Contents

Preface \hspace{1cm} \textit{xv}
About the Author \hspace{1cm} \textit{xvii}
List of Symbols \hspace{1cm} \textit{xix}

1 Introduction \hspace{1cm} 1
1.1 Block Diagram of RF Power Amplifiers \hspace{1cm} 1
1.2 Classes of Operation of RF Power Amplifiers \hspace{1cm} 3
1.3 Parameters of RF Power Amplifiers \hspace{1cm} 5
1.4 Conditions for 100\% Efficiency of Power Amplifiers \hspace{1cm} 7
1.5 Conditions for Nonzero Output Power at 100\% Efficiency of Power Amplifiers \hspace{1cm} 10
1.6 Output Power of Class E ZVS Amplifier \hspace{1cm} 11
1.7 Class E ZCS Amplifier \hspace{1cm} 14
1.8 Propagation of Electromagnetic Waves \hspace{1cm} 16
1.9 Frequency Spectrum \hspace{1cm} 19
1.10 Duplexing \hspace{1cm} 21
1.11 Multiple-access Techniques \hspace{1cm} 21
1.12 Nonlinear Distortion in Transmitters \hspace{1cm} 22
1.13 Harmonics of Carrier Frequency \hspace{1cm} 23
1.14 Intermodulation \hspace{1cm} 25
1.15 Dynamic Range of Power Amplifiers \hspace{1cm} 27
1.16 Analog Modulation \hspace{1cm} 28
  1.16.1 Amplitude Modulation \hspace{1cm} 29
  1.16.2 Phase Modulation \hspace{1cm} 32
  1.16.3 Frequency Modulation \hspace{1cm} 33
1.17 Digital Modulation \hspace{1cm} 36
  1.17.1 Amplitude-shift Keying \hspace{1cm} 36
  1.17.2 Phase-shift Keying \hspace{1cm} 37
  1.17.3 Frequency-shift Keying \hspace{1cm} 38
1.18 Radars \hspace{1cm} 39
1.19 Radio-frequency Identification \hspace{1cm} 40
1.20 Summary \hspace{1cm} 40
# CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.21</td>
<td>References</td>
<td>42</td>
</tr>
<tr>
<td>1.22</td>
<td>Review Questions</td>
<td>42</td>
</tr>
<tr>
<td>1.23</td>
<td>Problems</td>
<td>43</td>
</tr>
<tr>
<td>2</td>
<td>Class A RF Power Amplifier</td>
<td>45</td>
</tr>
<tr>
<td>2.1</td>
<td>Introduction</td>
<td>45</td>
</tr>
<tr>
<td>2.2</td>
<td>Circuit of Class A RF Power Amplifier</td>
<td>45</td>
</tr>
<tr>
<td>2.3</td>
<td>Power MOSFET Characteristics</td>
<td>47</td>
</tr>
<tr>
<td>2.4</td>
<td>Waveforms of Class A RF Amplifier</td>
<td>52</td>
</tr>
<tr>
<td>2.5</td>
<td>Parameters of Class A RF Power Amplifier</td>
<td>56</td>
</tr>
<tr>
<td>2.6</td>
<td>Parallel-resonant Circuit</td>
<td>59</td>
</tr>
<tr>
<td>2.7</td>
<td>Power Losses and Efficiency of Parallel Resonant Circuit</td>
<td>62</td>
</tr>
<tr>
<td>2.8</td>
<td>Impedance Matching Circuits</td>
<td>66</td>
</tr>
<tr>
<td>2.9</td>
<td>Class A RF Linear Amplifier</td>
<td>69</td>
</tr>
<tr>
<td>2.9.1</td>
<td>Amplifier of Variable-envelope Signals</td>
<td>69</td>
</tr>
<tr>
<td>2.9.2</td>
<td>Amplifiers of Constant-envelope Signals</td>
<td>70</td>
</tr>
<tr>
<td>2.10</td>
<td>Summary</td>
<td>71</td>
</tr>
<tr>
<td>2.11</td>
<td>References</td>
<td>71</td>
</tr>
<tr>
<td>2.12</td>
<td>Review Questions</td>
<td>72</td>
</tr>
<tr>
<td>2.13</td>
<td>Problems</td>
<td>72</td>
</tr>
<tr>
<td>3</td>
<td>Class AB, B, and C RF Power Amplifiers</td>
<td>75</td>
</tr>
<tr>
<td>3.1</td>
<td>Introduction</td>
<td>75</td>
</tr>
<tr>
<td>3.2</td>
<td>Class B RF Power Amplifier</td>
<td>75</td>
</tr>
<tr>
<td>3.2.1</td>
<td>Circuit of Class B RF Power Amplifier</td>
<td>75</td>
</tr>
<tr>
<td>3.2.2</td>
<td>Waveforms of Class B Amplifier</td>
<td>76</td>
</tr>
<tr>
<td>3.2.3</td>
<td>Power Relationships in Class B Amplifier</td>
<td>78</td>
</tr>
<tr>
<td>3.2.4</td>
<td>Efficiency of Class B Amplifier</td>
<td>80</td>
</tr>
<tr>
<td>3.3</td>
<td>Class AB and C RF Power Amplifiers</td>
<td>82</td>
</tr>
<tr>
<td>3.3.1</td>
<td>Waveforms of Class AB and C RF Power Amplifiers</td>
<td>82</td>
</tr>
<tr>
<td>3.3.2</td>
<td>Power of the Class AB, B, and C Amplifiers</td>
<td>86</td>
</tr>
<tr>
<td>3.3.3</td>
<td>Efficiency of the Class AB, B, and C Amplifiers</td>
<td>88</td>
</tr>
<tr>
<td>3.3.4</td>
<td>Parameters of Class AB Amplifier at $\theta = 120^\circ$</td>
<td>89</td>
</tr>
<tr>
<td>3.3.5</td>
<td>Parameters of Class C Amplifier at $\theta = 60^\circ$</td>
<td>91</td>
</tr>
<tr>
<td>3.3.6</td>
<td>Parameters of Class C Amplifier at $\theta = 45^\circ$</td>
<td>93</td>
</tr>
<tr>
<td>3.4</td>
<td>Push-pull Complementary Class AB, B, and C RF Power Amplifiers</td>
<td>95</td>
</tr>
<tr>
<td>3.4.1</td>
<td>Circuit</td>
<td>95</td>
</tr>
<tr>
<td>3.4.2</td>
<td>Even Harmonic Cancellation in Push-pull Amplifiers</td>
<td>96</td>
</tr>
<tr>
<td>3.4.3</td>
<td>Power Relationships</td>
<td>97</td>
</tr>
<tr>
<td>3.4.4</td>
<td>Device Stresses</td>
<td>98</td>
</tr>
<tr>
<td>3.5</td>
<td>Transformer-coupled Class B Push-pull Amplifier</td>
<td>99</td>
</tr>
<tr>
<td>3.5.1</td>
<td>Waveforms</td>
<td>99</td>
</tr>
<tr>
<td>3.5.2</td>
<td>Power Relationships</td>
<td>102</td>
</tr>
<tr>
<td>3.5.3</td>
<td>Device Stresses</td>
<td>102</td>
</tr>
<tr>
<td>3.6</td>
<td>Class AB, B, and C Amplifiers of Variable-envelope Signals</td>
<td>105</td>
</tr>
<tr>
<td>3.7</td>
<td>Summary</td>
<td>107</td>
</tr>
<tr>
<td>3.8</td>
<td>References</td>
<td>107</td>
</tr>
</tbody>
</table>
4 Class D RF Power Amplifiers

