



UNIVERSITI PUTRA MALAYSIA

**DESIGN OF MEMS INDUCTOR AND VARACTOR FOR LOW NOISE
VOLTAGE CONTROLLED OSCILLATORS**

MARYAM RAHIMI

FK 2009 41

**DESIGN OF MEMS INDUCTOR AND VARACTOR FOR LOW NOISE
VOLTAGE CONTROLLED OSCILLATORS**

**By
MARYAM RAHIMI**

**Thesis Submitted to the School of Graduate Studies, University Putra Malaysia, in
Fulfillment of the Requirements for the Degree of Master of Science**

January 2009



DEDICATIONS

“To My family members especially my beloved husband and my ever -encouraging parents for their love and support.”



Abstract of thesis presented to the Senate of university Putra Malaysia in fulfillment of the requirements for the degree of Master of Science

**DESIGN OF MEMS INDUCTOR AND VARACTOR FOR LOW NOISE
VOLTAGE CONTROLLED OSCILLATORS**

By

MARYAM RAHIMI

May 2008

Chairman : Professor Sudhanshu Shekhar Jamuar, PhD

Faculty : Engineering

Micro-Electro-Mechanical-Systems (MEMS) technology has been used to develop high quality factor (Q), low cost and low power consumption circuit blocks in RF communication systems.

This research focuses on the design of high-performance MEMS inductor and varactor for use in Complementary Metal-Oxide Semiconductor (CMOS) voltage controlled oscillators (VCO) operating at 2.4 GHz. The air suspended inductor has been designed using MEMS technology to reduce the resistive loss and the substrate loss. Low-resistivity material has been used. A MEMS two-gap tunable capacitor, using two parallel plates (one fixed and one movable), has been designed. The capacitance can be varied by applying low voltage to the movable plate. The pull-in voltage has been optimized to achieve low phase noise, low power consumption, and a wide frequency tuning range for VCO. The MEMS inductor and MEMS capacitor have been used in the design of VCO.



The inductor has been modeled with a physical, equivalent two-port model known as Yue's model to compute the parameters and Q factor of the inductor. The designed inductor has a Q factor of 27 and the inductance is about 2.87nH at 2.4GHz. The capacitor has a value of 2.04 pF capacitance and Q factor of 40 at 2.4 GHz.

The proposed MEMS inductor and varactor has been used in simulation of VCO to determine the effect of high Q factor on the VCO phase noise. The active part of the circuit has been designed using CMOS. Based on the simulation, low phase noise and low power consumption have been obtained simultaneously. The results of -117.7 dBc/Hz at 100 KHz and 11mW have been achieved for phase noise and power consumption of VCO respectively.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Master Sains

**REKABENTUK INDUKTOR DAN VARACTOR MEMS UNTUK PENGAYUN
TERKAWAL VOLTAN HINGAR RENDAH**

Oleh

MARYAM RAHIMI

Mei 2008

Pengerusi : Professor Sudhanshu Shekhar Jamuar, PhD

Fakulti : Kejuruteraan

Teknologi MEMS telah digunakan untuk membangunkan blok litar yang mempunyai faktor kualiti yang tinggi (Q), dengan kos yang rendah serta menggunakan kuasa elektrik yang minima dalam sistem telekomunikasi yang menggunakan frekuensi radio (RF).

Penyelidikan yang dijalankan tertumpu kepada rekaan inductor dan kapasitor MEMS berprestasi tinggi untuk digunakan di dalam CMOS (Semikonduktor pelengkap logam-oksida) VCO (Pengayun kawalan voltan) yang beroperasi pada 2.4GHz. Inductor Q tinggi yang tergantung di udara direka menggunakan teknologi MEMS untuk mengurangkan kehilangan rintangan substrat. Bahan berintangan rendah telah digunakan. Kapasitor boleh ubah direka menggunakan dua kepingan selari (Satu ditetapkan kedudukannya manakala satu lagi boleh bergerak). Kapasitor boleh diubah dengan mengaplikasikan voltan rendah terhadap kepingan bergerak. Voltan penarik-masuk telah

diptimumkan untuk mendapatkan lingar fasa yang rendah, menggunakan kuasa rendah dan mempunyai julat taran frekuensi yang lebar untuk VCO. Kedua-dua induktor dan kapasitor MEMS digunakan untuk rekaan VCO.

Induktor ini dimodalkan secara fizikal bersamaan dengan model dua port atau lebih dikenali sebagai model Yue untuk mengirakan parameter dan faktor Q induktor. Induktor yang direka mempunyai nilai faktor Q 27 dan ianya adalah lebih kurang 2.87nH pada 2.4GHz. Kapasitor pula mempunyai nilai kapasitan 2.04pF dengan factor Q 40 pada 2.4 GHz.

