Preface xiii

Acknowledgments xix

List of Figures xxi

List of Tables xxv

CHAPTER 1 Introduction 1

1.1 Fundamental Definitions 1
1.2 Elements of the Electromagnetic Environment 2
1.3 Nature of Interference 4
1.4 Regulatory Requirements—North America 5
1.5 Regulatory Requirements—Worldwide 6
1.6 Standards 7
    1.6.1 Basic Standards 7
    1.6.2 Generic Standards 8
    1.6.3 Product Family Standards 8
    1.6.4 Classification of ITE Products 9
1.7 Emission Requirements 9
1.8 Immunity Requirements 10
1.9 Additional Regulatory Requirements—North America 11
1.10 Supplemental Information 11
    References 12
CHAPTER 2 Printed Circuit Board Basics  
13  
2.1 Hidden RF Characteristic of Passive Components  
2.2 How and Why RF Energy Is Developed Within the PCB  
2.3 Magnetic Flux and Cancellation Requirements  
2.4 Routing Topology Configurations  
2.4.1 Microstrip  
2.4.2 Stripline  
2.5 Layer Stackup Assignment  
2.5.1 Single-Sided Assembly  
2.5.2 Double-Sided Assembly  
2.5.3 Four-Layer Stackup  
2.5.4 Six-Layer Stackup  
2.5.5 Eight-Layer Stackup  
2.5.6 Ten-Layer Stackup  
2.6 Radial Migration  
2.7 Common-Mode and Differential-Mode Currents  
2.7.1 Differential-Mode Currents  
2.7.2 Common-Mode Currents  
2.8 RF Current Density Distribution  
2.9 Grounding Methodologies  
2.9.1 Single-Point Grounding  
2.9.2 Multipoint Grounding  
2.10 Ground and Signal Loops (Excluding Eddy Currents)  
2.11 Aspect Ratio—Distance Between Ground Connections  
2.12 Image Planes  
2.13 Slots Within an Image Plane  
2.14 Functional Partitioning  
2.15 Critical Frequencies (λ/20)  
2.16 Logic Families  
2.16.1 Edge Rate Transitions  
References 60  

CHAPTER 3 Bypassing and Decoupling  
65  
3.1 Review of Resonance  
3.1.1 Series Resonance  
3.1.2 Parallel Resonance  
3.1.3 Parallel C-Series RL Resonance (Antiresonant Circuit)  
3.2 Physical Characteristics  
3.2.1 Impedance  
3.2.2 Capacitor Types  
3.2.3 Energy Storage  
3.2.4 Resonance  
3.3 Capacitors in Parallel  
3.4 Power and Ground Planes  
3.4.1 Calculating Power and Ground Plane Capacitance
3.4.2 Combined Effects of Planar and Discrete Capacitors 79
3.4.3 Buried Capacitance 79

3.5 Placement 81
3.5.1 Power Planes 81
3.5.2 Equivalent Circuit Model of a PCB 82
3.5.3 Decoupling Capacitors 82
3.5.4 Single- and Double-Sided Assemblies 86
3.5.5 Mounting Pads 86
3.5.6 Microvias 88

3.6 How to Properly Select a Capacitor 89
3.6.1 Bypass and Decoupling 89
3.6.2 Capacitive Effects on Signal Traces 91
3.6.3 Bulk 94

References 96

CHAPTER 4 Clock Circuits, Trace Routing, and Terminations 99

4.1 Creating Transmission Lines Within a PCB 99
4.2 Topology Configurations 101
  4.2.1 Microstrip Topology 101
  4.2.2 Embedded Microstrip Topology 102
  4.2.3 Single-Stripline Topology 104
  4.2.4 Dual or Asymmetric Stripline Topology 105
  4.2.5 Differential Microstrip and Stripline Topology 106

4.3 Propagation Delay and Dielectric Constant 111
4.4 Capacitive Loading of Signal Traces 112
4.5 Component Placement 114
4.6 Impedance Matching—Reflections and Ringing 116
4.7 Calculating Trace Lengths (Electrically Long Traces) 117
4.8 Trace Routing 122
  4.8.1 Single-Ended Transmission Lines 122
  4.8.2 Differential Pair Signaling 124

