RF MICROELECTRONICS

Second Edition

Behzad Razavi



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To the memory of my parents

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CONTENTS

PREFACE TO THE SECOND EDITION PREFACE TO THE FIRST EDITION ACKNOWLEDGMENTS ABOUT THE AUTHOR

CHAPTER 1 INTRODUCTION TO RF A TECHNOLOGY

- 1.1 A Wireless World
- 1.2 RF Design Is Challenging
- 1.3 The Big Picture

References

CHAPTER 2 BASIC CONCEPTS IN RF

- 2.1 General Considerations
 - 2.1.1 Units in RF Design
 - 2.1.2 Time Variance
 - 2.1.3 Nonlinearity
- 2.2 Effects of Nonlinearity
 - 2.2.1 Harmonic Distortion
 - 2.2.2 Gain Compression
 - 2.2.3 Cross Modulation
 - 2.2.4 Intermodulation
 - 2.2.5 Cascaded Nonlinear Stages
 - 2.2.6 AM/PM Conversion
- 2.3 Noise
 - 2.3.1 Noise as a Random Process
 - 2.3.2 Noise Spectrum

2862458 30-DEC-2011 155,69.203.1

	VU
	viv
	xxi
	xxiii
ND WIDELESS	
IND WIRELESS	1
	1
	1
	3
	4
	5
DESIGN	7
DESIGN	7
	7
	, 0
	12
	14
	14
	14
	10
	20
	21
	29
	33
	35
	36
	37
	(201 4
	VII

viii			Contents
	2.3.3	Effect of Transfer Function on Noise	39
	2.3.4	Device Noise	40
	2.3.5	Representation of Noise in Circuits	46
2.4	Sensiti	ivity and Dynamic Range	58
	2.4.1	Sensitivity	59
	2.4.2	Dynamic Range	60
2.5	Passiv	e Impedance Transformation	62
	2.5.1	Quality Factor	63
	2.5.2	Series-to-Parallel Conversion	63
	2.5.3	Basic Matching Networks	65
	2.5.4	Loss in Matching Networks	69
2.6	Scatter	ring Parameters	71
2.7	Analys	sis of Nonlinear Dynamic Systems	75
	2.7.1	Basic Considerations	75
2.8	Volteri	ra Series	77
	2.8.1	Method of Nonlinear Currents	81
Refe	rences		86
Prob	lems		86
CHAPTI	ER 3 (COMMUNICATION CONCEPTS	91
3.1	Genera	91	
3.2	Analog	g Modulation	93
	3.2.1	Amplitude Modulation	93
	3.2.2	Phase and Frequency Modulation	95
3.3	Digita	1 Modulation	99
	3.3.1	Intersymbol Interference	101
	3.3.2	Signal Constellations	105
	3.3.3	Quadrature Modulation	107
	3.3.4	GMSK and GFSK Modulation	112
	3.3.5	Quadrature Amplitude Modulation	114
	3.3.6	Orthogonal Frequency Division Multiplexing	115
3.4	Spectr	al Regrowth	118
3.5	Mobile	e RF Communications	119
3.6	Multip	ble Access Techniques	123
	3.6.1	Time and Frequency Division Duplexing	123
	3.6.2	Frequency-Division Multiple Access	125
	3.6.3	Time-Division Multiple Access	125
	3.6.4	Code-Division Multiple Access	126
3.7	Wirele	ess Standards	130
	3.7.1	GSM	132
	3.7.2	IS-95 CDMA	137
	3.7.3	Wideband CDMA	139
	3.7.4	Bluetooth	143
	3.7.5	IEEE802.11a/b/g	147

