

Integrated Circuits and Systems

Series Editor

Anantha Chandrakasan, Massachusetts Institute of Technology
Cambridge, Massachusetts

For other titles published in this series, go to
www.springer.com/series/7236

Eric Vittoz

Low-Power Crystal and MEMS Oscillators

The Experience of Watch Developments

 Springer

Eric Vittoz
Ecole Polytechnique Fédérale de Lausanne (EPFL)
1015 Lausanne
Switzerland
evittoz@ieee.org

ISSN 1558-9412
ISBN 978-90-481-9394-3 e-ISBN 978-90-481-9395-0
DOI 10.1007/978-90-481-9395-0
Springer Dordrecht Heidelberg London New York

Library of Congress Control Number: 2010930852

© Springer Science+Business Media B.V. 2010
No part of this work may be reproduced, stored in a retrieval system, or transmitted in any form or by any means, electronic, mechanical, photocopying, microfilming, recording or otherwise, without written permission from the Publisher, with the exception of any material supplied specifically for the purpose of being entered and executed on a computer system, for exclusive use by the purchaser of the work.

Cover design: Spi Publisher Services

Printed on acid-free paper

Springer is part of Springer Science+Business Media (www.springer.com)

To my wife Monique

Contents

- Preface xi
- Symbols xiii
- 1 Introduction** 1
 - 1.1 Applications of Quartz Crystal Oscillators 1
 - 1.2 Historical Notes 2
 - 1.3 The Book Structure 2
 - 1.4 Basics on Oscillators 4
- 2 Quartz and MEM Resonators** 7
 - 2.1 The Quartz Resonator 7
 - 2.2 Equivalent Circuit 8
 - 2.3 Figure of Merit 10
 - 2.4 Mechanical Energy and Power Dissipation 15
 - 2.5 Various Types of Quartz Resonators 15
 - 2.6 MEM Resonators 18
 - 2.6.1 Basic Generic Structure 18
 - 2.6.2 Symmetrical Transducers 21
- 3 General Theory of High-Q Oscillators** 23
 - 3.1 General Form of the Oscillator 23
 - 3.2 Stable Oscillation 25
 - 3.3 Critical Condition for Oscillation and Linear Approximation . 27
 - 3.4 Amplitude Limitation 27
 - 3.5 Start-up of Oscillation 29
 - 3.6 Duality 30
 - 3.7 Basic Considerations on Phase Noise 31
 - 3.7.1 Linear Circuit 31

- 3.7.2 Nonlinear Time Variant Circuit 33
- 3.8 Model of the MOS Transistor 36
- 4 Theory of the Pierce Oscillator 41**
 - 4.1 Basic Circuit 41
 - 4.2 Linear Analysis 42
 - 4.2.1 Linearized Circuit 42
 - 4.2.2 Lossless Circuit 46
 - 4.2.3 Phase Stability 50
 - 4.2.4 Relative Oscillator Voltages 51
 - 4.2.5 Effect of Losses 52
 - 4.2.6 Frequency Adjustment 54
 - 4.3 Nonlinear Analysis 55
 - 4.3.1 Numerical Example 55
 - 4.3.2 Distortion of the Gate Voltage 57
 - 4.3.3 Amplitude Limitation by the Transistor Transfer Function 58
 - 4.3.4 Energy and Power of Mechanical Oscillation 68
 - 4.3.5 Frequency Stability 69
 - 4.3.6 Elimination of Unwanted Modes 71
 - 4.4 Phase Noise 77
 - 4.4.1 Linear Effects on Phase Noise 77
 - 4.4.2 Phase Noise in the Nonlinear Time Variant Circuit 78
 - 4.5 Design Process 84
 - 4.5.1 Design Steps 84
 - 4.5.2 Design Examples 89
- 5 Implementations of the Pierce Oscillator 93**
 - 5.1 Grounded-Source Oscillator 93
 - 5.1.1 Basic Circuit 93
 - 5.1.2 Dynamic Behavior of Bias 95
 - 5.1.3 Dynamic Behavior of Oscillation Amplitude 97
 - 5.1.4 Design Examples 100
 - 5.1.5 Implementation of the Drain-to-Gate Resistor 102
 - 5.1.6 Increasing the Maximum Amplitude 106
 - 5.2 Amplitude Regulation 107
 - 5.2.1 Introduction 107
 - 5.2.2 Basic Regulator 108
 - 5.2.3 Amplitude Regulating Loop 115
 - 5.2.4 Simplified Regulator Using Linear Resistors 118