4.9 Routing Layers 126
  4.9.1 Which Layers to Route Traces On 126
  4.9.2 Layer Jumping—Use of Vias 129

4.10 Crosstalk 131
  4.10.1 Description of Crosstalk 131
  4.10.2 Design Techniques to Prevent Crosstalk 134

4.11 Trace Separation and the 3-W Rule 136
4.12 Guard/Shunt Traces 137
4.13 Trace Termination 141
  4.13.1 Series Termination 143
  4.13.2 End Termination 144
  4.13.3 Parallel Termination 145
  4.13.4 Thevenin Network 145
  4.13.5 AC Network 147
  4.13.6 Diode Network 147
CHAPTER 5  Interconnects and I/O 151

5.1 Partitioning 152
   5.1.1 Functional Subsystems 152
   5.1.2 Quiet Areas 152
   5.1.3 Internal Radiated Noise Coupling 153
5.2 Isolation and Partitioning (Moating) 154
   5.2.1 Method 1: Moating 155
   5.2.2 Method 2: Bridging in a Moat—Partitioning 157
5.3 Filtering and Grounding 159
   5.3.1 Filtering 159
   5.3.2 Why I/O Cables and Interconnects Radiate 162
   5.3.3 Grounding (I/O Connector) 163
5.4 Local Area Network I/O Layout 164
5.5 Video 167
5.6 Audio 171

References 173

CHAPTER 6  Electrostatic Discharge Protection 175

6.1 Introduction 175
6.2 Triboelectric Series 176
6.3 Failure Modes from an ESD Event 176
6.4 Design Techniques for ESD Protection 180
   6.4.1 Single- and Double-Sided PCBs 181
   6.4.2 Multilayer PCBs 183
6.5 Guard Band Implementation 188

References 190

CHAPTER 7  Backplanes, Ribbon Cables, and Daughter Cards 193

7.1 Basics 193
7.2 Connector Pinout Assignment 194
7.3 AC Chassis Planes 195
7.4 Backplane Construction 195
7.5 Interconnects 200
7.6 Mechanical 202
7.7 Signal Routing 203
7.8 Trace Length/Signal Termination 203
7.9 Crosstalk 204
7.10 Ground Loop Control 207
7.11 Ground Slots in Backplanes 207

References 209
CHAPTER 8  Additional Design Techniques 211

8.1 Localized Planes 211

8.1.1 Localized Decoupling Capacitor Implementation 213

8.2 20-H Rule 214

8.3 Trace Routing for Corners 220

8.3.1 Time Domain Analysis 221

8.3.2 Frequency Domain Analysis 223

8.3.3 Summary of Effects from Right- Angle Corners 224

8.4 Selecting Ferrite Components 224

8.5 Grounded Heatsinks 227

8.6 Lithium Battery Circuits 232

8.7 BNC Connectors 232

8.8 Creepage and Clearance Distances 233

8.9 Current-Carrying Capacity of Copper Traces 238

8.10 Film 241

References 246

APPENDIX A  Summary of Design Techniques 247

APPENDIX B  International EMC Requirements 273

APPENDIX C  The Decibel 285

APPENDIX D  Conversion Tables 289

BIBLIOGRAPHY AND REFERENCES 295

INDEX 301

ABOUT THE AUTHOR 307
List of Figures

Figure 1.1  Items Associated with the Three Elements of the EMI Environment. 3
Figure 1.2  Variants of EMI coupling paths. 4

Figure 2.1  Component characteristic at RF frequencies. 14
Figure 2.2  Closed-loop circuit. 17
Figure 2.3  Frequency representation of a closed-loop circuit. 18
Figure 2.4  Example of a PCB stackup configuration. 20
Figure 2.5  Microstrip and stripline topology configurations. 21
Figure 2.6  Single-sided layout—“very poor design concept.” 24
Figure 2.7  Single-layer stackup with radial structure for power routing and flow migration. 25
Figure 2.8  Two-layer PCB with power and ground grid structure. 26
Figure 2.9  Enhanced double-sided routing to accommodate RF return currents. 27
Figure 2.10  Example why two-layer stackups are not efficient for removing RF energy. 28
Figure 2.11  Four-layer stackup assignment—two configurations. 28
Figure 2.12  Four-layer stackup assignment—alternation configuration. 29
Figure 2.13a  Six-layer stackup assignment—configuration 1. 30
Figure 2.13b  Six-layer stackup assignment—configuration 2. 31
Figure 2.13c  Six-layer stackup assignment—configuration 3. 32
Figure 2.14a  Eight-layer stackup, configuration 1. 33
Figure 2.14b  Eight-layer stackup, configuration 2. 35
Figure 2.15a  Ten-layer stackup, sample configuration. 36
Figure 2.15b  Ten-layer stackup, sample configuration. 37
Figure 2.16  Radial migration concept. 39
Figure 2.17  Partitioning the PCB in regards to radial migration. 40
Figure 2.18  Common- and differential-mode current configurations. 40
Figure 2.19  RF current return path and distance spacing. 42
Figure 2.20  Current density distribution from trace to reference plane. 43
Figure 2.21  Field distribution for microstrip/stripline and co-planar strips. 43
Figure 2.22  Single-point grounding methods. 44
Figure 2.23  Multipoint grounding. 44
Figure 2.24  Hybrid (frequency selective) grounding configurations. 45
Figure 2.25  Resonance in a multipoint ground to chassis. 46
Figure 2.26  Ground loop control. 48
Figure 2.27  Example of aspect ratio. 49
Figure 2.28  Creative technique for providing multipoint ground connection. 50
Figure 2.29  Image plane concept. 52
Figure 2.30  Poor stackup assignment—no image plane for middle stripline layer. 53
List of Figures