4.1 Introduction
4.2 Circuit Description
4.3 Principle of Operation
4.3.1 Operation Below Resonance
4.3.2 Operation Above Resonance
4.4 Topologies of Class D Voltage-source RF Power Amplifiers
4.5 Analysis
4.5.1 Assumptions
4.5.2 Series-resonant Circuit
4.5.3 Input Impedance of Series-resonant Circuit
4.5.4 Currents, Voltages, and Powers
4.5.5 Current and Voltage Stresses
4.5.6 Operation Under Short-circuit and Open-circuit Conditions
4.6 Voltage Transfer Function
4.7 Bandwidth of Class D Amplifier
4.8 Efficiency of Half-bridge Class D Power Amplifier
4.8.1 Conduction Losses
4.8.2 Turn-on Switching Loss
4.8.3 Turn-off Switching Loss
4.9 Design Example
4.10 Class D RF Power Amplifier with Amplitude Modulation
4.11 Transformer-coupled Push-pull Class D Voltage-switching RF Power Amplifier
4.12 Class D Full-bridge RF Power Amplifier
4.12.1 Currents, Voltages, and Powers
4.12.2 Efficiency of Full-bridge Class D RF Power Amplifier
4.12.3 Operation Under Short-circuit and Open-circuit Conditions
4.12.4 Voltage Transfer Function
4.13 Phase Control of Full-bridge Class D Power Amplifier
4.14 Class D Current-switching RF Power Amplifier
4.14.1 Circuit and Waveforms
4.14.2 Power
4.14.3 Voltage and Current Stresses
4.14.4 Efficiency
4.15 Transformer-coupled Push-pull Class D Current-switching RF Power Amplifier
4.15.1 Waveforms
4.15.2 Power
4.15.3 Device Stresses
4.15.4 Efficiency
6.4 Analysis
   6.4.1 Steady-state Current and Voltage Waveforms 243
   6.4.2 Peak Switch Current and Voltage 245
   6.4.3 Fundamental-frequency Components 245