5.2.5	Elimination of Resistors	120
5.3	Extraction of the Oscillatory Signal	123
5.4	CMOS-Inverter Oscillator	124
5.4.1	Direct Implementation	124
5.4.2	Current-controlled CMOS-inverter oscillator.	129
5.5	Grounded-Drain Oscillator	132
5.5.1	Basic Implementation	132
5.5.2	Single-Substrate Implementation	133
6	Alternative Architectures	137
6.1	Introduction	137
6.2	Symmetrical Oscillator for Parallel Resonance	137
6.2.1	Basic Structure	137
6.2.2	Linear Analysis with the Parallel Resonator	139
6.2.3	Linear Analysis with the Series Motional Resonator	140
6.2.4	Effect of Losses	143
6.2.5	Nonlinear Analysis	144
6.2.6	Phase Noise	149
6.2.7	Practical Implementations	157
6.3	Symmetrical Oscillator for Series Resonance	164
6.3.1	Basic Structure	164
6.3.2	Linear Analysis	165
6.3.3	Nonlinear Analysis	172
6.3.4	Phase Noise	177
6.3.5	Practical Implementation	183
6.4	Van den Homberg Oscillator	190
6.4.1	Principle and Linear Analysis	190
6.4.2	Practical Implementation and Nonlinear Behavior	193
6.5	Comparison of Oscillators	194
6.5.1	Pierce Oscillator (1)	195
6.5.2	Van den Homberg Oscillator (2)	196
6.5.3	Parallel Resonance Oscillator (3)	196
6.5.4	Series Resonance Oscillator (4)	197
	Bibliography	201
	Index	203

Preface

In the early 60s, the watchmaking industry realized that the newly invented integrated circuit technology could possibly be applied to develop electronic wristwatches. But it was immediately obvious that the precision and stability required for the time base could not be obtained by purely electronic means. A mechanical resonator had to be used, combined with a transducer. The frequency of the resonator had to be low enough to limit the power consumption at the microwatt level, but its size had to be compatible with that of the watch. After unsuccessful results with metallic resonators at sonic frequencies, efforts were concentrated on reducing the size of a quartz crystal resonator. Several solutions were developed until a standard emerged with a thin tuning fork oscillating at 32 kHz and fabricated by chemical etching. After first developments in bipolar technology, CMOS was soon identified as the best choice to limit the power consumption of the oscillator and frequency divider chain below one microwatt. Low-power oscillator circuits were developed and progressively optimized for best frequency stability, which is the main requirement for timekeeping applications. More recent applications to portable communication devices require higher frequencies and a limited level of phase noise. Micro-electro-mechanical (MEM) resonators have been developed recently. They use piezoelectric or electrostatic transduction and are therefore electrically similar to a quartz resonator.

The precision and stability of a quartz is several orders of magnitude better than that of integrated electronic components. Hence, an ideal oscillator circuit should just compensate the losses of the resonator to maintain its oscillation on a desired mode at the desired level, without affecting the frequency or the phase of the oscillation. Optimum designs aim at approaching this ideal case while minimizing the power consumption.

This book includes the experience accumulated along more than 30 years by the author and his coworkers. The main part is dedicated to variants of the Pierce oscillator most frequently used in timekeeping applications. Other forms of oscillators that became important for RF applications have been added, as well as an analysis of phase noise. The knowledge is formalized in an analytical manner, in order to highlight the effect and the importance of the various design parameters. Computer simulations are limited to particular examples but have been used to crosscheck most of the analytical results.

Many collaborators of CEH (Centre Electronique Hologer, Watchmakers Electronic Center), and later of CSEM, have contributed to the know-how described in this book. Among them, by alphabetic order, Daniel Aebischer, Luc Astier, Serge Bitz, Marc Degrauwe, Christian Enz, Jean Fellrath, Armin Frei, Walter Hammer, Jean Hermann, Vincent von Kaenel, Henri Oguey, and David Ruffieux. Special thanks go to Christian Enz for the numerous discussions about oscillators and phase noise during the elaboration of this book.

Eric A. Vittoz
Cernier, Switzerland
February 2010

Symbols

Table 0.1 Symbols and their definitions.