Cadangan induktor dan kapasitor MEMS telah digunalan di dalam simulasi VCO bagi menentukan kesan faktor Q tinggi pada hangar fasa VCO. Bahagian aktif litar telah dibina menggunakan CMOS. Berdasar kepada simulasi, hangar fasa rendah dan penggunaan kuasa yang rendah telah dicapai.Keputusan yang diperoleh adalah -117.7dBc/Hz pada 100KHz dan 11mW telah kecapi untuk fasa hingar dan penggunaan kuasa VCO.

ACKNOWLEDGEMENTS

I wish to express my sincere gratitude to Professor Dr. Sudhanshu Shekhar Jamuar, the chairman of my supervisory committee, for his invaluable guidance, patience, understanding, encouragement and supervision throughout the course of study until the completion of this thesis.

I am also very grateful to other members of the supervisory committee, Dr. Mohd Nizar Hamidon and Dr. Mohd Rais Ahmad for their supports and comments.

I would like to express my special thanks to my truly friends, Miss Elham Moazami for being with me during this long way, Dr. Aziz Naghdivand for his help and advices at all times, EE department staff and numerous people who have walked with me along this way.

My deep heartfelt gratitude and love to my parents, Reza Rahimi and Nasrin Shahraki for their unconditional supports and encouragement, my lovely sister and brother Narges and Mehdi Rahimi for their love, help and understanding and my special thanks and appreciation to my beloved husband, Dr. Mehdi Bayat because of his assistance, support, help, encouragement and patience throughout this long process.



TABLE OF CONTENTS

	Page
DEDICATION	ii
ABSTRACT	iii
ABSTRAK	v
ACKNOWLEDGEMENT	vii
APPROVAL	ix
DECLARATION	x
LIST OF TABLES	xiv
LIST OF FIGURES	xv
LIST OF ABBREVIATIONS	xviii
CHAPTER	
1. GENERAL INTRODUCTION	1
1.1. Introduction	1
1.2. Voltage controlled oscillator	2
1.3. Micro-Electro-Mechanical systems	4
1.4. Problem statement	6
1.5. Objectives	7
1.6. Thesis layout	8
2. A REVIEW OF MEMS TECHNOLOGIES AND DEVICES	9
2.1. MEMS and Nanotechnology	9
2.2. MEMS applications	11
2.3. Fabricating MEMS devices	13
2.3.1. Deposition process	14
2.3.2. Lithography	14
2.3.3. Etching process	16
2.4. MEMS LC Tank	17
2.4.1. MEMS inductor	18
2.4.1.1. MEMS inductor specification	19
2.4.1.2. Equivalent lumped circuit model	20
2.4.1.3. Modeling of inductor	21
2.4.1.4. Review of previous works on inductor	23
2.4.2. MEMS varactor	27
2.4.2.1. MEMS varactor specification	27
2.4.2.2. MEMS varactor structures	28
2.4.2.3. Review of previous works on varactor	30
2.5. Basic principles of oscillator	31
2.5.1. Voltage controlled oscillator needs and requirements	32



2.5.2. Phase noise in VCO	33
2.5.3. Effect of phase noise in RF circuits	34
2.5.4. Analysis of phase noise and Leeson's model for estimating phase noise in an LC-tank	36
2.5.5. Review of previous works on varactor	37
2.6. Summary	39
3. METHODOLOGY	41
3.1. Introduction	41
3.2. Design of micromachined inductor	41
3.2.1. Layout design	43
3.2.2. Design and simulation process	46
3.2.2.1. Material and process	47
3.2.2.2. Design flow Process	48
3.3. Modeling and Q factor of inductor	51
3.3.1. Computation of parameters of Yue's model	51
3.3.2. Quality factor of inductor	53
3.4. Micro machined tunable capacitor	55
3.4.1. Mechanical model of varactor	55
3.4.2. Pull in effects	57
3.4.3. Design of capacitor using CoventorWare software	58
3.4.3.1. Material	58
3.4.3.2. Process	59
3.4.3.3. Q factor of the varactor	61
3.5. LC- tank	63
3.5.1. Quality factor of an LC-tank	63
3.6. Oscillators	64
3.7. CMOS varactor diode	68
3.7.1. Q of the varactor diode	71
3.8. Cross-coupled pair VCO design	72
3.9. Power dissipation	74
3.10. Summary	75
4. RESULTS AND DISCUSSION	77
4.1. Introduction	77
4.2. Greenhouse results for inductor	77
4.3. Simulation results for inductor from CoventorWare	78
4.4. Simulation results for capacitor from CoventorWare	83
4.5. Q factor results	85
4.6. VCO	86
4.7. Conclusions	89
5. CONCLUSION AND RECOMMENDATION	91

