Ain Shams University
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MEMS-Based Oscillators
A Thesis

Submitted in partial fulfillment for the
requirements of Master of Science degree in
Electrical Engineering

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Cairo, 2011

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Statement

This dissertation is submitted to Ain Shams University for the degree of Master of Science in Electrical Engineering (Electronics and Communications Engineering).

The work included in this thesis was carried out by the author at the Electronics and Communications Engineering Department, Faculty of Engineering, Ain Shams University, Cairo, Egypt.

No part of this thesis was submitted for a degree or a qualification at any other university or institution.

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Acknowledgments

All praise is due to Allah, the Most Merciful Lord of the Worlds, Who taught man what he knew not. I would like to thank God Almighty for bestowing upon me the chance, strength and ability to complete this work.

I need to express my profound love and gratitude to my mother who supported me with her unlimited love and unconditional care and who continuously encouraged me to finish this work. I am in deep debt to my wife for her fruitful love, distinct emotions and exceptional encouragement. I would also like to thank my brother and sister for their strong and valuable support.

I wish to express my gratitude to my supervisors, Professor Hisham Haddara and Dr. Ayman El-Sayed for their flexibility, guidance, encouragement, insightful thoughts and stimulating discussions. I have learnt a lot from both of them, on both the technical and personal levels.

I am also grateful to Yasseen Nada, Si-Ware senior MEMS design engineer, for his help in analyzing and simulating the MEMS structure used in this work. I am also grateful to Mohamed El-Kholy ex-Si-Ware analog staff engineer whose technical discussions were quite deep and fruitful.

I owe a lot to the whole Si-Ware family for facilitating my work and thesis writing; particularly, the Timing Products Division team and my direct managers Ayman Ahmed and Ahmed Helmy. Special thanks go to many of my colleagues in Si-Ware systems: Botros George, Mostafa Medhat, Hisham Omran, Ahmed El-Shennawy and Ahmed El-Kholy for their help in the thesis writing and structuring and handling paper work.

Many thanks are also due to my Professors at IC Lab, Ain Shams University, for their knowledge.

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2011

Abstract

Nabil Mohamed Sinoussi, "MEMS-Based Oscillators", Master of Science dissertation, Ain Shams University, 2011.

This thesis is concerned with the design of sustaining oscillator circuits for MEMS resonators in the scope of replacing Quartz crystals (XTALs) in frequency reference applications. The thesis discusses the challenges and difficulties in the design of a MEMS resonator oscillator (MRO) and which are imposed due to the resonator non-idealities.

A conclusive analysis of the resonator small signal model under capacitive loading is presented. The analysis deduces two parameters which effectively describe the resonator small signal response in terms of phase and gain. The analysis introduces a physical resonator parameter which is the effective Quality factor (Q_{eff}). (Q_{eff}) is proven to be the main measure in predicting the resonator performance inside an oscillator. Moreover, an anti-resonance cancellation technique is analyzed in details explaining the impact of imperfect cancellation on the shape of the resonator response. The analysis almost coincides with simulation results with less than 1% of error. Based upon this analysis, a new concept for the design of the sustaining amplifier circuit is developed which facilitates the design process by specifying the gain and phase requirements from the sustaining circuit.

Using an industrial free-free beam (FF) resonator, a practical MRO circuit is implemented using TSMC 0.13μm CMOS technology. The resonator has a fundamental resonance mode at 20MHz and spurious one at 4MHz. The oscillator operates at 20MHz and rejects the spurious resonance at 4MHz using a high order high-pass filter implemented within the sustaining circuit. The circuit is actually a variable gain amplifier (VGA) whose gain is controlled by an automatic gain control (AGC) circuit which forces the amplifier gain to track the resonator quality factor (Q-factor) variations across process and temperature. In order to protect it from power-handling non-linearities, the resonator is actuated by a limiting stage which controls its input power level.

By utilizing a flexible trimming infrastructure, the design is able to pass the combined process corners of both CMOS and MEMS technologies. At 1.1V supply and 180mVpp input signal to the resonator, the oscillator consumes a current of 500μA and achieves a phase noise of 113dBc/Hz at 1kHz offset from the 20MHz carrier.

Key words: MEMS, Resonators, VGA, AGC, Oscillators, anti-resonance cancellation,trimming, limiting stage.

Summary

This thesis consists of five chapters. Chapter 1 is an introduction to the thesis. It introduces the concept of Quartz crystals (XTALs) replacement and the advantages of the MEMS technology. Moreover, this chapter defines the scope and objectives of this thesis.

Chapter 2 is an overview on MEMS resonator oscillators, the accompanied design challenges and the state-of-art techniques in industry and literature that address these challenges.

Chapter 3 presents a conclusive analysis of the transfer characteristic of the small signal resonator model. The analysis extracts two descriptive parameters that can summarize the overall resonator response under capacitive loading. Moreover, an anti-resonance cancellation technique is extensively analyzed showing the impact of imperfect cancellation on the shape of the resonator response. The analysis is valid for either MEMS or Quartz resonator models.

Chapter 4 demonstrates the design of a MEMS resonator oscillator based upon an industrial free-free beam resonator.The circuit is a variable gain amplifier (VGA) whose gain is controlled by an automatic gain control (AGC) circuit which forces the amplifier gain to track the resonator quality factor (Q-factor) variations across process and temperature. In order to protect it from power-handling non-linearities, the resonator is actuated by a limiting stage which controls the input power level to the resonator. The detailed schematics of the different circuits are discussed. The simulation results are displayed.

Finally, Chapter 5 concludes and proposes future researches that can be based upon this thesis.

Contents

List of Abbreviations and Symbols

AC	Alternating Current
ADC	Analog to Digital Converter
AGC	Automatic Gain Control
ASIC	Application Specific Integrated Circuit
CC	Clamped-Clamped Beam
CMOS	Complementary Metal Oxide Semiconductor
DC	Direct Current
FEM	Finite Element Method
FF	Free-Free Beam
AGC	Automatic gain control.
HPF	High Pass Filter
IC	Integrated Circuit
LSB	Least Significant Bit
MEMS	Micro Electro-Mechanical Systems
MRO	MEMS Resonator Oscillator
MRO	MEMS Resonator Oscillator
OTA	Operational Transconductance Amplifier
PFD	Phase Frequency Detector

ppm	Part Per Million
PVT	Process, supply voltage and temperature variation.
Q-factor	Quality factor
TIA	Trans-Impedance Amplifier
VGA	Variable Gain Amplifier
XO	Quartz Crystal Oscillator
XTAL	Quartz Crystal
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ΔC	Equivalent anti-resonance capacitance after anti-resonance cancellation.
ω_D	Optimum oscillation angular frequency.
ω_{NC}	Modified anti-resonance angular frequency after ant-resonance cancellation.
ω_N	Anti-Resonance angular frequency.
ω_x	Natural resonance angular frequency.
C_c	Anti-Resonance cancellation capacitance.
C_L	Load capacitance.
C_p	Parasitic feed-through capacitance.
C_x	Resonator motional capacitance.
L_x	Resonator motional inductance.
Q_D	Q-Factor at angular frequency ω_D.
Q_{eff}	Effective Q-factor.
Q_{NC}	Q-factor at the modified anti-resonance angular frequency ω_{NC}.
Q_N	Q-Factor at angular frequency ω_N.
R_x	Resonator motional resistance.

Y_L	Load admittance.
Y_x	Crystal admittance.
DD	Depth of the phase dip in the resonator phase response.
DW	Width of the phase dip in the resonator phase response.
GR	Resonator gain ratio.