Contents

	Foreword	***xv***
	Acknowledgments	***xix***
1	**Introduction to Communications Circuits**	**1**
1.1	Introduction	1
1.2	Lower Frequency Analog Design and Microwave Design Versus Radio Frequency Integrated Circuit Design	2
1.2.1	Impedance Levels for Microwave and Low-Frequency Analog Design	2
1.2.2	Units for Microwave and Low-Frequency Analog Design	3
1.3	Radio Frequency Integrated Circuits Used in a Communications Transceiver	4
1.4	Overview	6
	References	6
2	**Issues in RFIC Design, Noise, Linearity, and Filtering**	**9**
2.1	Introduction	9

2.2	Noise	9
2.2.1	Thermal Noise	10
2.2.2	Available Noise Power	11
2.2.3	Available Power from Antenna	11
2.2.4	The Concept of Noise Figure	13
2.2.5	The Noise Figure of an Amplifier Circuit	14
2.2.6	The Noise Figure of Components in Series	16
2.3	Linearity and Distortion in RF Circuits	23
2.3.1	Power Series Expansion	23
2.3.2	Third-Order Intercept Point	27
2.3.3	Second-Order Intercept Point	29
2.3.4	The 1-dB Compression Point	30
2.3.5	Relationships Between 1-dB Compression and IP3 Points	31
2.3.6	Broadband Measures of Linearity	32
2.4	Dynamic Range	35
2.5	Filtering Issues	37
2.5.1	Image Signals and Image Reject Filtering	37
2.5.2	Blockers and Blocker Filtering	39
	References	41
	Selected Bibliography	42
3	**A Brief Review of Technology**	**43**
3.1	Introduction	43
3.2	Bipolar Transistor Description	43
3.3	β Current Dependence	46
3.4	Small-Signal Model	47
3.5	Small-Signal Parameters	48
3.6	High-Frequency Effects	49
3.6.1	f_T as a Function of Current	51
3.7	Noise in Bipolar Transistors	53
3.7.1	Thermal Noise in Transistor Components	53
3.7.2	Shot Noise	53
3.7.3	$1/f$ Noise	54

3.8	Base Shot Noise Discussion	55
3.9	Noise Sources in the Transistor Model	55
3.10	Bipolar Transistor Design Considerations	56
3.11	CMOS Transistors	57
3.11.1	NMOS	58
3.11.2	PMOS	58
3.11.3	CMOS Small-Signal Model Including Noise	58
3.11.4	CMOS Square Law Equations	60
	References	61
4	**Impedance Matching**	**63**
4.1	Introduction	63
4.2	Review of the Smith Chart	66
4.3	Impedance Matching	69
4.4	Conversions Between Series and Parallel Resistor-Inductor and Resistor-Capacitor Circuits	74
4.5	Tapped Capacitors and Inductors	76
4.6	The Concept of Mutual Inductance	78
4.7	Matching Using Transformers	81
4.8	Tuning a Transformer	82
4.9	The Bandwidth of an Impedance Transformation Network	83
4.10	Quality Factor of an LC Resonator	85
4.11	Transmission Lines	88
4.12	*S*, *Y*, and *Z* Parameters	89
	References	93
5	**The Use and Design of Passive Circuit Elements in IC Technologies**	**95**
5.1	Introduction	95
5.2	The Technology Back End and Metallization in IC Technologies	95

5.3	Sheet Resistance and the Skin Effect	97
5.4	Parasitic Capacitance	100
5.5	Parasitic Inductance	101
5.6	Current Handling in Metal Lines	102
5.7	Poly Resistors and Diffusion Resistors	103
5.8	Metal-Insulator-Metal Capacitors and Poly Capacitors	103
5.9	Applications of On-Chip Spiral Inductors and Transformers	104
5.10	Design of Inductors and Transformers	106
5.11	Some Basic Lumped Models for Inductors	108
5.12	Calculating the Inductance of Spirals	110
5.13	Self-Resonance of Inductors	110
5.14	The Quality Factor of an Inductor	111
5.15	Characterization of an Inductor	115
5.16	Some Notes About the Proper Use of Inductors	117
5.17	Layout of Spiral Inductors	119
5.18	Isolating the Inductor	121
5.19	The Use of Slotted Ground Shields and Inductors	122
5.20	Basic Transformer Layouts in IC Technologies	122
5.21	Multilevel Inductors	124
5.22	Characterizing Transformers for Use in ICs	127
5.23	On-Chip Transmission Lines	129
5.23.1	Effect of Transmission Line	130
5.23.2	Transmission Line Examples	131
5.24	High-Frequency Measurement of On-Chip Passives and Some Common De-Embedding Techniques	134

