

Contents

Preface	xiii
1 THE METHOD OF LINES	1
1.1 INTRODUCTION	1
1.2 MOL: FUNDAMENTALS OF DISCRETISATION	5
1.2.1 Qualitative description	5
1.2.2 Quantitative description of the discretisation	7
1.2.3 Numerical example	11
2 BASIC PRINCIPLES OF THE METHOD OF LINES	15
2.1 INTRODUCTION	15
2.2 BASIC EQUATIONS	16
2.2.1 Anisotropic material parameters	16
2.2.2 Relations between transversal electric and magnetic fields – generalised transmission line (GTL) equations	19
2.2.3 Relation to the analysis with vector potentials	21
2.2.4 GTL equations for 2D structures	22
2.2.5 Solution of the GTL equations	23
2.2.6 Numerical examples	25
2.3 EIGENMODES IN PLANAR WAVEGUIDE STRUCTURES WITH ANISOTROPIC LAYERS	26
2.3.1 Introduction	26
2.3.2 Analysis equations for eigenmodes in planar structures	30
2.3.3 Examples of system equations	33
2.3.4 Impedance/admittance transformation in multilayered structures	35
2.3.5 System equation in transformed domain	36
2.3.6 System equation in spatial domain	38
2.3.7 Matrix partition technique: two examples	40
2.3.8 Numerical results	43
2.4 ANALYSIS OF PLANAR CIRCUITS	45
2.4.1 Discretisation of the transmission line equations	45
2.4.2 Determination of the field components	52

2.5	FIELD AND IMPEDANCE/ADMITTANCE TRANSFORMATION	52
2.5.1	Introduction	52
2.5.2	Impedance/admittance transformation in multilayered and multisectioned structures	53
2.5.3	Impedance/admittance transformation with finite differences	61
2.5.4	Stable field transformation through layers and sections .	66
3	ANALYSIS OF RECTANGULAR WAVEGUIDE CIRCUITS	73
3.1	INTRODUCTION	73
3.2	CONCATENATIONS OF WAVEGUIDE SECTIONS	75
3.2.1	LSM and LSE modes in circular waveguide bends	76
3.2.2	LSM and LSE modes in straight waveguides	80
3.2.3	Impedance transformation at waveguide interfaces	82
3.2.4	Numerical results for concatenations	84
3.2.5	Numerical results for waveguide filters	87
3.3	WAVEGUIDE JUNCTIONS	90
3.3.1	E-plane junctions	93
3.3.2	H-plane junctions	96
3.3.3	Algorithm for generalised scattering parameters	98
3.3.4	Special junctions: E-plane 3-port junction	99
3.3.5	Matched E-plane bend	100
3.3.6	Analysis of waveguide bend discontinuities	103
3.3.7	Scattering parameters	110
3.3.8	Numerical results	110
3.4	ANALYSIS OF 3D WAVEGUIDE JUNCTIONS	115
3.4.1	General description	116
3.4.2	Basic equations	117
3.4.3	Discretisation scheme for propagation between A and B	118
3.4.4	Discontinuities	121
3.4.5	Coupling to other ports	122
3.4.6	Impedance/admittance transformation	125
3.4.7	Numerical results	126
4	ANALYSIS OF WAVEGUIDE STRUCTURES IN CYLINDRICAL COORDINATES	131
4.1	INTRODUCTION	131
4.2	GENERALISED TRANSMISSION LINE (GTL) EQUATIONS	132
4.2.1	Material parameters in a cylindrical coordinate system .	132
4.2.2	GTL equations for z -direction	133
4.2.3	GTL equations for ϕ -direction	137

