104
3.6.3.	Characterization of MEMS switch	104
3.6.4.	CLR parameter extraction	105
3.7.	Development of MEMS Phase Shifter	107
3.7.1.	Simulation of MEMS Phase Shifter	107
3.7.2.	Fabrication of MEMS Phase Shifter	108
3.7.3.	Characterization of MEMS Phase Shifter	109
3.7.4.	CLR Parameter extraction of MEMS Phase Shifter	111
3.8.	Conclusions	113
Chapter 4:	Thermally stable Low actuation voltage Bulk-micromachined Tunable RF MEMS Capacitor	115
4.1	Introduction	116
4.2	Types of MEMS Capacitor	119
4.2.1	Gap tuning capacitor	119
a.	Gap tuning capacitor with two plates	119
b.	Gap tuning capacitor with three plates	121
4.2.2.	Area Tuning capacitor	121
4.2.3.	Dielectric tuning capacitor	122
4.3.	Evolution of MEMS tunable capacitor	123
4.4.	Design consideration of tunable capacitor	137
4.5.	Design, Fabrication and Characterization of thermally stable tri-layer membrane based parallel plate tunable capacitor	139
4.5.1.	Design of Tunable capacitor	139
4.5.2.	Mechanical and EM analysis of tunable capacitor	141
a.	Mechanical analysis	141
(a)	Model analysis	141

(b) Pull-in voltage analysis	141
(c) Capacitance variation and linearity	142
b. EM analysis	144
4.5.3. Fabrication of Tunable Capacitor	144
4.5.4. Characterization of Tunable Capacitor	145
4.6. Conclusions	147
Chapter 5: Bulk-micromachined RF MEMS Inductor with improved ‘Q’ factor	148
5.1. Introduction	148
5.2. MEMS based Inductor	150
5.3. MEMS based Tunable Inductor	151
5.4. Challenges of MEMS Inductor	153
5.5. Research towards the performance improvement	156
5.6. Literature Survey	161
5.6.1. Planar Bulk-micromachined inductor	161
5.6.2. Self-Assembled Inductor	163
5.6.3. Inductor based on different processes	165
5.6.4. Tunable Inductor	166
5.6.5. Inductor based on different materials	168
5.7. Inductor Design Consideration	170
5.7.1. Effect of metallization thickness	171
5.7.2. Effect of parasitic capacitance	171
5.7.3. Effect of surface resistivity	171
5.7.4. Effect of passivation layer	172
5.7.5. Effect of width of the strip	172
5.7.6. Effect of spacing	172
5.7.7. Effect of magnetic cores	172
5.7.8. Effect of number of turns	172
5.7.9. Effect of air gaps	173
5.8. Design, Fabrication and Characterization of Novel MEMS Inductor	173
5.8.1. Design of Spiral Inductor	173
a. Design of Rectangular Spiral Inductor	174

b. Design of Circular Spiral Inductor	175
5.8.2. Simulation of Spiral Inductor	176
a. Simulation of Rectangular Spiral Inductor	176
b. Simulation of Circular Spiral Inductor	178
5.8.3. Fabrication of Spiral Inductor	180
5.8.4. Characterization of Spiral Inductor	181
5.9. Conclusions	183
6. Conclusions and Future Work	184
REFERENCES	187
APPENDIX I : MEMS Device Fabrication Process Flow and Mask Sets	218
PUBLICATIONS	231
BIO-DATA	232

