Table of Contents

Preface **i**

Introduction **1**

1 General theory of waveguides **5**
1.1 Basic relations for regular waveguides 6
1.1.1 Vector transmission-line equations 7
1.1.2 Longitudinal and transverse fields 8
1.2 Boundary conditions and waveguide modes in closed guides 9
1.2.1 Dirichlet and Neumann boundary conditions . . . 9
1.2.2 TE and TM modes 10
1.2.3 Lossy waveguide walls. Hybrid modes 13
1.2.4 TEM mode 13
1.3 Orthogonality of the modal fields 15
1.3.1 The proof 15
1.4 Fundamental properties of open waveguides 18
1.4.1 Boundary conditions for open waveguides 19
1.4.2 Eigenwaves in planar dielectric waveguides 20
1.5 Inhomogeneities in waveguides 24
1.5.1 Transmission-line theory applied to waveguides . . 24
1.5.2 Equivalent circuits for basic inhomogeneities . . . 25
1.6 Periodically inhomogeneous waveguides 33

2 Theory of high-frequency resonators **39**
2.1 Modes of closed and open resonators 39
2.1.1 Eigensolutions 39
2.1.2 Cylindrical resonators 40
2.1.3 Mode orthogonality 42
2.1.4 Losses in resonators. Quality factor 43
2.2 Excitation of resonators 44
2.2.1 Eigenfunction expansion 44
2.2.2 Excitation of resonators as sections of waveguides . 46

3 Waves in crystals and anisotropic waveguides 49
3.1 Electromagnetic properties of anisotropic crystals. Reciprocity . . . 49
3.2 Electromagnetic waves in nonmagnetic crystals . . . 51
3.2.1 Plane waves. Poynting vector . . . 52
3.2.2 Eigenwaves in uniaxial crystals . . . 53
3.3 Waveguides with anisotropic fillings . . . 57

4 Nonreciprocal media, waves in ferrite waveguides 63
4.1 Properties of magnetized ferrites . . . 63
4.2 Longitudinal propagation. Faraday effect . . . 68
4.3 Transverse propagation . . . 72
4.3.1 Microsrip line on ferrite substrate. Isolator . . . 74

5 Dielectric waveguides: classical methods for propagation constant calculations 79
5.1 Marcatili's method . . . 80
5.1.1 Rectangular dielectric rod waveguide in air . . . 82
5.1.2 Some properties of rectangular dielectric waveguides 83
5.1.3 How well does Marcatili's method work? . . . 84
5.2 Goell's method . . . 85
5.3 Open anisotropic waveguides . . . 87
5.3.1 Modification of Marcatili's method for the calculation of anisotropic rectangular dielectric waveguides 87
5.3.2 Application of Goell's method for the calculation of anisotropic rectangular dielectric waveguides . . 92
5.4 Comparison of modified Marcatili's and Goell's methods with experimental results . . . 95

6 Fabrication and measurements 103
6.1 Methods for material testing . . . 103
6.2 Open Fabri-Perot resonators for material testing in the millimeter-wave region . . . 104
6.2.1 Classical theory and its extensions . . . 106
6.3 Materials for millimeter-wave dielectric waveguides . . . 110

7 Excitation of millimeter-wave dielectric waveguides: computer simulations and experiments 115
7.1 Computer simulations with Finite Element Method . . . 117
7.1.1 Tapers of the dielectric waveguide . . . 117

7.1.2 Field distribution near the taper section 130
7.2 Experimental measurements of dielectric waveguides . . . 135
7.2.1 Waveguide samples and the experimental setup . . 135
7.2.2 Sapphire dielectric rod waveguides 136
7.2.3 GaAs dielectric waveguides 140
7.2.4 Horn-like structure implementation 144
7.2.5 Conclusions 146
7.3 Some notes about metal waveguides 146

8 Dielectric waveguide devices and integrated circuits 149
8.1 Dielectric waveguides for integrated circuits 149
8.1.1 Non-radiative dielectric waveguide 150
8.1.2 Dielectric waveguide circuits on metal and dielectric substrates 151
8.2 Passive devices 154
8.2.1 Whispering gallery resonator 154
8.2.2 Directional couplers 155
8.2.3 Phase shifters and attenuators 157
8.2.4 Isolators and circulators 160
8.3 Active devices 160
8.3.1 Theory of electromagnetic wave propagation in bulk negative resistance media 161
8.3.2 Experimental observations of millimeter-wave amplification with active waveguides 166
8.3.3 Slow electromagnetic wave amplification with drifting electrons in semiconductor waveguide structures 168
8.4 Dielectric waveguide antennas 170
8.4.1 Classification 170
8.4.2 Dielectric rod antennas 171
8.4.3 Leaky-wave antennas 172

Appendix A: Dyadics 181

Appendix B: Reciprocity theorem 185

Appendix C: Description of Matlab programs 187

Index 189