4.2.4	Analysis of circular (coaxial) waveguides with azimuthally-magnetised ferrites and azimuthally-magnetised solid plasma	140
4.2.5	GTL equations for r -direction	144
4.3	DISCRETISATION OF THE FIELDS AND SOLUTIONS	150
4.3.1	Equations for propagation in z -direction	150
4.3.2	Equations for propagation in ϕ -direction	153
4.3.3	Solution of the wave equations in z - and ϕ -direction	155
4.3.4	Equations for propagation in r -direction	155
4.4	SOLUTION IN RADIAL DIRECTION	155
4.4.1	Discretisation in z -direction – circular dielectric resonators	155
4.4.2	Discretisation in z -direction – propagation in ϕ -direction	162
4.4.3	Discretisation in ϕ -direction – eigenmodes in circular multilayered waveguides	171
4.4.4	Eigenmodes of circular waveguides with magnetised ferrite or plasma – discretisation in r -direction	186
4.4.5	Waveguide bends – discretisation in r -direction	202
4.4.6	Uniaxial anisotropic fibres with circular and noncircular cross-section – discretisation in ϕ -direction	208
4.5	DISCONTINUITIES IN CIRCULAR WAVEGUIDES – ONE-DIMENSIONAL DISCRETISATION IN RADIAL DIRECTION	216
4.5.1	Introduction	216
4.5.2	Basic equations for rotational symmetry	217
4.5.3	Solution of the equations for rotational symmetry	218
4.5.4	Admittance and impedance transformation	219
4.5.5	Open ending circular waveguide	220
4.5.6	Numerical results for discontinuities in circular waveguides	223
4.5.7	Numerical results for coaxial line discontinuities and coaxial filter devices	223
4.5.8	Non-rotational modes in circular waveguides	225
4.5.9	Numerical results and discussion	228
4.6	ANALYSIS OF GENERAL AXIALLY SYMMETRIC ANTENNAS WITH COAXIAL FEED LINES	229
4.6.1	Introduction	229
4.6.2	Theory	230
4.6.3	Regions with crossed lines	239
4.6.4	Two special cases	244
4.6.5	Port relations of section D	247
4.6.6	Numerical results	248
4.6.7	Further structures and remarks	249

4.7	DEVICES IN CYLINDRICAL COORDINATES – TWO-DIMENSIONAL DISCRETISATION	250
4.7.1	Discretisation in r - and ϕ -direction	250
4.7.2	Numerical results	253
4.7.3	Discretisation in r - and z -direction	253
4.7.4	Discretisation in ϕ - and z -direction	254
4.7.5	GTL equations for r -direction	255
5	ANALYSIS OF PERIODIC STRUCTURES	267
5.1	INTRODUCTION	267
5.2	PRINCIPLE BEHAVIOUR OF PERIODIC STRUCTURES	269
5.3	GENERAL THEORY OF PERIODIC STRUCTURES	274
5.3.1	Port relations for general two ports	274
5.3.2	Floquet modes for symmetric periods	274
5.3.3	Concatenation of N symmetric periods	280
5.3.4	Floquet modes for unsymmetric periods	281
5.3.5	Some further general relations in periodic structures	283
5.4	NUMERICAL RESULTS FOR PERIODIC STRUCTURES IN ONE DIRECTION	286
5.5	ANALYSIS OF PHOTONIC CRYSTALS	291
5.5.1	Determination of band diagrams	291
5.5.2	Waveguide circuits in photonic crystals	297
5.5.3	Numerical results for photonic crystal circuits	299
6	ANALYSIS OF COMPLEX STRUCTURES	311
6.1	LAYERS OF VARIABLE THICKNESS	311
6.1.1	Introduction	311
6.1.2	Matching conditions at curved interfaces	312
6.2	MICROSTRIP SHARP BEND	315
6.3	IMPEDANCE TRANSFORMATION AT DISCONTINUITIES	318
6.3.1	Impedance transformation at concatenated junctions	318
6.4	ANALYSIS OF PLANAR WAVEGUIDE JUNCTIONS	320
6.4.1	Main diagonal submatrices	322
6.4.2	Off-diagonal submatrices – coupling to perpendicular ports	323
6.5	NUMERICAL RESULTS	327
6.5.1	Discontinuities in microstrips	328
6.5.2	Waveguide junctions	333
7	PRECISE RESOLUTION WITH AN ENHANCED AND GENERALISED LINE ALGORITHM	345
7.1	INTRODUCTION	345
7.2	CROSSED DISCRETISATION LINES AND CARTESIAN COORDINATES	346
7.2.1	Theoretical background	346

