
Analysis and Design of Autonomous Microwave Circuits

ALMUDENA SUÁREZ



IEEE PRESS



WILEY

A JOHN WILEY & SONS, INC., PUBLICATION

Analysis and Design of Autonomous Microwave Circuits

*To my father Gerardo Suárez
and my mother Carmen Rodríguez*

Analysis and Design of Autonomous Microwave Circuits

ALMUDENA SUÁREZ



IEEE PRESS



WILEY

A JOHN WILEY & SONS, INC., PUBLICATION

Copyright © 2009 by John Wiley & Sons, Inc. All rights reserved.

Published by John Wiley & Sons, Inc., Hoboken, New Jersey.

Published simultaneously in Canada.

No part of this publication may be reproduced, stored in a retrieval system, or transmitted in any form or by any means, electronic, mechanical, photocopying, recording, scanning, or otherwise, except as permitted under Section 107 or 108 of the 1976 United States Copyright Act, without either the prior written permission of the Publisher, or authorization through payment of the appropriate per-copy fee to the Copyright Clearance Center, Inc., 222 Rosewood Drive, Danvers, MA 01923, (978) 750-8400, fax (978) 750-4470, or on the web at www.copyright.com. Requests to the Publisher for permission should be addressed to the Permissions Department, John Wiley & Sons, Inc., 111 River Street, Hoboken, NJ 07030, (201) 748-6011, fax (201) 748-6008, or online at <http://www.wiley.com/go/permission>.

Limit of Liability/Disclaimer of Warranty: While the publisher and author have used their best efforts in preparing this book, they make no representations or warranties with respect to the accuracy or completeness of the contents of this book and specifically disclaim any implied warranties of merchantability or fitness for a particular purpose. No warranty may be created or extended by sales representatives or written sales materials. The advice and strategies contained herein may not be suitable for your situation. You should consult with a professional where appropriate. Neither the publisher nor author shall be liable for any loss of profit or any other commercial damages, including but not limited to special, incidental, consequential, or other damages.

For general information on our other products and services or for technical support, please contact our Customer Care Department within the United States at (800) 762-2974, outside the United States at (317) 572-3993 or fax (317) 572-4002.

Wiley also publishes its books in a variety of electronic formats. Some content that appears in print may not be available in electronic formats. For more information about Wiley products, visit our web site at www.wiley.com.

Library of Congress Cataloging-in-Publication Data:

Suárez, Almudena.

Analysis and design of autonomous microwave circuits / Almudena Suárez.

p. cm. — (Wiley series in microwave and optical engineering)

Includes bibliographical references and index.

ISBN 978-0-470-05074-3 (cloth)

1. Microwaves circuits—Mathematical models. 2. Oscillators, Microwave—Design and construction. 3. Oscillators, Microwaves—Automatic control. 4. System analysis. I. Title.

TK7876.S759 2008

621.381'32—dc22

2008007472

Printed in the United States of America

10 9 8 7 6 5 4 3 2 1

Contents

Preface	xiii
1 Oscillator Dynamics	1
1.1 Introduction	1
1.2 Operational Principle of Free-Running Oscillators	3
1.3 Impedance–Admittance Analysis of an Oscillator	12
1.3.1 Steady-State Analysis	14
1.3.2 Stability of Steady-State Oscillation	17
1.3.3 Oscillation Startup	19
1.3.4 Formulation of Perturbed Oscillator Equations as an Eigenvalue Problem	21
1.3.5 Generalization of Oscillation Conditions to Multiport Networks	23
1.3.6 Design of Transistor-Based Oscillators from a Single Observation Port	25
1.4 Frequency-Domain Formulation of an Oscillator Circuit	32
1.4.1 Steady-State Formulation	32
1.4.2 Stability Analysis	36
1.5 Oscillator Dynamics	37
1.5.1 Equations and Steady-State Solutions	37
1.5.2 Stability Analysis	46
1.6 Phase Noise	62
References	64
2 Phase Noise	66
2.1 Introduction	66
2.2 Random Variables and Random Processes	68
2.2.1 Random Variables and Probability	68
2.2.2 Random Processes	71
2.2.3 Correlation Functions and Power Spectral Density	75
2.2.4 Stochastic Differential Equations	77