3.8	Apper	ndix I: Differential Phase Shift Ke
Refe	rences	
Prob	lems	
CHAPTI	ER 4	FRANSCEIVER ARCHITEC
4.1	Gener	al Considerations
4.2	Receiv	ver Architectures
	4.2.1	Basic Heterodyne Receivers
	4.2.2	Modern Heterodyne Receivers
	4.2.3	Direct-Conversion Receivers
	4.2.4	Image-Reject Receivers
	4.2.5	Low-IF Receivers
4.3	Transı	nitter Architectures
	4.3.1	General Considerations
	4.3.2	Direct-Conversion Transmitters
	4.3.3	Modern Direct-Conversion Tran
	4.3.4	Heterodyne Transmitters
	4.3.5	Other TX Architectures
4.4	OOK	Transceivers
Refe	rences	
Prob	lems	
CHAPTI	ER 5	LOW-NOISE AMPLIFIERS
CHAPTI 5.1	E R 5 I Gener	LOW-NOISE AMPLIFIERS al Considerations
CHAPTI 5.1 5.2	E R 5 I Gener Proble	LOW-NOISE AMPLIFIERS al Considerations em of Input Matching
CHAPTI 5.1 5.2 5.3	E R 5 1 Gener Proble LNA	LOW-NOISE AMPLIFIERS al Considerations em of Input Matching Topologies
5.1 5.2 5.3	ER 5 1 Gener Proble LNA ' 5.3.1	LOW-NOISE AMPLIFIERS al Considerations em of Input Matching Topologies Common-Source Stage with Inc
5.1 5.2 5.3	ER 5 1 Gener Proble LNA ' 5.3.1 5.3.2	LOW-NOISE AMPLIFIERS al Considerations em of Input Matching Topologies Common-Source Stage with Inc Common-Source Stage with Re
CHAPTI 5.1 5.2 5.3	ER 5 1 Gener Proble LNA ' 5.3.1 5.3.2 5.3.3	LOW-NOISE AMPLIFIERS al Considerations em of Input Matching Topologies Common-Source Stage with Inc Common-Source Stage with Re Common-Gate Stage
5.1 5.2 5.3	ER 5 1 Gener Proble LNA 7 5.3.1 5.3.2 5.3.3 5.3.4	LOW-NOISE AMPLIFIERS al Considerations em of Input Matching Topologies Common-Source Stage with Inc Common-Source Stage with Re Common-Gate Stage Cascode CS Stage with Inductiv
CHAPTI 5.1 5.2 5.3	ER 5 1 Gener Proble LNA 7 5.3.1 5.3.2 5.3.3 5.3.4 5.3.5	LOW-NOISE AMPLIFIERS al Considerations em of Input Matching Topologies Common-Source Stage with Inc Common-Source Stage with Re Common-Gate Stage Cascode CS Stage with Inductiv Variants of Common-Gate LNA
5.1 5.2 5.3	ER 5 1 Gener Proble LNA 7 5.3.1 5.3.2 5.3.3 5.3.4 5.3.5 5.3.6	LOW-NOISE AMPLIFIERS al Considerations em of Input Matching Topologies Common-Source Stage with Inc Common-Source Stage with Re Common-Gate Stage Cascode CS Stage with Inductiv Variants of Common-Gate LNA Noise-Cancelling LNAs
CHAPTI 5.1 5.2 5.3	ER 5 1 Gener Proble LNA 7 5.3.1 5.3.2 5.3.3 5.3.4 5.3.5 5.3.6 5.3.7	LOW-NOISE AMPLIFIERS al Considerations em of Input Matching Topologies Common-Source Stage with Inc Common-Source Stage with Re Common-Gate Stage Cascode CS Stage with Inductiv Variants of Common-Gate LNA Noise-Cancelling LNAs Reactance-Cancelling LNAs
CHAPTI 5.1 5.2 5.3	ER 5 1 Gener Proble LNA 7 5.3.1 5.3.2 5.3.3 5.3.4 5.3.5 5.3.6 5.3.7 Gain 5	LOW-NOISE AMPLIFIERS al Considerations em of Input Matching Topologies Common-Source Stage with Inc Common-Source Stage with Re Common-Gate Stage Cascode CS Stage with Inductiv Variants of Common-Gate LNA Noise-Cancelling LNAs Reactance-Cancelling LNAs Switching
5.1 5.2 5.3 5.4 5.5	ER 5 Gener Proble LNA 7 5.3.1 5.3.2 5.3.3 5.3.4 5.3.5 5.3.6 5.3.7 Gain 8 Band	LOW-NOISE AMPLIFIERS al Considerations em of Input Matching Topologies Common-Source Stage with Inc Common-Source Stage with Re Common-Gate Stage Cascode CS Stage with Inductiv Variants of Common-Gate LNA Noise-Cancelling LNAs Reactance-Cancelling LNAs Switching
5.1 5.2 5.3 5.4 5.5 5.6	ER 5 Gener Proble LNA 5.3.1 5.3.2 5.3.3 5.3.4 5.3.5 5.3.6 5.3.7 Gain 9 Band High-	LOW-NOISE AMPLIFIERS al Considerations em of Input Matching Topologies Common-Source Stage with Inc Common-Gate Stage Cascode CS Stage with Inductiv Variants of Common-Gate LNA Noise-Cancelling LNAs Reactance-Cancelling LNAs Switching Switching
5.1 5.2 5.3 5.4 5.5 5.6	ER 5 Gener Proble LNA 5.3.1 5.3.2 5.3.3 5.3.4 5.3.5 5.3.6 5.3.7 Gain 9 Band High-1 5.6.1	LOW-NOISE AMPLIFIERS al Considerations em of Input Matching Topologies Common-Source Stage with Inc Common-Source Stage with Re Common-Gate Stage Cascode CS Stage with Inductiv Variants of Common-Gate LNA Noise-Cancelling LNAs Reactance-Cancelling LNAs Switching Switching IP ₂ LNAs Differential LNAs
5.1 5.2 5.3 5.4 5.5 5.6	ER 5 Gener Proble LNA 5.3.1 5.3.2 5.3.3 5.3.4 5.3.5 5.3.6 5.3.7 Gain 5 Band High-1 5.6.1 5.6.1	LOW-NOISE AMPLIFIERS al Considerations em of Input Matching Topologies Common-Source Stage with Inc Common-Source Stage with Re Common-Gate Stage Cascode CS Stage with Inductiv Variants of Common-Gate LNA Noise-Cancelling LNAs Reactance-Cancelling LNAs Switching Switching IP ₂ LNAs Differential LNAs Other Methods of IP ₂ Improver
CHAPTI 5.1 5.2 5.3 5.4 5.5 5.6 5.7	ER 5 Gener Proble LNA 7 5.3.1 5.3.2 5.3.3 5.3.4 5.3.5 5.3.6 5.3.7 Gain 8 Band 1 High-1 5.6.1 5.6.2 Nonlin	LOW-NOISE AMPLIFIERS al Considerations em of Input Matching Topologies Common-Source Stage with Inc Common-Source Stage with Re Common-Gate Stage Cascode CS Stage with Inductiv Variants of Common-Gate LNA Noise-Cancelling LNAs Reactance-Cancelling LNAs Switching Switching Switching IP ₂ LNAs Differential LNAs Other Methods of IP ₂ Improvem- nearity Calculations
5.1 5.2 5.3 5.4 5.5 5.6 5.7	ER 5 1 Gener Proble LNA 7 5.3.1 5.3.2 5.3.3 5.3.4 5.3.5 5.3.6 5.3.7 Gain 8 Band 1 High-1 5.6.1 5.6.2 Nonlin 5.7.1	LOW-NOISE AMPLIFIERS al Considerations em of Input Matching Topologies Common-Source Stage with Inc Common-Source Stage with Re Common-Gate Stage Cascode CS Stage with Inductiv Variants of Common-Gate LNA Noise-Cancelling LNAs Reactance-Cancelling LNAs Switching Switching IP ₂ LNAs Differential LNAs Other Methods of IP ₂ Improvem nearity Calculations Degenerated CS Stage
CHAPTI 5.1 5.2 5.3 5.4 5.5 5.6 5.7	ER 5 1 Gener Proble LNA 5.3.1 5.3.2 5.3.3 5.3.4 5.3.5 5.3.6 5.3.7 Gain 5 Band High-1 5.6.1 5.6.1 5.6.2 Nonlin 5.7.1 5.7.2	LOW-NOISE AMPLIFIERS al Considerations em of Input Matching Topologies Common-Source Stage with Inc Common-Source Stage with Re Common-Gate Stage Cascode CS Stage with Inductiv Variants of Common-Gate LNA Noise-Cancelling LNAs Reactance-Cancelling LNAs Switching Switching IP ₂ LNAs Differential LNAs Other Methods of IP ₂ Improven nearity Calculations Degenerated CS Stage Undegenerated CS Stage
5.1 5.2 5.3 5.4 5.5 5.6 5.7	ER 5 1 Gener Proble LNA 7 5.3.1 5.3.2 5.3.3 5.3.4 5.3.5 5.3.6 5.3.7 Gain 8 Band 7 High-1 5.6.1 5.6.2 Nonlin 5.7.1 5.7.2 5.7.3	LOW-NOISE AMPLIFIERS al Considerations em of Input Matching Topologies Common-Source Stage with Inc Common-Source Stage with Re Common-Gate Stage Cascode CS Stage with Inductiv Variants of Common-Gate LNA Noise-Cancelling LNAs Reactance-Cancelling LNAs Switching Switching IP ₂ LNAs Differential LNAs Other Methods of IP ₂ Improven mearity Calculations Degenerated CS Stage Undegenerated CS Stage
CHAPTI 5.1 5.2 5.3 5.4 5.5 5.6 5.7	ER 5 1 Gener Proble LNA 5.3.1 5.3.2 5.3.3 5.3.4 5.3.5 5.3.6 5.3.7 Gain 9 Band 1 High-1 5.6.1 5.6.1 5.6.2 Nonlin 5.7.1 5.7.2 5.7.3 5.7.4	LOW-NOISE AMPLIFIERS al Considerations em of Input Matching Topologies Common-Source Stage with Inc Common-Source Stage with Re Common-Gate Stage Cascode CS Stage with Inductiv Variants of Common-Gate LNA Noise-Cancelling LNAs Reactance-Cancelling LNAs Switching Switching IP ₂ LNAs Differential LNAs Other Methods of IP ₂ Improven nearity Calculations Degenerated CS Stage Undegenerated CS Stage Differential and Quasi-Differential Pair