5.25	Packaging	135
5.25.1	Other Packaging Techniques	138
	References	139
6	**LNA Design**	**141**
6.1	Introduction and Basic Amplifiers	141
6.1.1	Common-Emitter Amplifier (Driver)	141
6.1.2	Simplified Expressions for Widely Separated Poles	146
6.1.3	The Common-Base Amplifier (Cascode)	146
6.1.4	The Common-Collector Amplifier (Emitter Follower)	148
6.2	Amplifiers with Feedback	152
6.2.1	Common-Emitter with Series Feedback (Emitter Degeneration)	152
6.2.2	The Common-Emitter with Shunt Feedback	154
6.3	Noise in Amplifiers	158
6.3.1	Input-Referred Noise Model of the Bipolar Transistor	159
6.3.2	Noise Figure of the Common-Emitter Amplifier	161
6.3.3	Input Matching of LNAs for Low Noise	163
6.3.4	Relationship Between Noise Figure and Bias Current	169
6.3.5	Effect of the Cascode on Noise Figure	170
6.3.6	Noise in the Common-Collector Amplifier	171
6.4	Linearity in Amplifiers	172
6.4.1	Exponential Nonlinearity in the Bipolar Transistor	172
6.4.2	Nonlinearity in the Output Impedance of the Bipolar Transistor	180
6.4.3	High-Frequency Nonlinearity in the Bipolar Transistor	182
6.4.4	Linearity in Common-Collector Configuration	182
6.5	Differential Pair (Emitter-Coupled Pair) and Other Differential Amplifiers	183
6.6	Low-Voltage Topologies for LNAs and the Use of On-Chip Transformers	184

6.7	DC Bias Networks	187
6.7.1	Temperature Effects	189
6.8	Broadband LNA Design Example	189
	References	194
	Selected Bibliography	195
7	**Mixers**	**197**
7.1	Introduction	197
7.2	Mixing with Nonlinearity	197
7.3	Basic Mixer Operation	198
7.4	Controlled Transconductance Mixer	198
7.5	Double-Balanced Mixer	200
7.6	Mixer with Switching of Upper Quad	202
7.6.1	Why LO Switching?	203
7.6.2	Picking the LO Level	204
7.6.3	Analysis of Switching Modulator	205
7.7	Mixer Noise	206
7.8	Linearity	215
7.8.1	Desired Nonlinearity	215
7.8.2	Undesired Nonlinearity	215
7.9	Improving Isolation	217
7.10	Image Reject and Single-Sideband Mixer	217
7.10.1	Alternative Single-Sideband Mixers	219
7.10.2	Generating 90° Phase Shift	220
7.10.3	Image Rejection with Amplitude and Phase Mismatch	224
7.11	Alternative Mixer Designs	227
7.11.1	The Moore Mixer	228
7.11.2	Mixers with Transformer Input	228
7.11.3	Mixer with Simultaneous Noise and Power Match	229
7.11.4	Mixers with Coupling Capacitors	230

7.12	General Design Comments	231
7.12.1	Sizing Transistors	232
7.12.2	Increasing Gain	232
7.12.3	Increasing IP3	232
7.12.4	Improving Noise Figure	233
7.12.5	Effect of Bond Pads and the Package	233
7.12.6	Matching, Bias Resistors, and Gain	234
7.13	CMOS Mixers	242
	References	244
	Selected Bibliography	244
8	**Voltage-Controlled Oscillators**	**245**
8.1	Introduction	245
8.2	Specification of Oscillator Properties	245
8.3	The LC Resonator	247
8.4	Adding Negative Resistance Through Feedback to the Resonator	248
8.5	Popular Implementations of Feedback to the Resonator	250
8.6	Configuration of the Amplifier (Colpitts or $-G_m$)	251
8.7	Analysis of an Oscillator as a Feedback System	252
8.7.1	Oscillator Closed-Loop Analysis	252
8.7.2	Capacitor Ratios with Colpitts Oscillators	255
8.7.3	Oscillator Open-Loop Analysis	258
8.7.4	Simplified Loop Gain Estimates	260
8.8	Negative Resistance Generated by the Amplifier	262
8.8.1	Negative Resistance of Colpitts Oscillator	262
8.8.2	Negative Resistance for Series and Parallel Circuits	263
8.8.3	Negative Resistance Analysis of $-G_m$ Oscillator	265
8.9	Comments on Oscillator Analysis	268
8.10	Basic Differential Oscillator Topologies	270

