Microstrip Lines and Slotlines

Third Edition

Ramesh Garg
Inder Bahl
Maurizio Bozzi
## Contents

Preface xi

### CHAPTER 1
Microstrip Lines I: Quasi-Static Analyses, Dispersion Models, and Measurements 1

1.1 Introduction 1

1.1.1 Planar Transmission Structures 1

1.1.2 Microstrip Field Configuration 3

1.1.3 Methods of Microstrip Analysis 4

1.2 Quasi-Static Analyses of a Microstrip 5

1.2.1 Modified Conformal Transformation Method 6

1.2.2 Finite Difference Method 11

1.2.3 Integral Equation Method 12

1.2.4 Variational Method in the Fourier Transform Domain 14

1.2.5 Segmentation and Boundary Element Method (SBEM) 16

1.3 Microstrip Dispersion Models 21

1.3.1 Coupled TEM Mode and TM Mode Model 21

1.3.2 An Empirical Relation 22

1.3.3 Dielectric-Loaded Ridged Waveguide Model 22

1.3.4 Empirical Formulae for Broad Frequency Range 24

1.3.5 Planar Waveguide Model 26

1.3.6 Some Comments 27

1.4 Microstrip Transitions 29

1.4.1 Coaxial-to-Microstrip Transition 30

1.4.2 Waveguide-to-Microstrip Transition 31

1.5 Microstrip Measurements 35

1.5.1 Substrate Dielectric Constant 36

1.5.2 Characteristic Impedance 41

1.5.3 Phase Velocity or Effective Dielectric Constant 42

1.5.4 Attenuation Constant 45

1.6 Fabrication 46

1.6.1 Printed Circuit Technologies 47

1.6.2 Hybrid Microwave Integrated Circuits 48

1.6.3 Monolithic Integrated Circuit Technologies 51

References 53
<table>
<thead>
<tr>
<th>Chapter 2</th>
<th>Microstrip Lines II: Fullwave Analyses, Design Considerations, and Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td>Methods of Fullwave Analysis</td>
</tr>
<tr>
<td>2.2</td>
<td>Analysis of an Open Microstrip</td>
</tr>
<tr>
<td>2.2.1</td>
<td>Integral Equation Method in the Space Domain</td>
</tr>
<tr>
<td>2.2.2</td>
<td>Galerkin's Method in the Spectral Domain</td>
</tr>
<tr>
<td>2.2.3</td>
<td>Discussion of Results</td>
</tr>
<tr>
<td>2.3</td>
<td>Analysis of an Enclosed Microstrip</td>
</tr>
<tr>
<td>2.3.1</td>
<td>Integral Equation Methods</td>
</tr>
<tr>
<td>2.3.2</td>
<td>Finite Difference Method</td>
</tr>
<tr>
<td>2.3.3</td>
<td>Discussion of Results</td>
</tr>
<tr>
<td>2.4</td>
<td>Design Considerations</td>
</tr>
<tr>
<td>2.4.1</td>
<td>Microstrip Losses</td>
</tr>
<tr>
<td>2.4.2</td>
<td>Power Handling Capability</td>
</tr>
<tr>
<td>2.4.3</td>
<td>Effect of Tolerances</td>
</tr>
<tr>
<td>2.4.4</td>
<td>Effect of Dielectric Anisotropy</td>
</tr>
<tr>
<td>2.4.5</td>
<td>Design Equations</td>
</tr>
<tr>
<td>2.4.6</td>
<td>Frequency Range of Operation</td>
</tr>
<tr>
<td>2.4.7</td>
<td>Lumped Element Model of Microstrip Interconnect</td>
</tr>
<tr>
<td>2.5</td>
<td>Other Types of Microstrip Lines</td>
</tr>
<tr>
<td>2.5.1</td>
<td>Suspended and Inverted Microstrip Lines</td>
</tr>
<tr>
<td>2.5.2</td>
<td>Multilayered Dielectric Microstrip</td>
</tr>
<tr>
<td>2.5.3</td>
<td>Thin Film Microstrip (TFM)</td>
</tr>
<tr>
<td>2.5.4</td>
<td>Valley Microstrip Lines</td>
</tr>
<tr>
<td>2.5.5</td>
<td>Buried Microstrip Line</td>
</tr>
<tr>
<td>2.5.6</td>
<td>Superconducting Microstrip Circuits</td>
</tr>
<tr>
<td>2.6</td>
<td>Microstrip Applications</td>
</tr>
<tr>
<td>2.6.1</td>
<td>Lumped Elements</td>
</tr>
<tr>
<td>2.6.2</td>
<td>Passive Components</td>
</tr>
<tr>
<td>2.6.3</td>
<td>Active Components</td>
</tr>
<tr>
<td>2.6.4</td>
<td>Packages and Assemblies</td>
</tr>
<tr>
<td>References</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Chapter 3</th>
<th>Microstrip Discontinuities I: Quasi-Static Analysis and Characterization</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.1</td>
<td>Introduction</td>
</tr>
<tr>
<td>3.2</td>
<td>Discontinuity Capacitance Evaluation</td>
</tr>
<tr>
<td>3.2.1</td>
<td>Matrix Inversion Method</td>
</tr>
<tr>
<td>3.2.2</td>
<td>Variational Method</td>
</tr>
<tr>
<td>3.2.3</td>
<td>Galerkin's Method in the Fourier Transform Domain</td>
</tr>
<tr>
<td>3.2.4</td>
<td>Use of Line Sources with Charge Reversal</td>
</tr>
<tr>
<td>3.3</td>
<td>Discontinuity Inductance Evaluation</td>
</tr>
<tr>
<td>3.4</td>
<td>Characterization of Various Discontinuities</td>
</tr>
<tr>
<td>3.4.1</td>
<td>Open Ends</td>
</tr>
<tr>
<td>3.4.2</td>
<td>Gaps in a Microstrip</td>
</tr>
</tbody>
</table>
3.4.3 Steps in Width 165
3.4.4 Bends 169
3.4.5 T-Junctions 170
3.4.6 Cross Junctions 174
3.4.7 Notch 176
3.4.8 RF Short and Via Hole 178
3.5 Compensated Microstrip Discontinuities 180
3.5.1 Step in Width 180
3.5.2 Bends 181
3.5.3 T-Junction 182
References 185