2.3	Noise Sources in Electronic Circuits	81
2.3.1	Thermal Noise	82
2.3.2	Shot Noise	83
2.3.3	Generation–Recombination Noise	84
2.3.4	Flicker Noise	85
2.3.5	Burst Noise	86
2.4	Derivation of the Oscillator Noise Spectrum Using Time-Domain Analysis	87
2.4.1	Oscillator with White Noise Sources	87
2.4.2	White and Colored Noise Sources	97
2.5	Frequency-Domain Analysis of a Noisy Oscillator	103
2.5.1	Frequency-Domain Representation of Noise Sources	103
2.5.2	Carrier Modulation Analysis	105
2.5.3	Frequency-Domain Calculation of Variance of the Phase Deviation	112
2.5.4	Comparison of Two Techniques for Frequency-Domain Analysis of Phase Noise	118
2.5.5	Amplitude Noise	120
	References	124
3	Bifurcation Analysis	126
3.1	Introduction	126
3.2	Representation of Solutions	127
3.2.1	Phase Space	127
3.2.2	Poincaré Map	128
3.3	Bifurcations	132
3.3.1	Local Bifurcations	133
3.3.2	Transformations Between Solution Poles	173
3.3.3	Global Bifurcations	173
	References	182
4	Injected Oscillators and Frequency Dividers	183
4.1	Introduction	183
4.2	Injection-Locked Oscillators	185
4.2.1	Analysis Based on Linearization About a Free-Running Solution	185
4.2.2	Nonlinear Analysis of Synchronized Solution Curves	190
4.2.3	Stability Analysis	193
4.2.4	Bifurcation Loci	198
4.2.5	Phase Variation Along Periodic Curves	206

4.2.6	Analysis of a FET-Based Oscillator	207
4.2.7	Phase Noise Analysis	211
4.3	Frequency Dividers	222
4.3.1	General Characteristics of a Frequency-Divided Solution	223
4.3.2	Harmonic Injection Frequency Dividers	225
4.3.3	Regenerative Frequency Dividers	239
4.3.4	Parametric Frequency Dividers	244
4.3.5	Phase Noise in Frequency Dividers	246
4.4	Subharmonically and Ultrasubharmonically Injection-Locked Oscillators	248
4.5	Self-Oscillating Mixers	254
	References	257
5	Nonlinear Circuit Simulation	259
5.1	Introduction	259
5.2	Time-Domain Integration	262
5.2.1	Time-Domain Modeling of Distributed Elements	264
5.2.2	Integration Algorithms	269
5.2.3	Convergence Considerations	274
5.3	Fast Time-Domain Techniques	279
5.3.1	Shooting Methods	279
5.3.2	Finite Differences in the Time Domain	281
5.4	Harmonic Balance	283
5.4.1	Formulation of a Harmonic Balance System	283
5.4.2	Nodal Harmonic Balance	285
5.4.3	Piecewise Harmonic Balance	292
5.4.4	Continuation Techniques	293
5.4.5	Algorithms for Calculation of Discrete Fourier Transforms	295
5.5	Harmonic Balance Analysis of Autonomous and Synchronized Circuits	298
5.5.1	Mixed Harmonic Balance Formulation	299
5.5.2	Auxiliary Generator Technique	300
5.6	Envelope Transient	313
5.6.1	Expression of Circuit Variables	315
5.6.2	Envelope Transient Formulation	316
5.6.3	Extension of the Envelope Transient Method to the Simulation of Autonomous Circuits	318

5.7	Conversion Matrix Approach	334
	References	338
6	Stability Analysis Using Harmonic Balance	343
6.1	Introduction	343
6.2	Local Stability Analysis	344
6.2.1	Small-Signal Regime	344
6.2.2	Large-Signal Regime	358
6.3	Stability Analysis of Free-Running Oscillators	369
6.4	Solution Curves Versus a Circuit Parameter	371
6.4.1	Parameter Switching Applied to Harmonic Balance Equations	372
6.4.2	Parameter Switching Applied to an Auxiliary Generator Equation	373
6.4.3	Arc-Length Continuation	376
6.5	Global Stability Analysis	377
6.5.1	Bifurcation Detection from the Characteristic Determinant of a Harmonic Balance System	379
6.5.2	Bifurcation Detection Using Auxiliary Generators	382
6.6	Bifurcation Synthesis and Control	394
6.6.1	Bifurcation Synthesis	394
6.6.2	Bifurcation Control	394
	References	398
7	Noise Analysis Using Harmonic Balance	400
7.1	Introduction	400
7.2	Noise in Semiconductor Devices	402
7.2.1	Noise in Field-Effect Transistors	402
7.2.2	Noise in Bipolar Transistors	404
7.2.3	Noise in Varactor Diodes	405
7.3	Decoupled Analysis of Phase and Amplitude Perturbations in a Harmonic Balance System	405
7.3.1	Perturbed Oscillator Equations	405
7.3.2	Phase Noise	408
7.3.3	Amplitude Noise	415
7.4	Coupled Phase and Amplitude Noise Calculation	420
7.5	Carrier Modulation Approach	423