Problems

	ix
eying	151
	152
	152
CTURES	155
	155
	160
	160
	171
	179
	200
	214
	226
	226
' S	227
ansmitters	238
	244
	248
	248
	249
	250
5	255
	255
	263
	266
nductive Load	266
esistive Feedback	269
	272
ive Degeneration	284
A	296
	300
	303
	305
	312
	313
	314
ement	323
	325
	325
	329
ntial Pairs	331
	332
	333
	333

x		Contents	Contents
CHAPT	ER 6 MIXERS	337	Refere
6.1	General Considerations	337	Proble
	6.1.1 Performance Parameters	338	
	6.1.2 Mixer Noise Figures	343	CHAPTE
	6.1.3 Single-Balanced and Double-Balanced Mixers	348	81
6.2	Passive Downconversion Mixers	350	82
	6.2.1 Gain	350	0.2
	6.2.2 LO Self-Mixing	357	
	6.2.3 Noise	357	83
	6.2.4 Input Impedance	364	8.4
	6.2.5 Current-Driven Passive Mixers	366	8.5
63	Active Downconversion Mixers	368	0.5
0.0	6.3.1 Conversion Gain	370	
	6.3.2 Noise in Active Mixers	377	9.6
	6.3.3 Linearity	387	8.0
64	Improved Mixer Topologies	303	
0.4	6.4.1 Active Mixers with Current Source Helpers	303	
	6.4.2 Active Mixers with Enhanced Transconductence	393	0.7
	6.4.2 Active Mixers with Link ID	394	8.7
	6.4.5 Active Mixers with Law Elister Noise	397	
65	0.4.4 Active Mixers with Low Flicker Noise	405	
0.0	Upconversion Mixers	408	
	6.5.1 Performance Requirements	408	
P (6.5.2 Upconversion Mixer Topologies	409	
Refe	rences	424	
Prob	lems	425	8.8
CHAPT	ER 7 PASSIVE DEVICES	429	8.9
7.1	General Considerations	429	8.10
7.2	Inductors	431	8.11
	7.2.1 Basic Structure	431	
	7.2.2 Inductor Geometries	435	
	7.2.3 Inductance Equations	436	
	7.2.4 Parasitic Capacitances	439	8.12
	7.2.5 Loss Mechanisms	444	Refere
	7.2.6 Inductor Modeling	455	Proble
	7.2.7 Alternative Inductor Structures	460	
7.3	Transformers	470	CHAPTE
	7.3.1 Transformer Structures	470	9.1
	7.3.2 Effect of Coupling Canacitance	475	1.10
	7.3.3 Transformer Modeling	475	92
74	Transmission Lines	476	7.2
7.7	7.4.1 T-Line Structures	478	
75	Varactors	478	
7.5	Constant Canacitors	400	
7.0	7.6.1 MOS Capacitors	490	
	7.6.2 Metal Plate Capacitors	403	
	1.0.2 Metal-Flate Capacitors	493	