## LIST OF FIGURES

<b>Figure 1.1</b>	Components of Microsystems.	1
<b>Figure 1.2:</b>	a) Bulk micromachining process, and (b) Surface micromachining process, and (c) LIGA.	5
<b>Fig. 1.3</b>	a) Comb-drive MEMS actuator and b) Micro gear (Image courtesy of Sandia National Laboratories, SUMMIT™ Technologies).	8
<b>Fig. 1.4</b>	a) The first commercial accelerometer from analog devices (1990) and b) capacitive sense plate (60 μm deep)	8
<b>Fig. 1.5</b>	a) Disposable blood pressure sensor connected to an IV line, (b) Disposable blood pressure sensors (as shipped), and (c) Intra-cardial Catheter tip sensors for monitoring blood pressure during cardiac catheterization, shown on the head of a pin	8
<b>Fig. 1.6</b>	A microphotograph of a micro-mirror by Alcatel-Lucent	9
<b>Fig. 1.7</b>	MEMS device development process	12
<b>Fig. 1.8</b>	(a) Metal to Metal contact switch, and (b) Capacitive shunt switch	14
<b>Fig. 1.9</b>	Metal to Metal contact switch and capacitive shunt switch	15
<b>Fig.1.10</b>	Applications of Phased array based system	18
<b>Fig. 1.11</b>	a) Conventional RF Transceiver, b) Possible RF MEMS receiver architecture using MEMS	20
<b>Fig. 1.12</b>	Reconfigurable Antenna	21
<b>Fig. 1.13</b>	Basic topology of Switch Matrix	22
<b>Fig. 1.14</b>	Digital capacitor bank implemented with switching elements and fixed-value capacitors	23
<b>Fig. 1.15</b>	Dielectric charging effect in MEMS switch	30
<b>Fig. 2.1</b>	MEMS shunt switch configuration in CPW and Microstrip	41
<b>Fig. 2.2</b>	Equivalent circuit model of MEMS shunt switch	43
<b>Fig. 2.3</b>	Fixed-fixed beam with concentrated load P and evenly distributed	47

	about the centre	
<b>Fig. 2.4</b>	Fixed-fixed beam modeled as a stretched wire with vertical load P	48
<b>Fig. 2.5</b>	3-D model and equivalent 1-D mechanical model	50
<b>Fig. 2.6</b>	Beam with multilayer structure	51
<b>Fig. 2.7</b>	Presence of holes in the membrane	53
<b>Fig. 2.8</b>	1-D non-linear MEMS model	54
<b>Fig. 2.9</b>	Top view of the central part of the membrane	58
<b>Fig. 2.10</b>	(a) Dimension of the membrane, (b) 2-D layout, and Top view of the central part of the membrane	59
<b>Fig. 2.11</b>	Pull-in voltage of switches of various arm length	60
<b>Fig. 2.12</b>	Simulated (a) Insertion loss and (b) Isolation of switch	61
<b>Fig. 2.13</b>	(a) Dimensional details (b) 2-D layout and (c) 3-D meshed layout	62
<b>Fig. 2.14</b>	Pull-in voltage of (a) 2-meander (b) 3-meander beam	63
<b>Fig. 2.15</b>	S-Parameter plot (a) Insertion loss (ON state). (b) Isolation (OFF state)	64
<b>Fig. 2.16</b>	Fabricated RF MMEMS switch (a) Straight arm and (b) Meander arm	65
<b>Fig. 2.17</b>	(a) Measured insertion loss, (b) Return loss and (c) Isolation of switches with straight arm	67
<b>Fig. 2.18</b>	Measured (a) insertion loss, (b) Return loss, and (c) Isolation of switches with Meander arms	69
<b>Fig. 2.19</b>	Schematic for RF MEMS switch using extracted CLR parameter.	72
<b>Fig. 2.20</b>	Simulated RF Performance plot of Straight arm using extracted CLR parameter	73
<b>Fig. 2.21</b>	Simulated RF Performance plot of Meander arm using extracted CLR parameter	74
<b>Fig. 2.22</b>	Switching time measurement plot of RF MEMS switch (a). ON time (b).OFF time	76
<b>Fig. 2.23</b>	Reliability measurement plot of RF MEMS switch	77
<b>Fig. 3.1</b>	Configuration for DMTL phase shifter with MEMS shunt switch over CPW transmission line	95
<b>Fig. 3.2</b>	The unit-length equivalent circuit of an unloaded CPW line	96

