Contents

Preface xiii

Acknowledgments xvii

1 Linear RF amplifier design—general considerations 1
  1.1 Introduction 1
  1.2 Power gain definitions 3
  1.3 Neutralization 7
  1.4 Unilateral transducer gain 8
    1.4.1 Unilateral figure of merit 10
    1.4.2 Illustrative example: unilateral gain calculations 12
    1.4.3 Amplifier design with single matching networks 13
    1.4.4 Unilateral constant gain circles 15
    1.4.5 Illustrative example: single-sided amplifier design 15
  1.5 RF circuit stability considerations 19
    1.5.1 What may cause RF oscillation 22
    1.5.2 Stability analysis with arbitrary source and load terminations 25
    1.5.3 Two-port stability considerations 30
    1.5.4 Stability circles 35
    1.5.5 Graphical forms of unconditional stability 40
    1.5.6 Graphical forms of potential instability 41
    1.5.7 Caution about multistage systems 42
  1.6 Stabilizing an active two-port 46
    1.6.1 Finding the minimum-loss resistor at the input of the device 47
    1.6.2 Broadband stability considerations 49
  1.7 Stabilization of a bipolar transistor 50
    1.7.1 Examining the effect of lossless feedback 50
    1.7.2 Device stabilization 51
  1.8 The dc bias techniques 59
    1.8.1 Passive dc bias networks 60
    1.8.2 Active dc bias circuits 63
    1.8.3 Feeding dc bias into the RF circuit 64
    1.8.4 The dc bias circuit simulation 65
    1.8.5 Filtering of dc bias networks 69
  1.9 Statistical and worst-case analyses 69
CONTENTS

1.10 Circuit layout considerations 71
1.11 Summary 74
1.12 Problems 74
   References 75
   Selected bibliography 76

2 Linear and low-noise RF amplifiers 77
  2.1 Introduction 77
  2.2 Bilateral RF amplifier design for maximum small-signal gain 78
     2.2.1 Illustrative exercise: amplifier design for maximum gain, $G_{\text{MAX}}$ 82
  2.3 Multistage amplifiers 88
     2.3.1 Cascading impedance-matched stages 88
     2.3.2 Cascading amplifiers by direct impedance matching 89
     2.3.3 Output power and impedance match considerations of cascaded amplifiers 92
  2.4 Operating gain design for maximum linear output power 94
     2.4.1 Operating gain design outline 95
     2.4.2 $G_e$ versus $P_{\text{OUT}}$ trade-offs 97
     2.4.3 Stability considerations 97
     2.4.4 Illustrative example: operating gain design for maximum linear power output 98
     2.4.5 Output match considerations 101
  2.5 Noise in RF circuits 102
     2.5.1 Review of noise sources in RF systems 102
     2.5.2 Two-port noise parameter definitions 106
  2.6 Available gain design technique 107
     2.6.1 Available gain design outline 108
     2.6.2 Low-noise amplifier design considerations 110
     2.6.3 Illustrative example: design of a single-ended 1.9-GHz LNA 111
     2.6.4 Balanced amplifiers 114
     2.6.5 Illustrative example: design of a balanced LNA for the 1.7- to 2.3-GHz frequency range 116
  2.7 Comparison of the various amplifier designs and Smith chart-based graphical design aids 121
  2.8 Broadband amplifiers 123
     2.8.1 Reactive match/mismatch approach 124
     2.8.2 Dissipative mismatch at input and/or output ports 125
     2.8.3 Amplifier-equalizer combinations 129
     2.8.4 Feedback amplifiers 129
     2.8.5 Distributed amplifiers 141
  2.9 Summary 142
  2.10 Problems 143
     References 144
     Selected bibliography 145
<table>
<thead>
<tr>
<th>CONTENTS</th>
<th>ix</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 Active RF devices and their modeling</td>
<td>147</td>
</tr>
<tr>
<td>3.1 The diode model</td>
<td>148</td>
</tr>
<tr>
<td>3.2 Two-port device models</td>
<td>150</td>
</tr>
<tr>
<td>3.2.1 The output terminals of a two-port RF device</td>
<td>150</td>
</tr>
<tr>
<td>3.2.2 The bipolar transistor</td>
<td>153</td>
</tr>
<tr>
<td>3.2.3 The heterojunction bipolar transistor</td>
<td>173</td>
</tr>
<tr>
<td>3.2.4 The GaAs MESFET</td>
<td>177</td>
</tr>
<tr>
<td>3.2.5 The high-electron mobility transistor</td>
<td>184</td>
</tr>
<tr>
<td>3.2.6 Silicon LDMOS and CMOS technologies</td>
<td>187</td>
</tr>
<tr>
<td>3.3 Problems</td>
<td>190</td>
</tr>
<tr>
<td>References</td>
<td>190</td>
</tr>
<tr>
<td>4 Nonlinear circuit simulation techniques</td>
<td>193</td>
</tr>
<tr>
<td>4.1 Classification of nonlinear circuit simulators</td>
<td>193</td>
</tr>
<tr>
<td>4.1.1 Analytical methods</td>
<td>194</td>
</tr>
<tr>
<td>4.1.2 Time-domain methods</td>
<td>194</td>
</tr>
<tr>
<td>4.1.3 Hybrid time- and frequency-domain techniques—harmonic balance</td>
<td>197</td>
</tr>
<tr>
<td>4.1.4 Frequency-domain techniques</td>
<td>200</td>
</tr>
<tr>
<td>4.2 The harmonic balance method</td>
<td>202</td>
</tr>
<tr>
<td>4.3 Harmonic balance analysis of oscillators</td>
<td>207</td>
</tr>
<tr>
<td>4.3.1 Oscillator analysis using probes</td>
<td>208</td>
</tr>
<tr>
<td>4.3.2 Oscillator analysis using reflection coefficients of the device and resonant load</td>
<td>209</td>
</tr>
<tr>
<td>4.3.3 Oscillator analysis using a directional coupler to measure open-loop gain</td>
<td>214</td>
</tr>
<tr>
<td>References</td>
<td>215</td>
</tr>
<tr>
<td>5 High-power RF transistor amplifier design</td>
<td>217</td>
</tr>
<tr>
<td>5.1 Nonlinear concepts</td>
<td>217</td>
</tr>
<tr>
<td>5.1.1 Some nonlinear phenomena</td>
<td>220</td>
</tr>
<tr>
<td>5.2 Quasi-linear power amplifier design</td>
<td>223</td>
</tr>
<tr>
<td>5.2.1 The amplifier load line</td>
<td>224</td>
</tr>
<tr>
<td>5.2.2 Load pull methods</td>
<td>232</td>
</tr>
<tr>
<td>5.3 Categories of amplifiers</td>
<td>243</td>
</tr>
<tr>
<td>5.3.1 Class-A amplifier</td>
<td>243</td>
</tr>
<tr>
<td>5.3.2 Class-B amplifier</td>
<td>248</td>
</tr>
<tr>
<td>5.3.3 Class-F amplifier</td>
<td>257</td>
</tr>
<tr>
<td>5.3.4 Comparison of class-A, class-B, class-F, and other operational modes</td>
<td>265</td>
</tr>
<tr>
<td>5.3.5 Switching-mode amplifiers</td>
<td>271</td>
</tr>
<tr>
<td>5.3.6 Cascaded power amplifier design</td>
<td>278</td>
</tr>
</tbody>
</table>
## CONTENTS