ences ems **R8 OSCILLATORS** Performance Parameters **Basic Principles** 8.2.1 Feedback View of Oscillators 8.2.2 One-Port View of Oscillators Cross-Coupled Oscillator Three-Point Oscillators Voltage-Controlled Oscillators 8.5.1 Tuning Range Limitations 8.5.2 Effect of Varactor Q LC VCOs with Wide Tuning Range 8.6.1 VCOs with Continuous Tuning 8.6.2 Amplitude Variation with Free 8.6.3 Discrete Tuning Phase Noise 8.7.1 Basic Concepts 8.7.2 Effect of Phase Noise 8.7.3 Analysis of Phase Noise: Appr 8.7.4 Analysis of Phase Noise: App 8.7.5 Noise of Bias Current Source 8.7.6 Figures of Merit of VCOs Design Procedure 8.8.1 Low-Noise VCOs LO Interface Mathematical Model of VCOs Quadrature Oscillators 8.11.1 Basic Concepts 8.11.2 Properties of Coupled Oscilla 8.11.3 Improved Quadrature Oscilla Appendix I: Simulation of Quadrature ences ms **R9** PHASE-LOCKED LOOPS Basic Concepts 9.1.1 Phase Detector Type-I PLLs 9.2.1 Alignment of a VCO's Phase 9.2.2 Simple PLL 9.2.3 Analysis of Simple PLL 9.2.4 Loop Dynamics 9.2.5 Frequency Multiplication 9.2.6 Drawbacks of Simple PLL

	xi
	495
	496
	497
	497
	501
	502
	508
	511
	517
	518
	521
	522
	524
g	524
Juency Tuning	532
	532
	536
	536
	539
roach I	544
roach II	557
	565
	570
	571
	573
	575
	577
	581
	581
ators	584
tors	589
Oscillators	592
	593
	594
	597
	597
	597
	600
	600
	601
	603
	606
	609
	611

Contents

03	Type-II PLL s	611
7.5	9.3.1 Phase/Frequency Detectors	612
	9.3.2 Charge Pumps	614
	9.3.3 Charge-Pump PLLs	615
	9.3.4 Transient Response	620
	9.3.5 Limitations of Continuous-Time Approximation	622
	9.3.6 Frequency-Multiplying CPPLL	623
	9.3.7 Higher-Order Loops	625
9.4	PFD/CP Nonidealities	627
	9.4.1 Up and Down Skew and Width Mismatch	627
	9.4.2 Voltage Compliance	630
	9.4.3 Charge Injection and Clock Feedthrough	630
	9.4.4 Random Mismatch between Up and Down Currents	632
	9.4.5 Channel-Length Modulation	633
	9.4.6 Circuit Techniques	634
9.5	Phase Noise in PLLs	638
	9.5.1 VCO Phase Noise	638
	9.5.2 Reference Phase Noise	643
9.6	Loop Bandwidth	645
9.7	Design Procedure	646
9.8	Appendix I: Phase Margin of Type-II PLLs	647
Refe	rences	651
Prob	lems	652
СНАРТИ	ER 10 INTEGER-N FREOUENCY SYNTHESIZERS	655
10.1	General Considerations	655
10.2	Basic Integer-N Synthesizer	659
10.3	Settling Behavior	661
10.4	Spur Reduction Techniques	664
10.5	PLL-Based Modulation	667
	10.5.1 In Loop Modulation	667

xii

10.2	Dasic I	integer-iv Synthesizer	0.09
10.3	Settling	g Behavior	661
10.4	Spur Re	eduction Techniques	664
10.5	PLL-Based Modulation		667
	10.5.1	In-Loop Modulation	667
	10.5.2	Modulation by Offset PLLs	670
10.6	Divider	r Design	673
	10.6.1	Pulse Swallow Divider	674
	10.6.2	Dual-Modulus Dividers	677
	10.6.3	Choice of Prescaler Modulus	682
	10.6.4	Divider Logic Styles	683
	10.6.5	Miller Divider	699
	10.6.6	Injection-Locked Dividers	707
	10.6.7	Divider Delay and Phase Noise	709
Refere	ences		712
Proble	ems		713

1	12 CON 12	
on	tents	2
2014	10.1110	

Contents			XIII
СНАРТЕ	R 11 F	FRACTIONAL-N SYNTHESIZERS	715
11.1	Basic C	Concepts	715
11.2	Randor	nization and Noise Shaping	718
	11.2.1	Modulus Randomization	718
	11.2.2	Basic Noise Shaping	722
	11.2.3	Higher-Order Noise Shaping	728
	11.2.4	Problem of Out-of-Band Noise	732
	11.2.5	Effect of Charge Pump Mismatch	733
11.3	Quantiz	zation Noise Reduction Techniques	738
	11.3.1	DAC Feedforward	738
	11.3.2	Fractional Divider	742
	11.3.3	Reference Doubling	743
	11.3.4	Multiphase Frequency Division	745
11.4	Append	dix I: Spectrum of Quantization Noise	748
Refere	ences		749
Proble	ems		749
СНАРТЕ	R 12 P	OWER AMPLIFIERS	751
12.1	Genera	l Considerations	751
	12.1.1	Effect of High Currents	754
	12.1.2	Efficiency	755
	12.1.3	Linearity	756
	12.1.4	Single-Ended and Differential PAs	758
12.2	Classifi	ication of Power Amplifiers	760
1000000	12.2.1	Class A Power Amplifiers	760
	12.2.2	Class B Power Amplifiers	764
	12.2.3	Class C Power Amplifiers	768
123	High-E	Efficiency Power Amplifiers	770
1210	1231	Class A Stage with Harmonic Enhancement	771
	12.3.2	Class E Stage	772
	12.3.3	Class E Power Amplifiers	775
124	Cascod	le Output Stages	776
12.4	Large_9	Signal Impedance Matching	780
12.5	Basic I	inearization Techniques	782
12.0	1261	Feedforward	782
	12.0.1	Cartesian Feedback	785
	12.0.2	Predictortion	780
	12.0.5	Envelope Feedback	701
127	Dolor N	Adulation	788
12.7	12.7.1	Posia Idea	790
	12.7.1	Date Modulation Januar	790
	12.7.2	Forar Woodulation Issues	793
	12.7.3	improved Polar Wodulation	790