6.5 Power Relationships 247
6.6 Element Values of Load Network 247
6.7 Design Example 248
6.8 Summary 249
6.9 References 249
6.10 Review Questions 249
6.11 Problems 250

7 Class DE RF Power Amplifier 251

7.1 Introduction 251
7.2 Analysis of Class DE RF Power Amplifier 251
7.3 Components 257
7.4 Device Stresses 258
7.5 Design Equations 258
7.6 Maximum Operating Frequency 258
7.7 Class DE Amplifier with Only One Shunt Capacitor 260
7.8 Components 263
7.9 Cancellation of Nonlinearities of Transistor Output Capacitances 264
7.10 Summary 264
7.11 References 264
7.12 Review Questions 265
7.13 Problems 265

8 Class F RF Power Amplifier 267

8.1 Introduction 267
8.2 Class F RF Power Amplifier with Third Harmonic 268
   8.2.1 Maximally Flat Class F3 Amplifier 271
   8.2.2 Maximum Drain Efficiency Class F3 Amplifier 276
8.3 Class F RF Power Amplifier with Third and Fifth Harmonics 281
   8.3.1 Maximally Flat Class F35 Amplifier 281
   8.3.2 Maximum Drain Efficiency Class F35 Amplifier 287
8.4 Class F RF Power Amplifier with Third, Fifth, and Seventh Harmonics 289
8.5 Class F RF Power Amplifier with Parallel-resonant Circuit and Quarter-wavelength Transmission Line 289
8.6 Class F RF Power Amplifier with Second Harmonic 295
   8.6.1 Maximally Flat Class F2 Amplifier 295
   8.6.2 Maximum Drain Efficiency Class F2 Amplifier 301
8.7 Class F RF Power Amplifier with Second and Fourth Harmonics 305
   8.7.1 Maximally Flat Class F24 Amplifier 305
   8.7.2 Maximum Drain Efficiency Class F24 Amplifier 310
8.8 Class F RF Power Amplifier with Second, Fourth, and Sixth Harmonics 312
CONTENTS

8.9 Class F RF Power Amplifier with Series-resonant Circuit and Quarter-wavelength Transmission Line 313
8.10 Summary 317
8.11 References 319
8.12 Review Questions 320
8.13 Problems 320

9 Linearization and Efficiency Improvement of RF Power Amplifiers 321
9.1 Introduction 321
9.2 Predistortion 322
9.3 Feedforward Linearization Technique 324
9.4 Negative Feedback Linearization Technique 326
9.5 Envelope Elimination and Restoration 330
9.6 Envelope Tracking 331
9.7 The Doherty Amplifier 332
  9.7.1 Condition for High Efficiency Over Wide Power Range 333
  9.7.2 Impedance Modulation Concept 334
  9.7.3 Equivalent Circuit of the Doherty Amplifier 335
  9.7.4 Power and Efficiency of Doherty Amplifier 336
9.8 Outphasing Power Amplifier 338
9.9 Summary 340
9.10 References 341
9.11 Review Questions 342
9.12 Problems 343

10 Integrated Inductors 345
10.1 Introduction 345
10.2 Skin Effect 345
10.3 Resistance of Rectangular Trace 348
10.4 Inductance of Straight Rectangular Trace 350
10.5 Meander Inductors 351
10.6 Inductance of Straight Round Conductor 353
10.7 Inductance of Circular Round Wire Loop 354
10.8 Inductance of Two-parallel Wire Loop 354
10.9 Inductance of Rectangle of Round Wire 355
10.10 Inductance of Polygon Round Wire Loop 355
10.11 Bondwire Inductors 355
10.12 Single-turn Planar Inductors 357
10.13 Inductance of Planar Square Loop 359
10.14 Planar Spiral Inductors 359
  10.14.1 Geometries of Planar Spiral Inductors 359
  10.14.2 Inductance of Square Planar Inductors 361
  10.14.3 Inductance of Hexagonal Spiral Inductors 369
  10.14.4 Inductance of Octagonal Spiral Inductors 370
  10.14.5 Inductance of Circular Spiral Inductors 371
10.15 Multimetal Spiral Inductors 372
10.16 Planar Transformers 373
CONTENTS

10.17 MEMS Inductors 374
10.18 Inductance of Coaxial Cable 376
10.19 Inductance of Two-wire Transmission Line 376
10.20 Eddy Currents in Integrated Inductors 376
10.21 Model of RF Integrated Inductors 377
10.22 PCB Integrated Inductors 378
10.23 Summary 379
10.24 References 380
10.25 Review Questions 382
10.26 Problems 383

Appendices 385

Appendix A SPICE Model of Power MOSFETs 387
Appendix B Introduction to SPICE 391
Appendix C Introduction to MATLAB 395
Answers to Problems 399
Index 403