5.4 Power amplifier design example 280  
5.4.1 Transistor selection 281  
5.4.2 Transistor characterization 282  
5.4.3 Matching the input and output of the device 286  
5.4.4 Harmonic tuning example 296  
5.5 Bias considerations 298  
5.5.1 Bias changes at the input 298  
5.5.2 Bias changes at the output 302  
5.5.3 Bias considerations with power devices 304  
5.6 Distortion reduction 307  
5.6.1 The importance of amplifier linearity 309  
5.6.2 Operating the amplifier backed off 311  
5.6.3 Predistortion 312  
5.6.4 Feedforward cancellation 317  
5.6.5 Device modification 319  
5.6.6 System-level reduction of distortion 325  
5.7 Problems 328  
References 334

6 Oscillators 337  
6.1 Principles of oscillator design 338  
6.1.1 Two-port oscillator design approach 338  
6.1.2 One-port oscillator design approach 349  
6.1.3 Transistor oscillator configurations 373  
6.1.4 Characterizing oscillator phase noise 390  
6.2 Oscillator design examples 404  
6.2.1 45.455-MHz Colpitts crystal oscillator design 404  
6.2.2 Design of a 3.7- to 4.2-GHz voltage-controlled oscillator 410  
6.3 Problems 429  
References 431

7 Mixers and frequency multipliers 433  
7.1 Mixer overview and their applications in systems 433  
7.2 Diode mixers and their topologies 442  
7.2.1 Single-ended mixer 443  
7.2.2 Single-balanced mixer 445  
7.2.3 Double-balanced mixer 451  
7.2.4 The image problem in mixers 455  
7.2.5 Harmonic components in mixers 460  
7.3 Transistor mixer design 464  
7.3.1 Active transistor mixers 464  
7.3.2 Resistive FET mixers 488  
7.3.3 Dual-gate FET mixers 494  
7.3.4 Comparison of mixers 500
# CONTENTS

7.4 Frequency multipliers—an overview 501
7.4.1 Frequency doublers 502
7.4.2 Arbitrary frequency multiplication 505
7.5 Problems 506
References 507

8 Circuits in systems—radio system applications 509
8.1 Mobile telephony systems 509
  8.1.1 Second generation mobile systems 510
  8.1.2 Third generation mobile systems 512
8.2 Software-defined radio 515
  8.2.1 RF digital processing 515
  8.2.2 Digital processing of a wideband IF 517
  8.2.3 Digital processing at baseband (direct conversion) 518
  8.2.4 Transceiver issues associated with software-defined radio 520
8.3 A 1.9-GHz radio chip set: design overview 522
  8.3.1 The air interface specification for PHS 522
  8.3.2 Component specification 523
  8.3.3 Component design 525
8.4 Integrated system chips: an overview 531
  8.4.1 RF receiver front ends 532
  8.4.2 RF upconverters and transmitter driver amplifiers 536
  8.4.3 Transceiver and complete radio solutions 538
  8.4.4 Power amplifier modules 543
8.5 Conclusion 544
References 545

Appendix 547
Summary of Basic Formulas – 1 547
Summary of Basic Formulas – 2 549

About the Authors 551

Index 553