100.00

 •
 •
P

	12.8	Outpha	sing	802
		12.8.1	Basic Idea	802
		12.8.2	Outphasing Issues	805
	12.9	Doherty	y Power Amplifier	811
	12.10	Design	Examples	814
		12.10.1	Cascode PA Examples	815
		12.10.2	Positive-Feedback PAs	819
		12.10.3	PAs with Power Combining	821
		12.10.4	Polar Modulation PAs	824
		12.10.5	Outphasing PA Example	826
	Refere	nces		830
	Proble	ms		831
СН	APTE	R 13 T	RANSCEIVER DESIGN EXAMPLE	833
	13.1	System	-Level Considerations	833
		13.1.1	Receiver	834
		13.1.2	Transmitter	838
		13.1.3	Frequency Synthesizer	840
		13.1.4	Frequency Planning	844
	13.2	Receive	er Design	848
		13.2.1	LNA Design	849
		13.2.2	Mixer Design	851
		13.2.3	AGC	856
	13.3	TX Des	sign	861
		13.3.1	PA Design	861
		13.3.2	Upconverter	867
	13.4	Synthes	sizer Design	869
		13.4.1	VCO Design	869
		13.4.2	Divider Design	878
		13.4.3	Loop Design	882
	Refere	ences		886
	Proble	ms		886

Contents

889

INDEX

PREFACE TO THE SECOND EDITION

In the 14 years since the first edition of this book, RF IC design has experienced a dramatic metamorphosis. Innovations in transceiver architectures, circuit topologies, and device structures have led to highly-integrated "radios" that span a broad spectrum of applications. Moreover, new analytical and modeling techniques have considerably improved our understanding of RF circuits and their underlying principles. A new edition was therefore due.

The second edition differs from the first in several respects:

- 1. I realized at the outset-three-and-a-half years ago-that simply adding "patches" to the first edition would not reflect today's RF microelectronics. I thus closed the first edition and began with a clean slate. The two editions have about 10% overlap.
- 2. I wanted the second edition to contain greater pedagogy, helping the reader understand both the fundamentals and the subtleties. I have thus incorporated hundreds of examples and problems.
- 3. I also wanted to teach design in addition to analysis. I have thus included step-bystep design procedures and examples. Furthermore, I have dedicated Chapter 13 to the step-by-step transistor-level design of a dual-band WiFi transceiver.
- 4. With the tremendous advances in RF design, some of the chapters have inevitably become longer and some have been split into two or more chapters. As a result, the second edition is nearly three times as long as the first.

Suggestions for Instructors and Students

The material in this book is much more than can be covered in one quarter or semester. The following is a possible sequence of the chapters that can be taught in one term with reasonable depth. Depending on the students' background and the instructor's preference, other combinations of topics can also be covered in one quarter or semester.

xvi

Chapter 1: Introduction to RF and Wireless Technology

This chapter provides the big picture and should be covered in about half an hour.

Chapter 2: Basic Concepts in RF Design

The following sections should be covered: General Considerations, Effects of Nonlinearity (the section on AM/PM Conversion can be skipped), Noise, and Sensitivity and Dynamic Range. (The sections on Passive Impedance Transformation, Scattering Parameters, and Analysis of Nonlinear Dynamic Systems can be skipped.) This chapter takes about six hours of lecture.

Chapter 3: Communication Concepts

This chapter can be covered minimally in a quarter system—for example, Analog Modulation, Quadrature Modulation, GMSK Modulation, Multiple Access Techniques, and the IEEE802.11a/b/g Standard. In a semester system, the concept of signal constellations can be introduced and a few more modulation schemes and wireless standards can be taught. This chapter takes about two hours in a quarter system and three hours in a semester system.

Chapter 4: Transceiver Architectures

This chapter is relatively long and should be taught selectively. The following sections should be covered: General Considerations, Basic and Modern Heterodyne Receivers, Direct-Conversion Receivers, Image-Reject Receivers, and Direct-Conversion Transmitters. In a semester system, Low-IF Receivers and Heterodyne Transmitters can be covered as well. This chapter takes about eight hours in a quarter system and ten hours in a semester system.

Chapter 5: Low-Noise Amplifiers

The following sections should be covered: General Considerations, Problem of Input Matching, and LNA Topologies. A semester system can also include Gain Switching and Band Switching or High-IP₂ LNAs. This chapter takes about six hours in a quarter system and eight hours in a semester system.

Chapter 6: Mixers

The following sections should be covered: General Considerations, Passive Downconversion Mixers (the computation of noise and input impedance of voltagedriven sampling mixers can be skipped), Active Downconversion Mixers, and Active Mixers with High IP₂. In a semester system, Active Mixers with Enhanced Transconductance, Active Mixers with Low Flicker Noise, and Upconversion Mixers can also be covered. This chapter takes about eight hours in a quarter system and ten hours in a semester system.