8.11	A Modified Common-Collector Colpitts Oscillator with Buffering	270
8.12	Several Refinements to the $-G_m$ Topology	270
8.13	The Effect of Parasitics on the Frequency of Oscillation	274
8.14	Large-Signal Nonlinearity in the Transistor	275
8.15	Bias Shifting During Startup	277
8.16	Oscillator Amplitude	277
8.17	Phase Noise	283
8.17.1	Linear or Additive Phase Noise and Leeson's Formula	283
8.17.2	Some Additional Notes About Low-Frequency Noise	291
8.17.3	Nonlinear Noise	292
8.18	Making the Oscillator Tunable	295
8.19	VCO Automatic-Amplitude Control Circuits	302
8.20	Other Oscillators	313
	References	316
	Selected Bibliography	317
9	**High-Frequency Filter Circuits**	**319**
9.1	Introduction	319
9.2	Second-Order Filters	320
9.3	Integrated RF Filters	321
9.3.1	A Simple Bandpass LC Filter	321
9.3.2	A Simple Bandstop Filter	322
9.3.3	An Alternative Bandstop Filter	323
9.4	Achieving Filters with Higher Q	327
9.4.1	Differential Bandpass LNA with Q-Tuned Load Resonator	327
9.4.2	A Bandstop Filter with Colpitts-Style Negative Resistance	329
9.4.3	Bandstop Filter with Transformer-Coupled $-G_m$ Negative Resistance	331

9.5	Some Simple Image Rejection Formulas	333
9.6	Linearity of the Negative Resistance Circuits	336
9.7	Noise Added Due to the Filter Circuitry	337
9.8	Automatic Q Tuning	339
9.9	Frequency Tuning	342
9.10	Higher-Order Filters	343
	References	346
	Selected Bibliography	347
10	**Power Amplifiers**	**349**
10.1	Introduction	349
10.2	Power Capability	350
10.3	Efficiency Calculations	350
10.4	Matching Considerations	351
10.4.1	Matching to S_{22}^* Versus Matching to Γ_{opt}	352
10.5	Class A, B, and C Amplifiers	353
10.5.1	Class A, B, and C Analysis	356
10.5.2	Class B Push-Pull Arrangements	362
10.5.3	Models for Transconductance	363
10.6	Class D Amplifiers	367
10.7	Class E Amplifiers	368
10.7.1	Analysis of Class E Amplifier	370
10.7.2	Class E Equations	371
10.7.3	Class E Equations for Finite Output Q	372
10.7.4	Saturation Voltage and Resistance	373
10.7.5	Transition Time	373
10.8	Class F Amplifiers	375
10.8.1	Variation on Class F: Second-Harmonic Peaking	379
10.8.2	Variation on Class F: Quarter-Wave Transmission Line	379
10.9	Class G and H Amplifiers	381
10.10	Class S Amplifiers	383

10.11 Summary of Amplifier Classes for RF Integrated Circuits 384
10.12 AC Load Line 385
10.13 Matching to Achieve Desired Power 385
10.14 Transistor Saturation 388
10.15 Current Limits 388
10.16 Current Limits in Integrated Inductors 390
10.17 Power Combining 390
10.18 Thermal Runaway—Ballasting 392
10.19 Breakdown Voltage 393
10.20 Packaging 394
10.21 Effects and Implications of Nonlinearity 394
10.21.1 Cross Modulation 395
10.21.2 AM-to-PM Conversion 395
10.21.3 Spectral Regrowth 395
10.21.4 Linearization Techniques 396
10.21.5 Feedforward 396
10.21.6 Feedback 397
10.22 CMOS Power Amplifier Example 398
References 399

About the Authors 401

Index 403