

# Introduction to Computer Methods for Microwave Circuit Analysis and Design

Janusz A. Dobrowolski

Warsaw University of Technology

Artech House  
Boston • London

# *Contents*

PREFACE	xiii
Chapter 1 INTRODUCTION	1
References	6
Chapter 2 MICROWAVE CIRCUIT MATRIX REPRESENTATIONS	7
2.1. Chain matrix representation	7
2.2. Scattering matrix representation	14
2.2.1. Physical interpretation of scattering parameters	18
2.2.2. Change of reference impedance	21
2.3. Transfer scattering matrix representation	22
2.3.1. Transfer scattering matrix of two-port elements	22
2.3.2. Generalized transfer scattering matrix representation	29
Example 2.1	36
Example 2.2	43
Example 2.3	44
2.4. Admittance matrix representation	45
2.5. Relations between different matrix representations of multiports	50
References	52
Chapter 3 COMPUTER-AIDED ANALYSIS OF MICROWAVE CIRCUITS	53
3.1. Microwave circuit analysis in terms of voltages and currents	53
3.1.1. Nodal admittance matrix method	54
Example 3.1	54
3.1.2. Numerical considerations	63
3.1.3. Computation of circuit functions	64
3.1.4. Multiport connection method based on an indefinite admittance matrix	66
3.1.5. Chain matrix method and its modifications	68
Example 3.2	72
3.2. Microwave circuit analysis in terms of wave variables	73
3.2.1. Connection scattering matrix method	73

---

	Example 3.3	79
3.2.2.	Multiport connection method	81
	Example 3.4	84
	Example 3.5	89
3.2.3.	Transfer scattering matrix method	90
3.2.4.	Generalized transfer scattering matrix method	92
	Example 3.6	100
	Example 3.7	104
References		105
<b>Chapter 4</b>	<b>COMPUTER-AIDED SENSITIVITY ANALYSIS</b>	
	<b>OF MICROWAVE CIRCUITS</b>	107
4.1.	Sensitivity definition	108
4.2.	Tellegen's theorem	109
4.3.	Sensitivity analysis of microwave networks described by the nodal admittance matrix	113
	4.3.1. The transposed matrix method	113
	4.3.2. The direct method	115
	4.3.3. Derivation of sensitivities of microwave circuits described by the admittance matrices	116
	4.3.4. Gradient vector computation of circuit functions	116
	Example 4.1	121
4.4.	Sensitivity analysis of microwave networks described by the scattering matrix	124
	4.4.1. The adjoint network method	124
	4.4.2. Sensitivity invariants of scattering matrices and their use for evaluation of differential scattering matrices	127
	Example 4.2	131
	4.4.3. The transposed matrix method for networks described by the connection scattering matrix	133
	4.4.4. Derivation of sensitivities of microwave circuits described by the scattering matrices	135
	4.4.5. The sensitivity analysis direct method for networks described by the connection scattering matrix	135
	4.4.6. Gradient vector computation of circuit functions	142
	4.4.7. Evaluation of group delay of microwave network transmission functions	147
	Example 4.3	149
4.5.	Second-order sensitivities of microwave networks	153
	4.5.1. Second-order sensitivity analysis by the adjoint network method	154
	4.5.2. Transposed matrix method for the second-order sensitivity	

	analysis for networks described by the connection scattering matrix	157
4.6.	Sensitivity analysis of cascaded two-port networks described by the chain matrices	158
	References	168
Chapter 5	<b>COMPUTER-AIDED NOISE ANALYSIS OF MICROWAVE CIRCUITS</b>	169
5.1.	Noise representation of noisy circuits	170
5.2.	Correlation matrices of noisy two-ports	179
5.3.	Relations between different noise correlation matrices of noisy two-ports	181
5.4.	Interconnections of noisy two-ports	181
5.5.	Correlation matrices of active two-ports and passive multiports	183
	Example 5.1	190
5.6.	Basic relationships for noisy two-ports	192
5.7.	Noise analysis of cascaded two-ports	195
5.8.	Noise analysis of circuits composed of interconnected two-ports	196
	Example 5.2	197
5.9.	Noise analysis of linear multiport networks of arbitrary topology by using the connection scattering matrix	199
	5.9.1. The algorithm for noise figure computation of a general multiport circuit	203
	Example 5.3	206
	5.9.2. The algorithm for computing the four noise parameters of a general multiport circuit	208
	5.9.3. Noise power first-order sensitivities	211
	5.9.4. Noise figure gradient computation	216
5.10.	Noise analysis of linear multiport networks of arbitrary topology by using the admittance matrix	217
	Example 5.4	220
	References	226
Chapter 6	<b>NUMERICAL METHODS FOR SOLVING SYSTEMS OF LINEAR ALGEBRAIC EQUATIONS</b>	229
6.1.	Gaussian elimination	230
	6.1.1. Operation count	232
6.2.	LU decomposition	233
	6.2.1. Gauss's algorithm	234
	6.2.2. Doolittle's algorithm	236
	6.2.3. Crout's algorithm	239