Chapter 7: Passive Devices

This chapter may not fit in a quarter system. In a semester system, about three hours can be spent on basic inductor structures and loss mechanisms and MOS varactors.

Chapter 8: Oscillators

This is a long chapter and should be taught selectively. The following sections should be covered: Basic Principles, Cross-Coupled Oscillator, Voltage-Controlled

Preface to the Second Edition

Oscillators, Low-Noise VCOs. In a quarter system, there is little time to cover phase noise. In a semester system, both approaches to phase noise analysis can be taught. This chapter takes about six hours in a quarter system and eight hours in a semester system.

Chapter 9: Phase-Locked Loops

This chapter forms the foundation for synthesizers. In fact, if taught carefully, this chapter naturally teaches integer-N synthesizers, allowing a quarter system to skip the next chapter. The following sections should be covered: Basic Concepts, Type-I PLLs, Type-II PLLs, and PFD/CP Nonidealities. A semester system can also include Phase Noise in PLLs and Design Procedure. This chapter takes about four hours in a quarter system and six hours in a semester system.

Chapter 10: Integer-N Synthesizers

This chapter is likely sacrificed in a quarter system. A semester system can spend about four hours on Spur Reduction Techniques and Divider Design.

Chapter 11: Fractional-N Synthesizers

This chapter is likely sacrificed in a quarter system. A semester system can spend about four hours on Randomization and Noise Shaping. The remaining sections may be skipped.

Chapter 12: Power Amplifiers

This is a long chapter and, unfortunately, is often sacrificed for other chapters. If coverage is desired, the following sections may be taught: General Considerations, Classification of Power Amplifiers, High-Efficiency Power Amplifiers, Cascode Output Stages, and Basic Linearization Techniques. These topics take about four hours of lecture. Another four hours can be spent on Doherty Power Amplifier, Polar Modulation, and Outphasing.

Chapter 13: Transceiver Design Example

This chapter provides a step-by-step design of a dual-band transceiver. It is possible to skip the state-of-the-art examples in Chapters 5, 6, and 8 to allow some time for this chapter. The system-level derivations may still need to be skipped. The RX, TX, and synthesizer transistor-level designs can be covered in about four hours.

A solutions manual is available for instructors via the Pearson Higher Education Instructor Resource Center web site: pearsonhighered.com/irc; and a set of Powerpoint slides is available for instructors at **informit.com/razavi**. Additional problems will be posted on the book's website (**informit.com/razavi**).

> —Behzad Razavi July 2011

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PREFACE TO THE FIRST EDITION

The annual worldwide sales of cellular phones has exceeded \$2.5B. With 4.5 million customers, home satellite networks comprise a \$2.5B industry. The global positioning system is expected to become a \$5B market by the year 2000. In Europe, the sales of equipment and services for mobile communications will reach \$30B by 1998. The statistics are overwhelming.

The radio frequency (RF) and wireless market has suddenly expanded to unimaginable dimensions. Devices such as pagers, cellular and cordless phones, cable modems, and RF identification tags are rapidly penetrating all aspects of our lives, evolving from luxury items to indispensable tools. Semiconductor and system companies, small and large, analog and digital, have seen the statistics and are striving to capture their own market share by introducing various RF products.

RF design is unique in that it draws upon many disciplines unrelated to integrated circuits (ICs). The RF knowledge base has grown for almost a century, creating a seemingly endless body of literature for the novice.

This book deals with the analysis and design of RF integrated circuits and systems. Providing a systematic treatment of RF electronics in a tutorial language, the book begins with the necessary background knowledge from microwave and communication theory and leads the reader to the design of RF transceivers and circuits. The text emphasizes both architecture and circuit level issues with respect to monolithic implementation in VLSI technologies. The primary focus is on bipolar and CMOS design, but most of the concepts can be applied to other technologies as well. The reader is assumed to have a basic understanding of analog IC design and the theory of signals and systems.

The book consists of nine chapters. Chapter 1 gives a general introduction, posing questions and providing motivation for subsequent chapters. Chapter 2 describes basic concepts in RF and microwave design, emphasizing the effects of nonlinearity and noise.

Chapters 3 and 4 take the reader to the communication system level, giving an overview of modulation, detection, multiple access techniques, and wireless standards. While initially appearing to be unnecessary, this material is in fact essential to the concurrent design of RF circuits and systems.

Chapter 5 deals with transceiver architectures, presenting various receiver and transmitter topologies along with their merits and drawbacks. This chapter also includes a number of case studies that exemplify the approaches taken in actual RF products.

Chapters 6 through 9 address the design of RF building blocks: low-noise amplifiers and mixers, oscillators, frequency synthesizers, and power amplifiers, with particular attention to minimizing the number of off-chip components. An important goal of these chapters is to demonstrate how the system requirements define the parameters of the circuits and how the performance of each circuit impacts that of the overall transceiver.

I have taught approximately 80% of the material in this book in a 4-unit graduate course at UCLA. Chapters 3, 4, 8, and 9 had to be shortened in a ten-week quarter, but in a semester system they can be covered more thoroughly.

Much of my RF design knowledge comes from interactions with colleagues. Helen Kim, Ting-Ping Liu, and Dan Avidor of Bell Laboratories, and David Su and Andrew Gzegorek of Hewlett-Packard Laboratories have contributed to the material in this book in many ways. The text was also reviewed by a number of experts: Stefan Heinen (Siemens), Bart Jansen (Hewlett-Packard), Ting-Ping Liu (Bell Labs), John Long (University of Toronto), Tadao Nakagawa (NTT), Gitty Nasserbakht (Texas Instruments), Ted Rappaport (Virginia Tech), Tirdad Sowlati (Gennum), Trudy Stetzler (Bell Labs), David Su (Hewlett-Packard), and Rick Wesel (UCLA). In addition, a number of UCLA students, including Farbod Behbahani, Hooman Darabi, John Leete, and Jacob Rael, "test drove" various chapters and provided useful feedback. I am indebted to all of the above for their kind assistance.