Symbol	Description	Reference
a	Power factor of the flicker noise current	(6.71)
A	Normalized transconductance in series resonance oscillator	(6.108)
B	Normalized bandwidth in series resonance oscillator	(6.108)
C_a, C_b	Functional capacitors	Fig. 6.37
C_D	Capacitance between drains	Fig. 6.1
C_L	Load capacitance in series resonance oscillator	Fig. 6.16
$C_m (C_{m,i})$	Motional capacitance (of mode i)	Fig. 2.2
C_P	Total parallel capacitance of the resonator	(2.22)
C_s	Series connection of C_1 and C_2	(4.9)
C_S	Capacitance between sources	Fig. 6.1
C_0	Parallel capacitance of the dipole resonator	(2.1)
C_1	Total gate-to-source capacitance	Fig. 4.1
C_2	Total drain-to-source capacitance	Fig. 4.1
C_3	Total capacitance across the motional impedance	Fig. 2.2
E_m	Energy of mechanical oscillation	(2.23)
f	Frequency	
f_m	Motional resonant frequency	(4.140)
f_s	Frequency of stable oscillation	(3.24)
$f_s(m_v)$	Fundamental function in strong inversion	(6.37)
$f_w(v_{in})$	Fundamental function in weak inversion	(6.30)
F_a	Flicker noise current constant	(6.71)
G_a	Reference conductance for the flicker noise current	(6.71)
G_{ds}	Residual output conductance in saturation	(3.57)
G_m	Gate transconductance of a transistor	(3.53)

continued on next page

continued from previous page

Symbol	Description	Reference
G_{ms}	Source transconductance of a transistor	(3.49)
G_{md}	Drain transconductance of a transistor	(3.49)
$G_{mcr\text{it}}$	Critical transconductance for oscillation	Fig. 4.4
$G_{mcr\text{it}0}$	Critical transconductance for lossless circuit	Fig. 4.6
$G_{m\text{lim}}$	Limit transconductance in series resonance oscillator	(6.109)
$G_{m\text{max}}$	Maximum possible transconductance for oscillation	Fig. 4.4
G_{mopt}	Optimum value of transconductance	Fig. 4.4
$G_{m(1)}$	Transconductance for the fundamental frequency	(4.54)
G_{vi}	Transconductance of the regulator	(5.52)
$h_s(m_i)$	Transconductance function in strong inversion	(6.142)
$I_{B0}(x)$	Modified Bessel function of order 0	(4.59)
$I_{B1}(x)$	Modified Bessel function of order 1	(4.61)
I_c	Circuit current	Fig. 3.1
I_{cs}	Value of I_c at stable oscillation	(3.6)
I_D	Drain current	Fig. 3.10
I_{D0}	DC component of drain current	(5.1.2)
$I_{D(1)}$	Fundamental component of I_D	Fig. 4.13
I_F	Forward component of drain current	(3.40)
I_m	Motional current	Fig. 2.2
I_{ms}	Value of I_m at stable oscillation	(3.6)
I_R	Reverse component of drain current	(3.40)
I_{spec}	Specific current of a transistor	(3.41)
I_0	Bias current of the oscillator	Fig. 4.13
I_{0start}	Start-up value of bias current	(5.45)
I_{0crit}	Critical value of bias current I_0	Fig. 4.14
$I_{0crit\text{min}}$	Critical current in weak inversion	(4.64)
I_1	Complex value of the sinusoidal drain current	6.3.2.3
IC	Inversion coefficient of a transistor	(3.45)
IC_0	Inversion coefficient at $I_0 = I_{0crit}$	(4.72)
k_c	Capacitive attenuation factor	(4.69)
K_f	Flicker noise voltage constant of a transistor	(3.62)
K_{fi}	Flicker noise current function	(3.36)
K_{fv}	Flicker noise voltage function	(3.35)
K_g	Transconductance ratio	Fig. 6.37
K_i	Mirror ratio in the regulator	Fig. 5.9
K_{iv}	Gain parameter of $ V_1 (I_{D0})$	(5.24)
K_I	Level of specific current	(6.92)
K_m	Margin factor	(4.17)
K_r	Ratio of transfer parameters	Fig. 5.4