Figure 2.31 Image plane violation with traces. ........................................... 54
Figure 2.32 Loop areas with vias in the image plane. ................................. 54
Figure 2.33 Ground loops when using through-hole components (slots in planes). 56
Figure 2.34 Crossing a slot and allowing RF return current to pass. ................. 56
Figure 2.35 Functional grouping and multipoint grounding implementation. .... 58
Figure 2.36 Functional partitioning. ......................................................... 59
Figure 2.37 Output switching time versus propagation delay. ......................... 61

Figure 3.1 Physical characteristics of a capacitor with leads. ....................... 66
Figure 3.2 Series resonant circuit. ......................................................... 67
Figure 3.3 Parallel resonant circuit. ....................................................... 68
Figure 3.4 Parallel C—series RL resonant circuit. ...................................... 68
Figure 3.5 Magnitude of impedance due to different dielectric material. ......... 72
Figure 3.6 Self-resonant frequency of through-hole capacitors. ..................... 73
Figure 3.7 Self-resonant frequency of SMT capacitors. ............................... 74
Figure 3.8 Resonant effect from two capacitors in parallel. ......................... 76
Figure 3.9 Decoupling effects of power ground planes with discrete capacitors. 80
Figure 3.10 Implementation of buried capacitance. .................................... 81
Figure 3.11 Equivalent representation of a PCB. ........................................ 83
Figure 3.12 Power distribution model for loop control. ............................... 83
Figure 3.13 Retrofit decoupling capacitor—DIP mounting style. .................... 84
Figure 3.14 Various mounting methodologies. .......................................... 85
Figure 3.15 Placement of decoupling capacitors, single- and double-sided board. 87
Figure 3.16 Comparison of connection methods for SMT components. ............ 87
Figure 3.17 Capacitor placement patterns for optimal performance—multilayer implementation. ............................................................... 88
Figure 3.18 Capacitor placement recommendation ................................. 89
Figure 3.19 Capacitive effects on clock signals. ...................................... 92
Figure 3.20 Capacitor equations, charging and discharging. ....................... 93

Figure 4.1 Finished trace width dimensions after etching. ......................... 100
Figure 4.2 Surface microstrip topology. ................................................. 102
Figure 4.3 Embedded microstrip topology. ............................................ 103
Figure 4.4 Single-stripline topology. ..................................................... 105
Figure 4.5 Dual or asymmetric stripline topology. ................................... 106
Figure 4.6 Differential trace routing topology. ...................................... 107
Figure 4.7 Differential pair routing formats. ......................................... 109
Figure 4.8 Overshoot, undershoot, and ringing classification. ..................... 116
Figure 4.9 Maximum unterminated line length vs. signal edge rate (FR-4 material). 119
Figure 4.10 Termination of clock traces. ............................................... 123
Figure 4.11 Routing differential signal traces. ........................................ 125
Figure 4.12 Example of routing layers for clock signals. ............................ 127
Figure 4.13 Routing clock traces microstrip. .......................................... 128
Figure 4.14 Routing clock traces stripline. ........................................... 128
Figure 4.15 Routing a ground trace to assure a compete RF return path exists. 130
Figure 4.16 How to route the first trace within a PCB. ............................ 131
Figure 4.17 Three-conductor representation of a transmission line illustrating crosstalk. 132
Figure 4.18 Forward and backward crosstalk effects. ............................. 132
Figure 4.19 Fundamental representation of crosstalk. ................................ 133
Figure 4.20 Calculating crosstalk separation. ........................................ 135
Figure 4.21 Designing with the 3-W rule. ............................................. 136
Figure 4.22 Parallel differential pair routing and the 3-W rule. .................... 137
Figure 4.23 Shunt and guard trace configuration. ................................... 138
Figure 4.24 Guard trace implementation. .............................................. 141
**List of Figures**