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> —Behzad Razavi July 1997

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Even after several rounds of self-editing, it is possible that typos or subtle mistakes have eluded the author. Sometimes, an explanation that is clear to the author may not be so to the reader. And, occasionally, the author may have missed a point or a recent development. A detailed review of the book by others thus becomes necessary. The following individuals meticulously reviewed various chapters, discovered my mistakes, and made valuable suggestions:

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The book's production was proficiently managed by the staff at Prentice Hall, including Bernard Goodwin and Julie Nahil. I would like to thank both.

As with my other books, my wife, Angelina, typed the entire second edition in Latex and selflessly helped me in this three-and-a-half-year endeavor. I am grateful to her.

-Behzad Razavi

ABOUT THE AUTHOR

Behzad Razavi received the BSEE degree from Sharif University of Technology in 1985 and MSEE and PhDEE degrees from Stanford University in 1988 and 1992, respectively. He was with AT&T Bell Laboratories and Hewlett-Packard Laboratories until 1996. Since 1996, he has been associate professor and, subsequently, professor of electrical engineering at University of California, Los Angeles. His current research includes wireless transceivers, frequency synthesizers, phase-locking and clock recovery for high-speed data communications, and data converters.

Professor Razavi was an adjunct professor at Princeton University from 1992 to 1994, and at Stanford University in 1995. He served on the Technical Program Committees of the International Solid-State Circuits Conference (ISSCC) from 1993 to 2002 and VLSI Circuits Symposium from 1998 to 2002. He has also served as guest editor and associate editor of the IEEE Journal of Solid-State Circuits, IEEE Transactions on Circuits and Systems, and International Journal of High Speed Electronics.

Professor Razavi received the Beatrice Winner Award for Editorial Excellence at the 1994 ISSCC; the best paper award at the 1994 European Solid-State Circuits Conference; the best panel award at the 1995 and 1997 ISSCC; the TRW Innovative Teaching Award in 1997; the best paper award at the IEEE Custom Integrated Circuits Conference (CICC) in 1998; and McGraw-Hill First Edition of the Year Award in 2001. He was the co-recipient of both the Jack Kilby Outstanding Student Paper Award and the Beatrice Winner Award for Editorial Excellence at the 2001 ISSCC. He received the Lockheed Martin Excellence in Teaching Award in 2006; the UCLA Faculty Senate Teaching Award in 2007; and the CICC Best Invited Paper Award in 2009. He was also recognized as one of the top ten authors in the fifty-year history of ISSCC. He received the IEEE Donald Pederson Award in Solid-State Circuits in 2012.

Professor Razavi is an IEEE Distinguished Lecturer, a Fellow of IEEE, and the author of *Principles of Data Conversion System Design*, *RF Microelectronics*, *First Edition* (translated to Chinese, Japanese, and Korean), *Design of Analog CMOS Integrated Circuits* (translated to Chinese, Japanese, and Korean), *Design of Integrated Circuits for*

xxii

Optical Communications, and Fundamentals of Microelectronics (translated to Korean and Portuguese), and the editor of Monolithic Phase-Locked Loops and Clock Recovery Circuits and Phase-Locking in High-Performance Systems.

INTRODUCTION TO RF AND WIRELESS TECHNOLOGY

Compare two RF transceivers designed for cell phones:

"A 2.7-V GSM RF Transceiver IC" [1] (published in 1997)

"A Single-Chip 10-Band WCDMA/HSDPA 4-Band GSM/EDGE SAW-Less CMOS Receiver with DigRF 3G Interface and +90-dBm IIP₂" [2] (published in 2009)

Why is the latter much more complex than the former? Does the latter have a higher performance or only greater functionality? Which one costs more? Which one consumes a higher power? What do all the acronyms GSM, WCDMA, HSDPA, EDGE, SAW, and IIP₂ mean? Why do we care?

The field of RF communication has grown rapidly over the past two decades, reaching far into our lives and livelihood. Our cell phones serve as an encyclopedia, a shopping terminus, a GPS guide, a weather monitor, and a telephone—all thanks to their wireless communication devices. We can now measure a patient's brain or heart activity and transmit the results wirelessly, allowing the patient to move around untethered. We use RF devices to track merchandise, pets, cattle, children, and convicts.

1.1 A WIRELESS WORLD

Wireless communication has become almost as ubiquitous as electricity; our refrigerators and ovens may not have a wireless device at this time, but it is envisioned that our homes will eventually incorporate a wireless network that controls every device and appliance. High-speed wireless links will allow seamless connections among our laptops, digital cameras, camcorders, cell phones, printers, TVs, microwave ovens, etc. Today's WiFi and Bluetooth connections are simple examples of such links.

How did wireless communication take over the world? A confluence of factors has contributed to this explosive growth. The principal reason for the popularity of wireless

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communication is the ever-decreasing cost of electronics. Today's cell phones cost about the same as those a decade ago but they offer many more functions and features: many frequency bands and communication modes, WiFi, Bluetooth, GPS, computing, storage, a digital camera, and a user-friendly interface. This affordability finds its roots in integration, i.e., how much functionality can be placed on a single chip-or, rather, how few components are left off-chip. The integration, in turn, owes its steady rise to (1) the scaling of VLSI processes, particularly, CMOS technology, and (2) innovations in RF architectures, circuits, and devices.