5.1.Conclusion	91
5.1.1. MEMS inductor	92
5.1.2. MEMS capacitor	94
5.1.3. VCO phase noise	95
5.1.4. VCO power consumption	96
5.2. Scope of future research	96
REFERENCES	98
APPENDICES	105
BIODATA OF THE STUDENT	108



LIST OF TABLES

Table	page
2.1 Examples of present and future application areas for MEMS.	12
2.2 Summary of reviewing MEMS tunable capacitors.	30
2.3 Summary of reviewing VCO.	38
4.1 Calculated value of inductor using Matlab.	78
4.2 The inductance and resistance obtained from CoventorWare analysis.	81
4.3 The calculated parameters of inductor.	86
5.1 Comparison and validation of inductor results	93
5.2 Comparison and validation of varactor results	95



LIST OF FIGURES

Figure	Page
1.1 Block diagram of a generic wireless transceiver.	2
1.2 Classification of oscillators.	2
1.3 Colpitts oscillator	4
1.4 Block diagram of a Transceiver	6
2.1 General Process of photolithography	16
2.2 Positive feedback system with frequency- selective network $F(s)$.	18
2.3 On-chip inductor different shapes: (a) Square, (b) Hexagonal, (c) Octagonal and (d) Circular	19
2.4 Distributed capacitance and series resistance in the inductor	20
2.5 A simple equivalent circuit of the high-frequency inductor	20
2.6 Frequency response of the impedance of an RFC	21
2.7 Lumped inductor models: (1) Meyer's model, (2) Ashby's model, (3) Burghartz's model, (4) Yue's model	22
2.8 Schematic model of a parallel-plate capacitor	28
2.9 Schematic model of the three-parallel-plate tunable capacitor	29
2.10 Schematic model of the double-air-gap tunable capacitor	29
2.11 The structure of positive feedback loop oscillator	31
2.12 Definition of VCO	32
2.13 Output of (a) ideal oscillator, (b) practical with phase noise oscillator	34

2.14	(a) Effect of oscillator phase noise in a receiver, (b) Effect of oscillator phase noise in a transmitter	35
2.15	Flicker and thermal noise of an amplifier	37
3.1	The layout of inductor	44
3.2	The current direction in each segment of inductor	46
3.3	Process table of CoventorWare	48
3.4	The fabrication process of inductor	49
3.5	Layout of designed inductor	49
3.6	Meshing flow in CoventorWare	50
3.7	Lumped inductor model (Yue's model)	51
3.8	The fixed ended beam will be formed after applying voltage	56
3.9	The mechanical model of MEMS varactor	56
3.10	Two gap tunable capacitor structure	59
3.11	The dimensions of capacitor	60
3.12	The design flow of capacitor	61
3.13	Distributed RC model of the micromachined tunable capacitor	62
3.14	(a) Direct feedback from drain to source, (b) Feedback with an impedance transformer	65
3.15	(a) Colpitt's, (b) Hartley oscillators	66
3.16	A VCO topology with a tail current at the source of NMOS pair	67
3.17	The response of the B-S-D varactor by applying voltage to the gate	69
3.18	Circuit to characterize the varactor	70
3.19	Varactor capacitance versus bias voltage characterize	71



3.20	VCO circuit with positive and negative resistance	73
4.1	Mesh model of inductor	78
4.2	Changes of inductance (a) and resistance (b) of inductor versus frequency	80
4.3	Current density in conductor	82
4.4	Conductor current density flow in vectors	83
4.5	The mesh model of capacitor	83
4.6	The results of capacitor by MemElectro analyzer	84
4.7(a)	Deformation of beam under stress, results of MemMech analyzer	85
4.7(b)	Optimized beam without considerable deformation	85
4.8	The schematic of the oscillator using ADS	88
4.9	Output of oscillator	89
4.10	Phase noise measurement of oscillator	89



LIST OF ABBREVIATIONS/ NOTATIONS

Abbreviations

2D	Two Dimension
3D	Three Dimension
AC	Alternating Current
ADS	Agilent's Advanced Design System Program
AM	Amplitude Modulation
BEM	Boundary Element Method
BICMOS	Bipolar Complementary Metal Oxide Semiconductor
BW	Band Width
CMOS	Complementary Metal Oxide Semiconductor
CPW	Coplanar Waveguide
CVD	Chemical Vapor Deposition
DAC	Digital to Analog Converter
DC	Direct Current
DNA	Deoxyribonucleic Acid
DRIE	Deep Reactive Ion Etching
FBAR	Film Bulk Acoustic Resonators
FEM	Finite Element Method
FG	Functionally graded
GMD	Geometric Mean Distance
HP	Hewlett-Packard Company