7.2.2	Lines in vertical direction	351
7.2.3	Lines in horizontal direction	357
7.3	SPECIAL STRUCTURES IN CARTESIAN COORDINATES	361
7.3.1	Groove guide	361
7.3.2	Coplanar waveguide	363
7.4	CROSSED DISCRETISATION LINES AND CYLINDRICAL COORDINATES	366
7.4.1	Principle of analysis	366
7.4.2	General formulas for eigenmode calculation	366
7.4.3	Discretisation lines in radial direction	367
7.4.4	Discretisation lines in azimuthal direction	368
7.4.5	Coupling to neighbouring ports	369
7.4.6	Steps of the analysis procedure	373
7.5	NUMERICAL RESULTS	373
8	WAVEGUIDE STRUCTURES WITH MATERIALS OF GENERAL ANISOTROPY IN ARBITRARY ORTHOGONAL COORDINATE SYSTEMS	377
8.1	GENERALISED TRANSMISSION LINE EQUATIONS	377
8.1.1	Material properties	377
8.1.2	Maxwell's equations in matrix notation	377
8.1.3	Generalised transmission line equations in Cartesian coordinates for general anisotropic material	379
8.1.4	Generalised transmission line equations for general anisotropic material in arbitrary orthogonal coordinates	381
8.1.5	Boundary conditions	383
8.1.6	Interpolation matrices	384
8.2	DISCRETISATION	385
8.2.1	Two-dimensional discretisation	385
8.2.2	One-dimensional discretisation	386
8.3	SOLUTION OF THE DIFFERENTIAL EQUATIONS	388
8.3.1	General solution	388
8.3.2	Field relation between interfaces A and B	389
8.4	ANALYSIS OF WAVEGUIDE JUNCTIONS AND SHARP BENDS WITH GENERAL ANISOTROPIC MATERIAL BY USING ORTHOGONAL PROPAGATING WAVES	389
8.4.1	Introduction	389
8.4.2	Theory	389
8.4.3	Main diagonal submatrices	391
8.4.4	Off-diagonal submatrices – coupling to other ports	393
8.4.5	Steps of the analysis procedure	398
8.5	NUMERICAL RESULTS	398
8.6	ANALYSIS OF WAVEGUIDE STRUCTURES IN SPHERICAL COORDINATES	399

8.6.1	Introduction	399
8.6.2	Generalised transmission line equations in spherical coordinates	400
8.6.3	Analysis of special devices – conformal antennas	408
8.6.4	Analysis of special devices – conical horn antennas . . .	413
8.6.5	Numerical results	419
8.7	ELLIPTICAL COORDINATES	420
8.7.1	GTL equations for z -direction	421
8.7.2	GTL equations for ξ -direction	422
8.7.3	GTL equations for η -direction	423
8.7.4	Hollow waveguides with elliptic cross-section	424
9	SUMMARY AND PROSPECT FOR THE FUTURE	429
A	DISCRETISATION SCHEMES AND DIFFERENCE OPERATORS	433
A.1	DETERMINATION OF THE EIGENVALUES AND EIGENVECTORS OF P	433
A.1.1	Calculation of the matrices δ	436
A.1.2	Derivation of the eigenvalues of the Neumann problem from those of the Dirichlet problem	438
A.1.3	The component of ε_r at an abrupt transition	439
A.1.4	Eigenvalues and eigenvectors for periodic boundary conditions	441
A.1.5	Discretisation for non-ideal places of the boundaries . .	442
A.2	ABSORBING BOUNDARY CONDITIONS (ABCs)	444
A.2.1	Introduction ¹	444
A.2.2	Factorisation of the Helmholtz equation	445
A.2.3	Padé approximation	446
A.2.4	Polynomial approximations	447
A.2.5	Construction of the difference operator for ABCs	449
A.2.6	Special boundary conditions (SBCs)	450
A.2.7	Numerical results	450
A.2.8	ABCs for cylindrical coordinates	453
A.2.9	Periodic boundary conditions	455
A.3	HIGHER-ORDER DIFFERENCE OPERATORS [11]	456
A.3.1	Introduction ³	456
A.3.2	Theory	457
A.3.3	Numerical results	459
A.4	NON-EQUIDISTANT DISCRETISATION	460
A.4.1	Introduction	460
A.4.2	Theory	460
A.4.3	Interpolation	464
A.4.4	Numerical results	466

A.5	REFLECTIONS IN DISCRETISATION GRIDS	468
A.5.1	Introduction	468
A.5.2	Dispersion relations	468
A.5.3	Reflections at discretisation transitions	471
A.6	FIELD EXTRAPOLATION FOR NEUMANN BOUNDARY CONDITIONS	475
A.7	ABOUT THE NATURE OF THE METHOD OF LINES . . .	476
A.7.1	Introduction	476
A.7.2	Relation between shielded structures and periodic ones .	477
A.7.3	Method of Lines and discrete Fourier transformation . .	478
A.7.4	Discussion	479
A.8	RELATION BETWEEN THE MODE MATCHING METHOD (MMM) AND THE METHOD OF LINES (MoL) FOR INHOMOGENEOUS MEDIA	480
A.9	RECIPROCITY AND ITS CONSEQUENCES	483
B	TRANSMISSION LINE EQUATIONS	491
B.1	TRANSMISSION LINE EQUATIONS IN FIELD VECTOR NOTATION	491
B.2	DERIVATION OF THE MULTICONDUCTOR TRANSMISSION LINE EQUATIONS	492
C	SCATTERING PARAMETERS	497
D	EQUIVALENT CIRCUITS FOR DISCONTINUITIES	499
E	APPROXIMATE METALLIC LOSS CALCULATION IN CONFORMAL STRUCTURES	501
	Index	503