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.25</td>
<td>Common termination methods.</td>
<td>142</td>
</tr>
<tr>
<td>4.26</td>
<td>Series termination circuit.</td>
<td>143</td>
</tr>
<tr>
<td>4.27</td>
<td>Implementing end terminators on a PCB.</td>
<td>144</td>
</tr>
<tr>
<td>4.28</td>
<td>Parallel termination circuit.</td>
<td>145</td>
</tr>
<tr>
<td>4.29</td>
<td>Thevenin termination circuit.</td>
<td>146</td>
</tr>
<tr>
<td>4.30</td>
<td>AC network circuit.</td>
<td>147</td>
</tr>
<tr>
<td>4.31</td>
<td>Diode termination—two configurations.</td>
<td>148</td>
</tr>
<tr>
<td>4.32</td>
<td>Differential- and common-mode signaling comparison.</td>
<td>149</td>
</tr>
<tr>
<td>5.1</td>
<td>Quiet area partitioning.</td>
<td>153</td>
</tr>
<tr>
<td>5.2</td>
<td>Using isolation with a moat—method 1.</td>
<td>156</td>
</tr>
<tr>
<td>5.3</td>
<td>Partitioning I/O using a bridge in a moat—method 2.</td>
<td>157</td>
</tr>
<tr>
<td>5.4</td>
<td>Violating the concept of moating.</td>
<td>157</td>
</tr>
<tr>
<td>5.5</td>
<td>Digital and analog partitioning.</td>
<td>158</td>
</tr>
<tr>
<td>5.6</td>
<td>I/O filtering methods.</td>
<td>160</td>
</tr>
<tr>
<td>5.7</td>
<td>How common-mode energy gets developed on an interconnect cable.</td>
<td>163</td>
</tr>
<tr>
<td>5.8</td>
<td>Multipoint grounding of I/O faceplate or bracket.</td>
<td>164</td>
</tr>
<tr>
<td>5.9</td>
<td>Suggested layout for network and telecommunication interfaces.</td>
<td>165</td>
</tr>
<tr>
<td>5.10</td>
<td>Suggested layout for coaxial based interconnects.</td>
<td>166</td>
</tr>
<tr>
<td>5.11</td>
<td>Suggested layout for fiber optic interconnects.</td>
<td>166</td>
</tr>
<tr>
<td>5.12</td>
<td>Suggested layout for a sophisticated fiber interface.</td>
<td>167</td>
</tr>
<tr>
<td>5.13</td>
<td>Routing 75-ohm traces on a 50-ohm stackup assembly.</td>
<td>168</td>
</tr>
<tr>
<td>5.14</td>
<td>Video circuitry layout concept.</td>
<td>170</td>
</tr>
<tr>
<td>5.15</td>
<td>Audio circuitry layout concept.</td>
<td>172</td>
</tr>
<tr>
<td>6.1</td>
<td>Failure modes caused by an ESD event.</td>
<td>178</td>
</tr>
<tr>
<td>6.2</td>
<td>Ground bounce in single- and double-sided PCBs caused by an ESD event.</td>
<td>181</td>
</tr>
<tr>
<td>6.3</td>
<td>Loop areas: single- and double-side layouts.</td>
<td>182</td>
</tr>
<tr>
<td>6.4</td>
<td>Implementation techniques to minimize loop area on single- and double-sided PCBs.</td>
<td>183</td>
</tr>
<tr>
<td>6.5</td>
<td>Spark-gap implementation.</td>
<td>184</td>
</tr>
<tr>
<td>6.6</td>
<td>Routing signal traces close to ground.</td>
<td>187</td>
</tr>
<tr>
<td>6.7</td>
<td>ESD guard band implementation.</td>
<td>189</td>
</tr>
<tr>
<td>7.1</td>
<td>Recommended layout of ground return pins for interconnects.</td>
<td>194</td>
</tr>
<tr>
<td>7.2</td>
<td>Interboard radiated coupling.</td>
<td>198</td>
</tr>
<tr>
<td>7.3</td>
<td>Backplane interconnect impedance considerations.</td>
<td>201</td>
</tr>
<tr>
<td>7.4</td>
<td>Preventing crosstalk using various interconnect configurations with parallel trace routes.</td>
<td>205</td>
</tr>
<tr>
<td>7.5</td>
<td>Differential pair twisting.</td>
<td>206</td>
</tr>
<tr>
<td>7.6</td>
<td>Ground loop control in a backplane or ribbon cable assembly.</td>
<td>206</td>
</tr>
<tr>
<td>7.7</td>
<td>Ground slots in a backplane or parallel bus structure.</td>
<td>208</td>
</tr>
<tr>
<td>8.1</td>
<td>Localized plane (ground potential).</td>
<td>212</td>
</tr>
<tr>
<td>8.2</td>
<td>Localized decoupling capacitor implementation built internal to a board stackup.</td>
<td>214</td>
</tr>
<tr>
<td>8.3</td>
<td>RF fringing effects from power and ground planes.</td>
<td>215</td>
</tr>
<tr>
<td>8.4</td>
<td>Implementing the 20-H rule.</td>
<td>216</td>
</tr>
<tr>
<td>8.5</td>
<td>Application of the 20-H rule and power plane isolation.</td>
<td>217</td>
</tr>
<tr>
<td>8.6</td>
<td>Transmission line equivalent circuits of the power and ground planes.</td>
<td>218</td>
</tr>
<tr>
<td>8.7</td>
<td>Corner configurations.</td>
<td>221</td>
</tr>
<tr>
<td>8.8</td>
<td>Time domain plot on effects of a right-angle corner.</td>
<td>223</td>
</tr>
<tr>
<td>8.9</td>
<td>Grounded heatsink theory of operation.</td>
<td>229</td>
</tr>
<tr>
<td>8.10</td>
<td>Grounded heatsink implementation.</td>
<td>229</td>
</tr>
<tr>
<td>Figure 8.11</td>
<td>Grounding the heatsink.</td>
<td>.230</td>
</tr>
<tr>
<td>-------------</td>
<td>------------------------</td>
<td>-----</td>
</tr>
<tr>
<td>Figure 8.12</td>
<td>Lithium battery protection design requirement.</td>
<td>.232</td>
</tr>
<tr>
<td>Figure 8.13</td>
<td>BNC connector configurations.</td>
<td>.233</td>
</tr>
<tr>
<td>Figure 8.14</td>
<td>Creepage and clearance distance definition.</td>
<td>.234</td>
</tr>
<tr>
<td>Figure 8.15</td>
<td>Current-carrying capacity of copper traces.</td>
<td>.239</td>
</tr>
<tr>
<td>Figure 8.16</td>
<td>Stacking strips and trace width description.</td>
<td>.242</td>
</tr>
<tr>
<td>Figure 8.17</td>
<td>Sample ten-layer PCB stackup definition.</td>
<td>.244</td>
</tr>
<tr>
<td>Figure 8.18</td>
<td>Example of stackup details.</td>
<td>.245</td>
</tr>
</tbody>
</table>
List of Tables