IC	Integrated Circuit
LC-tank	A parallel circuit consists of an inductor and a capacitor
LNA's	Low Noise Amplifiers
LO	Local Oscillator
MCM	Multi Layer Thin Film Multi Chip Module
MEMS	Micro Electro Mechanical Systems
MIM	Metal Insulator Metal
MMIC	Monolithic Microwave ICs
MOSFET	Metal Oxide Semiconductor Field Effect Transistor
MUMPS	Multi User MEMS Processes
NEC	Nippon Electric Company
OPS	Oxide Porous Silicon
PA	Power Amplifier
PCR	Polymerase Chain Reaction
PCS	Personal Communication Systems
PDMA	Plastic Deformation Magnetic Assembly
PLL	Phase Locked Loop
PM	Phase Modulation
PVD	Physical Vapor Deposition
Q	Quality
RF	Radio Frequency
SMM	Sacrificial Metallic Mode
SOI	Silicon on Insulator



SSPA	Solid State Power Amplifier
STMs	Scanning Tuning Microscopes
TSMC	Taiwan Semiconductor Manufacturing Company
VAC	Large Value AC Signal
VCO	Voltage Controlled Oscillator
VDC	High DC Control Voltage
VLSI	Very Large Scale Integration
WLAN	Wireless Local Area Networks



LIST OF NOTATION

Notations

δ	Skin effect
A	Gain of amplifier
A_a	Area of the plates in capacitor
A_{Loop}	Gain of close loop system
β	Transfer function of feedback network
C	Capacitance
C_d	Parasitic capacitance
C_D	Total capacitance
C_f	Shunt capacitance
C_{gdo}	Gate-drain capacitor
C_{max}	Maximum capacitor in MOSFET
C_s	Series capacitance
C_{st}	Substrate capacitance
C_{SuB}	Capacitance per unit area for silicon substrate
C_{OX}	Oxide capacitance from metal layer to the substrate
d	Mean distance between two segments
d_{in}	Inner dimension of inductor
d_{out}	Outer dimension of inductor
d_p	Gap between plates in capacitor

ϵ_0	Permittivity of free space
ϵ_r	Relative permittivity
$\epsilon(t)$	Amplitude fluctuation
$\Delta\phi(t)$	Phase fluctuation
f	Frequency
F	Noise factor of amplifier
f_c	Corner frequency
F_d	Work
F_e	Electrostatic force
f_m	Offset frequency
g	Gap between upper electrode of capacitor and sense electrode
g_m	Transconductance of the MOSFET
G_{SUB}	Conductance per unit area for silicon substrate
I_D	Drain current
I_o	Output current
J	Current density
J_j	Imaginary part of current density
J_r	Real part of current density
k	Spring constant
K	Boltzmann's constant



K_p	Gain factor of MOSFET
L	Inductance
$l(f_m)$	Ratio of the power in one phase modulation sideband at one offset frequency
L_n	Self inductance
l_n	Length of n^{th} segments of inductor
L_T	Total inductance
l_i	i^{th} segment of inductor
m	Mass
M	Mutual inductance
MUZ	Zero bulk mobility in CMOS
N	number of turns of inductor
N_n	Number of gate ringers
ρ	Metal resistivity
P_{av}	Power consumption
P_0	Power of the VCO at output
Q	Quality factor
Q_m	Measured quality factor of capacitor
R_d	Distributed resistance
R_{eq}	Equivalent parallel resistance of the tank
R_{inn}	Input resistance of NMOS



R_{inp}	Input resistance of PMOS
R_p	Sheet resistance of capacitor plate
R_s	Resistance of metal layers
R_{si}	Substrate resistance
s	Space between metals in inductor
$S_\phi(f_m)$	Signal carried power in each frequency
t	Thickness of metal layer
T	Absolute temperature
T_m	Kinetic energy
t_{ox}	Thickness of the oxide layer
$t_{ox}M_S - M_U$	Oxide thickness between the wire and underpass tap
μ	Permeability
U_e	Potential energy in capacitors plates
U_K	Potential energy in spring
v	Velocity
$V_{D,Sat}$	Saturation voltage
V_{gs}	Gate-source voltage
V_n	Noise voltage in a resistor
V_0	Amplitude of output signal of VCO
V_p	Pull-in voltage
$V(t)$	Output signal of VCO