<b>Fig. 3.3</b>	The unit-length equivalent circuit of a loaded CPW line	97
<b>Fig. 3.4</b>	(a) Dimensional details (b) 2-D layout and (c) 3-D layout	101
<b>Fig. 3.5</b>	(a) 2-D Pull-in plot and (b) 3-D pull-in plot	102
<b>Fig. 3.6</b>	Different mode shapes a) Mode1 b) Mode 2 c) Mode 3 and d) Mode 4	102
<b>Fig. 3.7</b>	S-Parameter plot (a) Insertion loss (ON state) (b) Isolation (OFF state)	103
<b>Fig. 3.8</b>	(a) Fabricated MEMS Switch (b) SEM image	104
<b>Fig. 3.9</b>	(a) Measured Insertion Loss (dB) and Return Loss (dB) of fabricated MEMS switch (b) Measured isolation (dB) of fabricated MEMS Switch	105
<b>Fig. 3.10</b>	(a) Lumped equivalent circuit, (b) Simulation model of equivalent circuit	106
<b>Fig. 3.11</b>	(a) Insertion and Return loss plot (b) Isolation plot of Lumped equivalent circuit	107
<b>Fig. 3.12</b>	(a) UP state (b) DOWN state of MEMS Phase Shifter	108
<b>Fig. 3.13</b>	Fabricated MEMS Phase Shifter	109
<b>Fig. 3.14</b>	(a) Measured I.L. plot, (b) Measured R.L. plot of MEMS Phase Shifter and (c) Measured phase difference plot of MEMS Phase Shifter	111
<b>Fig. 3.15</b>	(a) Equivalent circuit of MEMS Phase Shifter	112
<b>Fig. 3.15</b>	(b) R.L. plot of equivalent circuit of MEMS Phase Shifter	112
<b>Fig. 3.15</b>	(c) Phase difference plot of equivalent circuit of MEMS Phase Shifter	113
<b>Fig. 4.1</b>	Schematic model of conventional two-parallel-plate tunable capacitors	120
<b>Fig. 4.2</b>	Schematic model of conventional three-parallel-plate tunable capacitors	121
<b>Fig. 4.3</b>	3-D view of fabricated area tunable capacitors	122
<b>Fig. 4.4</b>	Dielectric tuned capacitor.	123
<b>Fig. 4.5</b>	(a) 2-D layout and (b) 3-D layout of tunable capacitor	139
<b>Fig. 4.6</b>	Top view of the tunable capacitor	140

<b>Fig. 4.7</b>	(a) Modal analysis of tri-layer membrane, and (b) All metal membrane	141
<b>Fig. 4.8</b>	(a) Pull-in voltage of tri-layer membrane, b) All metal membrane	142
<b>Fig. 4.9</b>	(a) Capacitance vs voltage performance of tri-layer membrane and all metal membrane.	143
	(b) Linearity Vs Voltage Plot (Series1 –Tri-layer & Series 2-All Metal)	143
<b>Fig. 4.10</b>	Simulated ‘Q’ factor of tunable capacitor	144
<b>Fig. 4.11</b>	Fabricated Tunable Capacitor with Tri-layer membrane and b) SEM image.	144
<b>Fig. 4.12</b>	(a) Measurement set up, and (b) Capacitance variation meas. Vs simulated	146
<b>Fig. 5.1</b>	(a) Spiral Inductor, and (b) Equivalent circuit model of planar inductor.	170
<b>Fig. 5.2</b>	(a) 2-layout, and (b) 3-D layout of rectangular spiral inductor	174
<b>Fig. 5.3</b>	Tri-layer arrangement of the rectangular spiral inductor coil	174
<b>Fig. 5.4</b>	(a) 2-layout, and (b) 3-D layout of circular spiral inductor	175
<b>Fig. 5.5</b>	Tri-layer arrangement of the circular spiral inductor coil	175
<b>Fig. 5.6</b>	(a) 3-D simulation setup, (b) ‘Q’ factor plot, and (c) Inductance plot of rectangular spiral inductor	177
<b>Fig. 5.7</b>	3-D simulation setup of rectangular inductor with an all metal membrane	177
<b>Fig. 5.8</b>	‘Q’ factor comparison between tri-layer and all metal membrane inductor coil	178
<b>Fig. 5.9</b>	(a) 3-D simulation setup, (b) ‘Q’ factor plot, and (c) Inductance plot of circular spiral inductor	179
<b>Fig. 5.10</b>	3-D simulation setup of inductor with an all metal membrane	180
<b>Fig. 5.11</b>	‘Q’ factor comparison between tri-layer and all metal membrane based circular inductor coil	180
<b>Fig. 5.12</b>	Fabricated (a) Rectangular, (b) Circular Spiral Inductor	181