Along with higher integration levels, the performance of RF circuits has also improved. For example, the power consumption necessary for a given function has decreased and the speed of RF circuits has increased. Figure 1.1 illustrates some of the trends in RF integrated circuits (ICs) and technology for the past two decades. The minimum feature size of CMOS



Figure 1.1 Trends in RF circuits and technology.

Sec. 1.2. RF Design Is Challenging

technology has fallen from 0.5 μ m to 40 nm, the transit frequency,¹ f_T , of NMOS devices has risen from about 12 GHz to several hundred gigahertz, and the speed of RF oscillators has gone from 1.2 GHz to 300 GHz. Also shown is the number of RF and wireless design papers presented at the International Solid-State Circuits Conference (ISSCC) each year, revealing the fast-growing activity in this field.

1.2 RF DESIGN IS CHALLENGING

Despite many decades of work on RF and microwave theory and two decades of research on RF ICs, the design and implementation of RF circuits and transceivers remain challenging. This is for three reasons. First, as shown in Fig. 1.2, RF design draws upon a multitude of disciplines, requiring a good understanding of fields that are seemingly irrelevant to integrated circuits. Most of these fields have been under study for more than half a century, presenting a massive body of knowledge to a person entering RF IC design. One objective of this book is to provide the necessary background from these disciplines without overwhelming the reader.

Second, RF circuits and transceivers must deal with numerous trade-offs, summarized in the "RF design hexagon" of Fig. 1.3. For example, to lower the noise of a front-end amplifier, we must consume a greater power or sacrifice linearity. We will encounter these trade-offs throughout this book.

Third, the demand for higher performance, lower cost, and greater functionality continues to present new challenges. The early RF IC design work in the 1990s strove to integrate one transceiver-perhaps along with the digital baseband processor-on a single chip. Today's efforts, on the other hand, aim to accommodate multiple transceivers operating in different frequency bands for different wireless standards (e.g., Bluetooth, WiFi, GPS, etc.). The two papers mentioned at the beginning of this chapter exemplify this trend. It is interesting to note that the silicon chip area of early single-transceiver systems was



Figure 1.2 Various disciplines necessary in RF design.

^{1.} The transit frequency is defined as the frequency at which the small-signal current gain of a device falls to unity.

Chap. 1. Introduction to RF and Wireless Technology



Figure 1.3 RF design hexagon.

dominated by the digital baseband processor, allowing RF and analog designers some latitude in the choice of their circuit and device topologies. In today's designs, however, the multiple transceivers tend to occupy a larger area than the baseband processor, requiring that RF and analog sections be designed with much care about their area consumption. For example, while on-chip spiral inductors (which have a large footprint) were utilized in abundance in older systems, they are now used only sparingly.

THE BIG PICTURE 1.3

The objective of an RF transceiver is to transmit and receive information. We envision that the transmitter (TX) somehow processes the voice or data signal and applies the result to the antenna [Fig. 1.4(a)]. Similarly, the receiver (RX) senses the signal picked up by the antenna and processes it so as to reconstruct the original voice or data information. Each black box in Fig. 1.4(a) contains a great many functions, but we can readily make two observations: (1) the TX must drive the antenna with a high power level so that the transmitted signal is strong enough to reach far distances, and (2) the RX may sense a small signal (e.g., when a cell phone is used in the basement of a building) and must first amplify the signal with low noise. We now architect our transceiver as shown in Fig. 1.4(b), where the signal to be transmitted is first applied to a "modulator" or "upconverter" so that its center frequency goes from zero to, say, $f_c = 2.4$ GHz. The result drives the antenna through a "power amplifier" (PA). On the receiver side, the signal is sensed by a "lownoise amplifier" (LNA) and subsequently by a "downconverter" or "demodulator" (also known as a "detector").

The upconversion and downconversion paths in Fig. 1.4(b) are driven by an oscillator, which itself is controlled by a "frequency synthesizer." Figure 1.4(c) shows the overall transceiver.² The system looks deceptively simple, but we will need the next 900 pages to cover its RF sections. And perhaps another 900 pages to cover the analog-to-digital and digital-to-analog converters.

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^{2.} In some cases, the modulator and the upconverter are one and the same. In some other cases, the modulation is performed in the digital domain before upconversion. Most receivers demodulate and detect the signal digitally, requiring only a downconverter in the analog domain.

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BASIC CONCEPTS IN RF DESIGN

RF design draws upon many concepts from a variety of fields, including signals and systems, electromagnetics and microwave theory, and communications. Nonetheless, RF design has developed its own analytical methods and its own language. For example, while the nonlinear behavior of analog circuits may be characterized by "harmonic distortion," that of RF circuits is quantified by very different measures.

This chapter deals with general concepts that prove essential to the analysis and design of RF circuits, closing the gaps with respect to other fields such as analog design, microwave theory, and communication systems. The outline is shown below.

Nonlinearity	Noise	Impedance Transformation
= Harmonic Distortion	= Noise Spectrum	Series–Parallel Conversion
Compression	Device Noise	Matching Networks
Intermodulation	Noise in Circuits	S-Parameters
Dynamic Nonlinear Systems		

2.1 GENERAL CONSIDERATIONS

2.1.1 Units in RF Design

RF design has traditionally employed certain units to express gains and signal levels. It is helpful to review these units at the outset so that we can comfortably use them in our subsequent studies.

The voltage gain, V_{out}/V_{in} , and power gain, P_{out}/P_{in} , are expressed in decibels (dB):

 $A_V|_{\rm dB} = 20\log$

6

 $A_P|_{\rm dB} = 10\log$

CHAPTER



$\frac{V_{out}}{V_{in}}$	(2.1)
$\frac{P_{out}}{P_{in}}$.	(2.2)