continued on next page

continued from previous page

Symbol	Description	Reference
K_s	Ratio of specific currents	(6.82)
K_t	Transconductance ratio	(6.175)
K_w	Width ratio in the regulator	(5.43)
$L_m (L_{m,i})$	Motional inductance (of mode i)	Fig. 2.2
m_i	Index of current modulation	(6.133)
m_v	Index of voltage modulation	(4.122)
m_{vd}	Index of voltage modulation for a differential pair	(6.35)
M	Figure of merit	(2.9)
M_D	Figure of merit of the resonator used as a dipole	(2.22)
M_L	Figure of merit of the resonator used as a loaded dipole	(6.7)
M_0	Intrinsic figure of merit of the resonator	(2.10)
n	Slope factor of a transistor	(3.40)
p	Frequency pulling	(2.7)
p_c	Frequency pulling at critical condition for oscillation	(3.10)
p_{pa}	Frequency pulling at parallel resonance	(2.15)
p_s	Frequency pulling at stable oscillation	(3.7)
p_{se}	Frequency pulling at series resonance	(2.14)
P_m	Power dissipated in the resonator	(2.24)
$Q (Q_i)$	Quality factor (of mode i)	(2.3)
Q_b	Quality factor of the bias circuit	(5.12)
R_{iv}	Slope of the amplitude $ V_1 (I_0)$	Fig. 5.3
R_L	Load resistance	Fig. 6.16
$R_m (R_{m,i})$	Motional resistance (of mode i)	Fig. 2.2
R_n	Negative resistance of the circuit	(3.2)
R_{n0}	Value of R_n for the linear circuit	(3.12)
s_{vi}	Normalized slope of the regulator	Fig. 5.10
s_{iv}	Normalized slope of the amplitude	Fig. 4.17
$S_{I_n^2}$	Current noise spectrum	(4.107)
$S_{I_{nD}^2}$	Drain current channel noise spectrum	(3.59)
$S_{I_{nL}^2}$	Loop Current noise spectrum	(3.27)
$S_{V_n^2}$	Voltage noise spectrum	(4.107)
$S_{V_{nG}^2}$	Gate voltage flicker noise spectrum	(3.62)
$S_{\phi_n^2}$	Phase noise power spectrum	(3.29)
t	Time	
U_T	Thermodynamic voltage	(3.40)
V	Voltage across the resonator	Fig. 2.2
V_B	Supply voltage (battery voltage)	Fig. 5.1
v_c	Value of $ V_c $ normalized to nU_T	(6.130)
V_c	Control voltage of a transistor	(6.129)

continued on next page

continued from previous page

Symbol	Description	Reference
V_D	Drain voltage	Fig. 3.10
V_{Dsat}	Saturation value of drain voltage	(3.46)
v_e	Normalized effective DC gate voltage	(4.57)
V_G	Gate voltage	Fig. 3.10
V_{G0}	DC component of gate voltage	(4.52)
v_{in}	Value of $ V_{in} $ normalized to nU_T	(6.31)
V_{in}	Differential input voltage	Fig. 6.5
V_M	Channel length modulation voltage	(3.57)
V_n	Open-loop noise voltage of the circuit	3.7.1
V_S	Source voltage	Fig. 3.10
V_{T0}	Threshold voltage of a transistor	(3.40)
$V_{(1)}$	Complex value of fundamental component of V	(3.1)
v_1	value of $ V_1 $ normalized to nU_T	(4.57)
V_1	Complex value of gate-to-source voltage	Fig. 4.8
V_2	Complex value of drain-to-source voltage	Fig. 4.8
V_3	Complex value of drain-to-gate voltage	Fig. 4.8
Z_c	Impedance of the linear circuit	(3.8)
$Z_{c(1)}$	Circuit impedance for fundamental frequency	(3.1)
Z_{c0}	Circuit impedance without parallel capacitance	(6.3)
Z_D	Impedance between drains	Fig. 6.3
Z_L	Load impedance	Fig. 6.16
$Z_m (Z_{m,i})$	Motional impedance (of mode i)	Fig. 2.2
Z_p	Total parallel impedance	(2.12)
Z_S	Impedance between sources	Fig. 6.3
Z_1	Total gate-to-source impedance	Fig. 4.3
Z_2	Total drain-to-source impedance	Fig. 4.3
Z_3	Total drain-to-gate impedance	Fig. 4.3
α	Ratio of critical transconductance	(4.98)
α_i	Noise current modulation function	Fig. 3.9
α_v	Noise voltage modulation function	Fig. 3.9
α_0	Value of α for the lossless case	(4.99)
β	Transfer parameter of a transistor	(3.44)
$\Delta\omega$	Noise frequency offset	(3.28)
ϵ_{max}	Maximum relative mismatch	(6.15)
ϵ_0	Permittivity of free space	(2.27)
γ	Noise excess factor of the oscillator	Fig. 3.7
γ_t	Channel noise excess factor of a transistor	(3.60)
Γ_i	Effective impulse sensitivity function for noise current	(3.34)
Γ_v	Effective impulse sensitivity function for noise voltage	(3.32)

continued on next page

continued from previous page

Symbol	Description	Reference
τ	Time constant of oscillation growth	(3.16)
τ_0	Start-up value of τ	(3.15)
ω	Approximate angular frequency of oscillation	
ω_m ($\omega_{m,i}$)	angular frequency of resonance (of mode i)	(2.2)
ω_n	Angular frequency at which noise is considered	(4.106)
ω_s	Angular frequency at stable oscillation	(3.24)
Ω_{civ}	Cut-off angular frequency of $ V_1 (I_{D0})$	(5.26)
Ω_0	Resonant angular frequency of bias circuit	(5.10)
Ω_1	Unity gain frequency of the regulation loop	(5.71)