<b>Fig. 5.13</b>	Measured and Simulated Q plot of (a) Rectangular and (b) Spiral Inductor	182
<b>Fig. 6.1</b>	(a) Proposed schematic of tunable filter, and (b) Simulated results	185
<b>Fig. A1</b>	MEMS device development process	219
<b>Fig. A2</b>	Switch masks Set	220
<b>Fig. A3</b>	Phase shifter mask sets	223
<b>Fig. A4</b>	Tunable Capacitor mask sets	225
<b>Fig. A5</b>	Inductor mask sets	228

## LIST OF TABLES

<b>Table 1.1</b>	Application of MEMS and Microsystems	9
<b>Table 2.1</b>	Comparison of switch characteristics (Switch with straight arms)	78
<b>Table 2.2</b>	Comparison of switch characteristics (Switch with meander arms)	79
<b>Table 2.3</b>	Comparison of shunt switch works	80
<b>Table 3.1</b>	Comparison of DMTL Phase Shifters works	114
<b>Table 4.1</b>	Comparison of tunable capacitors works	146
<b>Table 5.1</b>	Comparison of inductor works	183

## LIST OF ABBREVIATION

AlN	: Aluminum Nitride
Al	: Aluminum
Al <sub>2</sub> O <sub>3</sub>	: Alumina
Au	: Gold
BaSrTiO <sub>3</sub>	: Barium StronciumTitanate
BEOL	: Back End of Line
BiCMOS	: Bipolar CMOS
CeNSE	: Centre for Nano-Science and Engineering
CMOS	: Complementry metal oxide semiconductor)
CNT	: Carbon Nano Tube
COMP	: Compressive Molding Planarization
CPW	: Co-planar waveguide
DMTL	: Distributed MEMS Transmission Line
DRIE	: Deep reactive-ion etching
DPFM	: Double Polysiliconfour metal
EIRP	: Effective Isotropic Radiated Power
ESR	: Equivalent Series Resistance

ECDM	: Electrochemical discharge machining
EMC	: Electro Magnetic Compatibility
EMI	: Electromagnetic Interference
FBAR	: Film Bulk Acoustic Resonator
FEM	: Finite element method
FETs	: Field effect transistors
FOGs	: Fiber-optic gyros
FOM	: Figure of Merit
FMR	: Ferromagnetic-resonant
GaAs	: Gallium Arsenide
GAETEC	: Gallium Arsenide Enabled Technology Centre
GHz	: Giga Hertz
GPS	: Global Positioning System
GSM	: Global system for mobile communications
HDICPCVD	: High Density Inductively coupled plasma chemical vapor deposition
HEMT	: High Electron Mobility Transistor
pHEMT	: Pseudomorphic High Electron Mobility Transistor
HIS	: High impedance surface
HMICs	: Hybrid Monolithic Integrated Circuits
HP	: Hewlett Packard (HP).
HRS	: High Resistivity Substrate
IC	: Integrated circuit
ICP	: Inductively coupled plasma