Table 1.1  Additional North American Standards .......................................................... 11

Table 2.1  Example of Stackup Assignments ............................................................... 38
Table 2.2  Impedance of a 10 by 10 in. (25.4 × 25.4 cm) Copper Metal Plane ............... 45
Table 2.3  λ/20 Wavelength at Various Frequencies .................................................. 60
Table 2.4  Sample Chart of Logic Families, Illustrating Spectral Bandwidth of RF Energy .... 62

Table 3.1  Summary of Various Capacitor Types ...................................................... 70
Table 3.2  Approximate Self-Resonant Frequency of Various Capacitors (lead-length dependent) .................................................................................................................. 71
Table 3.3  Magnitude of Impedance of a 5-nH Inductor versus Frequency ....................... 73
Table 3.4  Typical Usage of Capacitor Families and Operating Range ......................... 77

Table 4.1  Velocity of Propagation for Various Topologies (Dielectric Constant = 4.3) .... 112
Table 4.2  Termination Types and Characteristic Properties ......................................... 143
Table 4.3  Comparison of Termination Types for Paired Signals .................................. 150

Table 6.1  Triboelectric Series ....................................................................................... 177

Table 8.1  Frequency Range for Several Types of Ferrite Material ................................. 226
Table 8.2  Comparison of Impedance from Common Ferrite Bead Materials ................. 227
Table 8.3  Clearance Distances for Primary Current Carrying Traces ............................ 235
Table 8.4  Additional Clearance Distances for Use with High-voltage Applications ........ 236
Table 8.5  Clearance Distance Chart for Secondary Circuits ....................................... 237
Table 8.6  Creepage Distances Requirements ................................................................ 238
Table 8.7  Conversion Chart for PCB Finished Trace Widths Related to Standard Wire Gauges .................................................................................................................... 240