6.3.	Bifactorization	243
6.4.	Pivoting	246
6.5.	Numerical problems and error mechanisms	248
	6.5.1. Numerical conditioning of a system of linear equations	248
	6.5.2. Round-off error growth and proper choice of pivots	252
6.6.	Complex matrix equations	253
	References	254
<b>Chapter 7 SPARSE MATRIX TECHNIQUES</b>		<b>257</b>
7.1.	Storage schemes for sparse matrices	258
	7.1.1. Static storage schemes with ordered lists	258
	7.1.2. Dynamic storage schemes with linked lists	259
7.2.	Pivot selection strategies for sparse matrices	261
	7.2.1. Static ( <i>a priori</i> ) ordering	262
	7.2.2. Dynamic ordering	262
7.3.	Implementation of sparse matrix techniques	264
	7.3.1. Compiled code techniques	266
	7.3.2. Looping indexed code techniques	267
	7.3.3. Interpretable code techniques	268
	References	269
<b>Chapter 8 SPARSE MATRIX TECHNIQUES FOR ANALYSIS OF MICROWAVE CIRCUITS DESCRIBED BY THE CONNECTION SCATTERING MATRIX</b>		<b>271</b>
8.1.	Characteristics of circuit equations with the connection scattering matrix	272
8.2.	Connection scattering matrix ordering strategy	273
8.3.	Storage scheme of the connection scattering matrix	274
8.4.	Procedure for generation of the indexing, addressing, and ordering arrays	277
8.5.	Simulation and ordering procedure	278
	8.5.1. Pivotal search—matrix ordering	279
	8.5.2. Indexing and addressing modifications	280
8.6.	Reduction procedure	288
8.7.	Solution procedure	289
	References	291
<b>Chapter 9 TOLERANCE ANALYSIS OF MICROWAVE CIRCUITS</b>		<b>293</b>
9.1.	Fundamental concepts	293
9.2.	Deterministic tolerance analysis	297
	9.2.1. Worst-case tolerance analysis by the sensitivity approach	297
	9.2.2. Worst-case tolerance analysis by the large change sensitivity approach	298
9.3.	Statistical tolerance analysis	300

9.3.1.	The method of statistical moments—computation of statistical parameters of circuit functions	301
9.3.2.	Computation of the yield by using the method of statistical moments	306
9.3.3.	Monte Carlo method for tolerance analysis	307
9.3.4.	Generation of pseudorandom parameter values	308
9.3.5.	Accuracy of the Monte Carlo method and required number of samples	310
References		313
Chapter 10	<b>TOLERANCE DESIGN OF MICROWAVE CIRCUITS</b>	315
10.1.	Basic considerations	317
10.2.	Deterministic approach to tolerance design	319
10.3.	Statistical approach to tolerance design	322
	10.3.1. The gravity method	323
	10.3.2. The parametric sampling method	323
10.4.	Worst-case design	328
References		329
Chapter 11	<b>OPTIMIZATION TECHNIQUES FOR MICROWAVE CIRCUIT DESIGN</b>	331
11.1.	Basic concepts and definitions	331
	11.1.1. Definition of the optimization problem	331
	11.1.2. Convexity	335
	11.1.3. Constraints	335
	Example 11.1	338
	11.1.4. Continuous functions and their derivatives	339
	11.1.5. Conjugate directions	343
11.2.	Variables and functions	344
	11.2.1. The physical system and its simulation models	344
	Example 11.2	345
	11.2.2. Design specifications and error functions	347
	11.2.3. Objective functions in CAD of microwave circuits	351
	Example 11.3	355
	Example 11.4	356
	Example 11.5	358
	Example 11.6	360
11.3.	Basic gradient-based methods for unconstrained function minimization	361
	11.3.1. Steepest descent method	363
	11.3.2. Conjugate gradient methods	364
	11.3.3. The Newton method	366
	11.3.4. Quasi-Newton methods	367
	11.3.5. Line search	368

---

11.4.	Gradient-based methods for constrained function minimization	370
11.4.1.	Kuhn-Tucker conditions	370
11.4.2.	Constrained quasi-Newton methods	373
11.4.3.	Penalty-multiplier methods (augmented Lagrangian methods)	377
11.5.	Multiple objective optimization	379
11.5.1.	Constrained Gauss-Newton methods for multiple objective functions	381
11.5.2.	Constrained quasi-Newton methods for multiple objective functions	385
	Example 11.7	389
	Example 11.8	390
	References	393
	Appendix 1 VECTOR AND MATRIX NORMS, RANKS	397
	Appendix 2 SPARSE MATRIX SOLVER	401
	Appendix 3 BASICS OF STATISTICAL ANALYSIS	417
	INDEX	423