IIP3	: Third-order intercept point
I.L.	: Insertion loss
IOT	: Internet of Things
IPD	: Integrated Passive Devices
LCP	: Liquid Crystal Polymer
LIGA	: Lithography (Lithographie), Electroforming (Galvanoformung), and Plasticmoulding (Abformung)
LTCC	: Low Temperature Co-Fired Ceramic
LF	: Linearity factor
LNAs	: Low Noise Amplifiers
LPCVD	: Low Pressure Chemical Vapor Deposition
MST	: Micro systems technology
MOEMS	: Micro Electro optical systems
$\mu$ TAS	: Micro total analysis systems
MAM	: metal-air-metal
MESA	: Micro-Elevator by Self Assembly
MESFET	: Metal Semi-conductor Field Effect Transistor
MEMS	: Micro Electro Mechanical Systems
MESFETs	: Metal–semiconductor field effect transistors
MHz	: Mega Hertz
MICs	: Monolithic Intrgrated Circuits
MIM	: Metal-Insulator-Metal
MMICs	: Monolithic microwave integrated circuits

$\mu$ NMR	:Micro-nuclear magnetic resonance
MNPM	: Magnetic-nano-particles-medium
MTR	: Maximum tuning range
MUMPs	: Multi User MEMS Polysilicon process
NiFe	: Nickel-Iron
NLC	: Nematic Liquid Crystal
Ni-Fe	: Nickel-Ferrite
nH	: Nano-Henry
OPS	: Oxidized Porous Silicon
PA	: Power Amplifier
PAA	: Porous Anodic Alumina
PCB	: Printed Circuit Board
PMMA	: Poly Methyl Metha Acrylate
PolyMUMPS	: Poly Multi User MUMPS
PoP	: Package on Package
pH	: Pico-Henry
PGS	: Patterned Ground Shields
PDMA	: Plastic Deformation Magnetic Assembly
PDA's	: Personal data assistants
PECVD	: Plasma Enhanced Chemical Vapor Deposition
pHEMT	: Pseudomorphic High Electron Mobility Transistor
PZT	: Lead zirconium tetitanate

QSC	: Quadruple Series Capacitor
RF	: Radio Frequency
RF MEMS	: RF Micro Electrical Mechanical systems
RFICs	: RF integrated circuits
RFIDs	: Radio Frequency Identification Tags
RIE	: Reactive Ion Etching
R.L.	: Return Loss
RSC	: Rockwell Scientific Centre
SAW	: Surface Acoustic Wave
SCAP	: Silicon capacitive pressure sensor
SCREAM	: single crystal reactive etching and metallization
Si	: Silicon
SiP	: System in Package
SiO <sub>2</sub>	: Silicon di-Oxide
SITAR	: Society for Integrated Circuit and Applied Research
SOC	: System on Chip
SOI	: Silicon –On-Insulator
SOS	: Silicon-on-Sapphire
SPST	: Single-Pole Single-Throw
SPDT	: Single Pole Double Throw
SPNT	: Single Pole N throw
SRF	: Self-resonant frequency
SSLDE	: Silicon Sacrificial Layer Dry Etching

