UNIVERSITI PUTRA MALAYSIA

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

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By
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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

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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

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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 kapacitor MEMS berprestasi tinggi untuk digunakan di dalam CMOS (Semikonduktor pelengkap logam-oksida) VCO (Pengayun kawalan voltan) yang beroperasi pada 2.4GHz. Induktor *Q* tinggi yang tergantung di udara direka menggunakan teknologi MEMS untuk mengurangkan kehilangan rintangan substrat. Bahan berintangan rendah telah digunakan. Kapacitor 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

dioptimumkan untuk mendapatkan lingar fasa yang rendah, menggunakan kuasa rendah dan mempunyai julat taraan 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 kapacitor MEMS telah digunalan di dalam simulasi VCO bagi menentukan kesan faktor Q tinggi pada hangar fasa VCO. Bahagian aktif litar telah dibina mengguunaken 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.

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TABLE OF CONTENTS

CHAPTER

LIST OF TABLES

LIST OF FIGURES

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_{si}	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
$\varepsilon(t)$	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
lY_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-sourcevoltage
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