CHAPTER 4

Microstrip Discontinuities II: Fullwave Analysis and Measurements 189
4.1 Planar Waveguide Analysis 189
4.1.1 Discontinuity Characterization 189
4.1.2 Compensation of Discontinuity Reactances 208
4.1.3 Radiation and Parasitic Coupling 209
4.2 Fullwave Analysis of Discontinuities 218
4.2.1 Galerkin’s Method in the Spectral Domain 219
4.2.2 Integral Equation Solution in the Space Domain 222
4.2.3 Time Domain Methods for Microstrip Discontinuity Characterization 223
4.3 Discontinuity Measurements 227
4.3.1 Linear Resonator Method 228
4.3.2 Ring Resonator Method 232
4.3.3 Scattering Parameters Measurement Method 235
References 236

CHAPTER 5

Slotlines 239
5.1 Introduction 239
5.2 Slotline Analysis 239
5.2.1 Approximate Analysis 241
5.2.2 Transverse Resonance Method 243
5.2.3 Galerkin’s Method in the Spectral Domain 246
5.3 Design Considerations 251
5.3.1 Closed-Form Expressions 251
5.3.2 Effect of Metal Thickness 254
5.3.3 Effect of Tolerances 255
5.3.4 Losses in Slotline 256
5.4 Slotline Discontinuities 258
5.4.1 Short End Discontinuity 258
5.4.2 Open End Discontinuity 259
5.5 Variants of Slotline 262
5.5.1 Coupled Microstrip-Slotline 262
7.4.2 Conductor Loss 387
7.4.3 Radiation and Surface Wave Losses 393
7.5 Effect of Tolerances 396
7.6 Comparison with Microstrip Line and Slotline 399
7.7 Transitions 401
  7.7.1 Coax-to-CPW Transitions 401
  7.7.2 Microstrip-to-CPS Transitions 403
  7.7.3 Microstrip-to-CPW Transition 405
  7.7.4 CPW-to-CPS Transitions 406
  7.7.5 CPS-to-Slotline Transitions 406
  7.7.6 Slotline-to-CPW Transitions 407
7.8 Discontinuities in Coplanar Lines 410
  7.8.1 CAD Models for Discontinuities in Coplanar Waveguide Circuits 410
  7.8.2 CAD Models for Discontinuities in Coplanar Strips Circuits 415
7.9 Coplanar Line Circuits 417
  7.9.1 Circuits with Series and Shunt Reactances in CPW 418
  7.9.2 Circuits Using Slotline-CPW Junctions 420
References 425

CHAPTER 8
Coupled Microstrip Lines 433
8.1 Introduction 433
8.2 General Analysis of Coupled Lines 434
  8.2.1 Methods of Analysis 434
  8.2.2 Coupled Mode Approach 435
  8.2.3 Even- and Odd-Mode Approach 439
8.3 Characteristics of Coupled Microstrip Lines 442
  8.3.1 Quasi-Static Analysis 442
  8.3.2 Fullwave Analysis 449
  8.3.3 Dispersion Models 456
8.4 Measurements on Coupled Microstrip Lines 459
  8.4.1 Impedance Measurements 459
  8.4.2 Phase Constant Measurements 460
8.5 Design Considerations for Coupled Microstrip Lines 461
  8.5.1 Design Equations 462
  8.5.2 Losses 469
  8.5.3 Effect of Fabrication Tolerances 473
  8.5.4 Coupled Microstrip Lines with Dielectric Overlays 474
  8.5.5 Effect of Dielectric Anisotropy 478
8.6 Slot-Coupled Microstrip Lines 478
8.7 Coupled Multiconductor Microstrip Lines 483
8.8 Discontinuities in Coupled Microstrip Lines 485
  8.8.1 Network Model 485
  8.8.2 Open-End Discontinuity 490
References 491