7.5.1	Direct Calculation of Phase and Amplitude Noise Spectra	424
7.5.2	Calculation of Variance of the Phase Deviation $\sigma_\theta^2(t)$	425
7.6	Conversion Matrix Approach	425
7.6.1	Calculation of Complex Sidebands $\Delta\overline{X}_T$	426
7.6.2	Determination of Phase and Amplitude Noise Spectra	428
7.7	Noise in Synchronized Oscillators	431
7.7.1	Conversion Matrix Approach	432
7.7.2	Semianalytical Formulation	433
	References	442
8	Harmonic Balance Techniques for Oscillator Design	444
8.1	Introduction	444
8.2	Oscillator Synthesis	446
8.2.1	Oscillation Startup Conditions	446
8.2.2	Steady-State Design Using One-Harmonic Accuracy	453
8.2.3	Multiharmonic Steady-State Design	456
8.3	Design of Voltage-Controlled Oscillators	460
8.3.1	Technique for Increasing Oscillation Bandwidth	460
8.3.2	Technique to Preset the Oscillation Band	462
8.3.3	Technique to Linearize the VCO Characteristic	464
8.4	Maximization of Oscillator Efficiency	467
8.4.1	Class E Design	467
8.4.2	Class F Design	473
8.4.3	General Load–Pull System	476
8.5	Control of Oscillator Transients	477
8.5.1	Reduction of Oscillator Startup Time	478
8.5.2	Improvement in the Modulated Response of a Voltage-Controlled Oscillator	483
8.6	Phase Noise Reduction	485
	Appendix	490
	References	493
9	Stabilization Techniques for Phase Noise Reduction	496
9.1	Introduction	496

9.2	Self-Injection Topology	498
9.2.1	Steady-State Solution	498
9.2.2	Stability Analysis	502
9.2.3	Phase Noise Analysis	503
9.3	Use of High- Q Resonators	507
9.4	Stabilization Loop	512
9.5	Transistor-Based Oscillators	516
9.5.1	Harmonic Balance Analysis	516
9.5.2	Semianalytical Formulation	517
9.5.3	Application to a 5-GHz MESFET-Based Oscillator	518
	References	521
10	Coupled-Oscillator Systems	523
10.1	Introduction	523
10.2	Oscillator Systems with Global Coupling	526
10.2.1	Simplified Analysis of Oscillation Modes	526
10.2.2	Applications of Globally Coupled Oscillators	530
10.2.3	Stability Analysis of a Steady-State Periodic Regime	537
10.2.4	Phase Noise	541
10.2.5	Analysis and Design Using Harmonic Balance	546
10.3	Coupled-Oscillator Systems for Beam Steering	555
10.3.1	Analytical Study of Oscillator-Array Operation	557
10.3.2	Harmonic Balance Analysis	561
10.3.3	Semianalytical Formulation	569
10.3.4	Determination of Coexisting Solutions	572
10.3.5	Stability Analysis	577
10.3.6	Phase Noise Analysis	580
10.3.7	Comparison Between Weak and Strong Oscillator Coupling	585
10.3.8	Forced Operation of a Coupled-Oscillator Array	590
	References	592
11	Simulation Techniques for Frequency-Divider Design	594
11.1	Introduction	594
11.2	Types of frequency dividers	595
11.3	Design of Transistor-Based Regenerative Frequency Dividers	597

xii CONTENTS

12.5.3	Stabilization Technique for the Entire Tuning Voltage Range	683
12.6	Stabilization of Multifunction MMIC Chips	686
12.6.1	Analyses at the Lumped-Element Schematic Level	689
12.6.2	Analyses at the Layout Level	689
	References	693
Index		697

Preface

Autonomous circuits are capable of sustaining a steady-state oscillation at a frequency different from those delivered by input generators or their harmonic frequencies. The most obvious example is the free-running oscillator, generating a periodic solution from the energy delivered by direct-current (dc) sources only. Another example is the frequency divider, giving rise to a subharmonic frequency of the input periodic source. In injection-locked regimes, the oscillation frequency agrees with a multiple or submultiple of the input frequency, and this relationship is maintained within certain input frequency and input power intervals. Free-running oscillators and frequency dividers are used primarily in the frequency generation and frequency conversion stages of communication systems. Other applications of injection-locked oscillators take advantage of their high phase sensitivity with respect to their bias sources and component values to obtain phase shifters and phase-shift-keying modulators. In turn, the coupled-oscillator systems are composed of oscillator circuits connected through linear networks which operate in synchronous manner at a single fundamental frequency. They can be used for a variety of purposes. Multidevice oscillators with a global coupling network are applied for power combination at the fundamental frequency, or at a given harmonic component of this frequency. On the other hand, one- and two-dimensional oscillator systems with nearest-neighbor coupling can be used for beam steering in phased arrays. The beam steering capability comes from the fact that it is possible to synthesize a constant phase shift progression with a very simple tuning procedure by varying the tuning voltages of the peripheral elements only.

The autonomous circuits must contain amplitude-sensitive devices to enable the self-sustained oscillation: that is, an oscillation that does not grow unboundedly (which would be unphysical) or decays to zero. Thus, they must necessarily be nonlinear. The analysis of autonomous circuits is difficult due to this inherent nonlinearity and the usual coexistence of the oscillatory solution with a mathematical solution for which the circuit does not oscillate. As a simple example, consider the case of a free-running oscillator, which can always be solved for a dc solution even when the oscillatory solution is the only solution observed physically. The physical solutions are capable of recovering from the small perturbations, that are always present in real life, coming from noise or small fluctuations. They are robust versus small perturbations or *stable*. In fact, the stability analysis of a given mathematical solution is the verification of its physical existence. This analysis should be carried out in all circuits containing nonlinear devices and it is essential in autonomous