Contents

Preface ix
Acknowledgements xi

1 A Basic Review of TEM-mode Transmission Line Theory 1
1.1 The concept of radio-frequency transmission lines 1
1.2 Primary transmission line constants 2
1.3 Secondary constants for transmission lines 3
1.4 Transmission line impedances 5
1.5 Reflection and voltage standing-wave ratio 7
1.6 Half-, quarter-, and eighth-wavelength lines 7
1.7 Simple (narrow-band) matching 8
1.8 Equivalent two-port networks 10
1.9 Chain ($ABCD$) parameters for a uniform length of loss-free transmission line 12
1.10 Parallel-coupled transmission lines: basic properties 14

2 Transmission Line Options for Microwave Integrated Circuits (MICs) 17
2.1 Introductory remarks 17
2.2 Microwave frequencies and applications 17
2.3 MIC transmission line structures 19
2.4 Choice of substrate for hybrid microcircuits 25
2.5 Thin-film manufacture 31
2.6 Thick-film manufacture 33
2.7 Thin-film transfer components 35
2.8 Mid-film technology 35
2.9 Monolithic technology 37

3 Static-TEM Parameters and Design at Lower Frequencies 41
3.1 The microstrip MIC design problem 41
3.2 The quasi-TEM mode of propagation 43
3.3 Static-TEM parameters 44
3.4 Approximate graphical synthesis 49

3.5 Formulae for accurate static-TEM calculations . . . 51
3.6 Computer-based analysis techniques . . . 54
3.7 A worked example of static-TEM synthesis . . . 55
3.8 Microstrip on a dielectrically anisotropic substrate . . . 57
3.9 Microstrip on a ferrite substrate . . . 63
3.10 Effects of finite strip thickness, metallic enclosure, and manufacturing tolerances . . . 66
3.11 Pulse propagation along microstrip lines . . . 70
3.12 Recommendations relating to the static-TEM approaches . . . 72

4 Behaviour and Design at High Frequencies 77

4.1 The scope of this chapter . . . 77
4.2 Dispersion in microstrip . . . 78
4.3 Approximate calculations with dispersion . . . 79
4.4 Accurate design formulae . . . 84
4.5 Effects due to ferrite, and to dielectrically anisotropic substrates . . . 90
4.6 Design requiring dispersion calculations: a worked example . . . 92
4.7 Field solutions . . . 94
4.8 Frequency dependence of the microstrip characteristic impedance . . . 100
4.9 Operating frequency limitations . . . 104
4.10 Power losses and parasitic coupling . . . 109
4.11 Superconducting microstrips . . . 117
4.12 Microstrip characteristic impedance—comments on recent theoretical work . . . 120
4.13 Design recommendations . . . 121

5 Discontinuities in Microstrip 127

5.1 The main discontinuities . . . 127
5.2 The foreshortened open circuit . . . 129
5.3 The series gap . . . 133
5.4 Microstrip short circuits . . . 136
5.5 Further discontinuities . . . 138
5.6 The right-angled bend or 'corner' . . . 138
5.7 'Matched' microstrip bends: compensation techniques . . . 140
5.8 Step changes in width (impedance steps) . . . 141
5.9 Narrow transverse slit . . . 144
5.10 The microstrip T-junction . . . 145
5.11 Compensated T-junctions . . . 149
5.12 Cross-junctions . . . 149
5.13 Frequency dependence of discontinuity effects . . . 151
5.14 Recommendations for the calculation of discontinuities . . . 165

6 Parallel-coupled Microstrip Lines and Directional Couplers 173

6.1 Structure and applications . . . 173
6.2 Parameters and initial specification . . . 174
6.3 Coupled microstrip lines . . . 175
6.4 Characteristic impedances in terms of the coupling factor (C') . . . 177

6.5 Semi-empirical analysis formulae as a design aid 180
6.6 An approximate synthesis technique 182
6.7 A specific example: design of a −10 dB microstrip coupler 185
6.8 Coupled-region length 187
6.9 Frequency response 190
6.10 Coupler directivity 198
6.11 Special coupler designs with improved performance 199
6.12 Thickness effects, power losses, and fabrication tolerances 214
6.13 Planar combline directional couplers 217
6.14 Crosstalk and signal distortion between microstrip lines used in digital systems 218
6.15 Choice of structure and design recommendations 221

7 Power Capabilities, Transitions, and Measurement Techniques 229

7.1 Power-handling capabilities 229
7.2 Coaxial-to-microstrip transitions 232
7.3 Waveguide-to-microstrip transitions 233
7.4 Transitions between other media and microstrip 238
7.5 Instrumentation systems for microstrip measurements 240
7.6 Measurement of substrate properties 243
7.7 Microstrip resonator methods 245
7.8 *Q*-factor measurements 257
7.9 Measurements on parallel-coupled microstrips 258
7.10 Standing-wave indicators in microstrip 261
7.11 Time-domain reflectometry (TDR) techniques 262

8 Passive MICs 267

8.1 Terminations and attenuators 267
8.2 Branch-type couplers and power dividers 268
8.3 A suitable strategy for microwave filter design 277
8.4 Band-pass filters 288
8.5 Spur-line band-stop filters 304
8.6 Passive MICs with switching elements 307
8.7 Isolators and circulators 307

9 Active MICs and MMICs 313

9.1 Introduction 313
9.2 Amplifiers 315
9.3 Oscillators 340
9.4 Active microwave filters 345
9.5 Microstrip circuits for high-speed pulse systems 347

10 Microstrip Antennas 353

10.1 Fundamental aspects 353
10.2 Microstrip patch antennas and linear arrays 356
10.3 Rear-fed and multiple-layer arrays 359

Appendix A **Analysis of Parallel-coupled TEM-mode Transmission Lines** 365
Appendix B **External *Q*-factor of a Straight-edged, Open-circuited Microstrip Resonator** 373
Appendix C **An Outline of Scattering Parameter Theory** 381
Appendix D **Overview of Proprietary CAD/CAE Packages for RF and Microwave Applications** 399
Index 405