STAR-C : Semiconductor Technology and Research Centre

STO : Strontium Titanate Oxide

TEM : Transverse-Electric-Magnetic

TiO<sub>2</sub> : Titanium Oxide

TIJ : thermal inkjet technology

TRM : Transmit Receive Module

TSV : Through Silicon Vias

TTD : True-time delay

UAVs : Unmanned Aerial Vehicles

UMTS : Universal mobile telecommunications system

VCOs : Voltage controlled oscillators

VSWR : Voltage Standing Wave Ratio

WLAN : Wireless Local Area Network

WLCSP : Wafer Level Chip Scale Package

YIG : Yttrium-iron-garnet

## LIST OF SYMBOLS

$A$	: Area of the capacitor plate
$Au$	: Gold
$b$	: Damping Co-efficient
$\alpha$	: Alpha-Line loss in Np/m
$C_{up}$	: Up-state Capacitance
$C_{down}$	: Down state capacitance
$C$	: Capacitance
$C_b$	: Capacitance associated with the MEMS Bridge
$C_{pp}$	: Parallel plate capacitance
$C_f$	: Fringing field capacitance
$C_l$	: Loaded Line Capacitance
$C_{on}$	: On-state capacitance
$C_{off}$	: Off-state capacitance
$C_{ratio}$	: Capacitance Ratio
$C_t$	: Unit Length Capacitance
$\Delta$	: Delta

$\delta$	: Skin depth
dB	: Decibel
E	: Young's Modulus
$\epsilon_0$	: Permittivity of the air
$\epsilon_{\text{eff}}$	: Effective Dielectric constant
$\epsilon_r$	: Relative permittivity of the medium
fF	: Femto-farad
$f_0$	: Resonant Frequency
$f_{\text{cutoff}}$	: Cut-off Frequency
$F_c$	: Vander-wall force
$F_e$	: Electrostatic Pull-down force
G	: Torsional modulus
I	: Moment of Inertia
J	: Torsional constant
k	: Spring Constant
$K_z$	: Total spring constant
$K'$	: Spring constant due to stiffness of the bridge
$K''$	: Spring constant due to biaxial residual stress within the bridge
$K(k')$	: Complete elliptic integral of the first kind
$K_s$	: Stress stiffening spring constant
L	: Inductance
$L_t$	: Unit Length Inductance
$M_s$	: Saturation Magnetization

MV/cm	: Mega-volts per centimeter
$\mu_0$	: Permeability of the medium in air
$\mu$	: Permeability
$\mu\text{s}$	: Micro-second
Np	: Neper- Ratio of gain or Loss of electronic signals
$\omega$	: Omega- Angular Frequency
pF	: Pico-Farad
$P_{\text{loss}}$	: Power loss in the bridge
R	: Resistance
$R_s$	: Series Resistance
$t_d$	: Dielectric thickness
$g_0$	: Initial Gap Height
$\mu\text{s}$	: Micro-second
$\pi$	: Pi
P	: Load distributed across the entire beam
$P_{\text{loss}}$	: Power loss in the bridge
$q(x,z)$	: Distributed load due to the electrostatic actuating force and the mechanical contact force
Q	: Quality factor
$R_{\text{cpw}}$	: Resistance of CPW line
$\rho$	: Resistivity
$\rho_{\text{si}}$	: Resistivity of the substrate
$\Delta$	: Delta- difference between two entities

$\sigma$	: Sigma-Conductivity of the medium
$\sigma_0$	: Bi-axial residual stress
$s$	: Periodic spacing between two adjacent MEMS bridges
$S_{11}$	: Reflection Coefficient
$S_{21}$	: Transmission Coefficient
$SF_6$	: Sulphur Hexa Fluoride
$SiO_2$	: Silicon di-Oxide
$Si_3N_4$	: Silicon Nitride
$t$	: Thickness of the beam
$t_d$	: Thickness of the Dielectric layer
$t_s$	: Switching Time
$V_{pull-in}$	: Pull-in voltage
$V_s$	: Applied Voltage
$V_t$	: Phase velocity
$V_{th}$	: Threshold voltage
$\nu$	: Poission's Ratio
$\omega_B$	: Bragg Frequency
$w$	: Width of the beam
$W$	: Width of the actuation electrode
$w_b$	: Width of the bridge
$X_e$	: Weighted volumetric average
$\xi$	: Force per unit length
$Z_0$	: Characteristic Impedance

- $Z_b$  : Impedance of the beam
- $Z_l$  : Characteristic impedance of loaded line
- $Z_{lu}$  : Characteristic impedance of loaded line in UP state
- $Z_{ld}$  : Characteristic impedance of loaded line in DOWN state