Contents

1 Introduction **1**
1.1 Complex materials and modern technology 1
1.2 Literature 5
1.3 Overview of the book 6
1.4 Basic notations 8
References 10

I Theory of bi-anisotropic media **13**

2 Field equations and constitutive relations **15**
2.1 Factorisation of forces in electromagnetics. The Lorentz force 15
2.2 The Maxwell–Lorentz equations 18
2.3 Field equations of macroscopic electromagnetics 20
2.4 Material relations for linear spatially dispersive media . 22
2.4.1 Spatial dispersion and material relations 23
2.4.2 Isotropic media with weak spatial dispersion . . 27
2.5 Lorentz reciprocity theorem 28
2.6 Field energy in bi-anisotropic media 29
2.7 Lossless bi-anisotropic media 32
2.8 Momentum of electromagnetic field in bi-anisotropic media 33
2.9 Kramers–Kronig relations and sum rules for material parameters 34
2.10 Classification of bi-anisotropic materials 37
2.10.1 Reciprocal media 38
2.10.2 Nonreciprocal media 40
References 41

3 Symmetry concepts in electromagnetics **45**
3.1 Space–reversal and time–reversal symmetry 45
3.1.1 Space inversion in classical electrodynamics: is the electric charge a scalar or a pseudoscalar? . . 45

3.1.2 Time inversion in classical electrodynamics . . . 49
3.2 Dual-symmetrical formulation of electromagnetics 49
3.2.1 Normalised fields 50
3.2.2 Medium effects 53
3.3 Onsager–Casimir principle in macroscopic electrodynamics of bi-anisotropic media 57
3.3.1 Symmetry relations 57
3.3.2 Onsager–Casimir principle in different media formalisms 59
3.3.3 Time-reversal and space-reversal symmetries working together 61
3.3.4 Onsager–Casimir principle in the dually symmetrical formulation 63
3.4 Lorentz transformations of electromagnetic fields and moving media 65
3.4.1 Lorentz transformations 65
3.4.2 Material equations in electromagnetics of moving bi-anisotropic media 68
3.4.3 Is the tensor of electromagnetic field a true tensor or a pseudotensor? 70
References 71

4 Spatial dispersion **75**
4.1 First-order spatial dispersion 75
4.2 Magnetoelectric coupling and spatial dispersion of permittivity 77
4.3 Interface conditions for spatially dispersive media 81
References 84

5 Nonreciprocal bi-anisotropic media **85**
5.1 Nonreciprocal magnetoelectric effects 85
5.2 Man-made nonreciprocal magnetoelectric media 90
5.2.1 Magnetoelectric dyadics of an artificial nonreciprocal particle 90
5.2.2 Magnetoelectric phenomena in artificial nonreciprocal media 92
5.2.3 Plane waves in “moving” chiral composites . . . 94
5.3 Isotropic nonreciprocal materials 95
References 97

6 Material tensors for ideal crystals and artificial composites **101**
6.1 Spatial symmetry of ideal crystals and the structure of the constitutive tensors 101

6.1.1 Symmetry description 101
6.1.2 Restrictions on the material parameters 105
6.2 Constitutive tensors of the second rank 106
6.3 Constitutive pseudotensors of the second rank 113
6.3.1 Symmetry restrictions 113
6.3.2 Forms of material tensors and pseudotensors . . 115
References 118

7 Physical modelling of bi-anisotropic media 119
7.1 Polarizabilities of reciprocal bi-anisotropic particles . . . 119
7.1.1 Introductory remarks 119
7.1.2 Antenna model for wire-and-loop elements 121
7.1.3 Electrically small particles 127
7.1.4 Polarizabilities of omega particles 131
7.1.5 Comparison with numerical and experimental results 133
7.2 Effective medium modelling 137
7.2.1 Average polarization and macroscopic medium . 138
7.2.2 Maxwell Garnett approach 143
7.2.3 Maxwell Garnett model for spherical bi-anisotropic scatterers 148
7.2.4 Illustrations 149
7.3 Reciprocal bi-anisotropic composite materials 152
7.3.1 Properties of isotropic chiral composites 152
7.3.2 Uniaxial chiral composites 154
7.3.3 Bi-anisotropic composites 166
References 169

8 Waves in bi-anisotropic media 173
8.1 Plane waves in uniaxial bi-anisotropic media 173
8.1.1 Field equations and propagation factors 174
8.1.2 Special cases 176
8.2 Reflection and transmission in slabs of bi-anisotropic media 179
8.2.1 Reflection and transmission in uniaxial omega slabs 179
8.2.2 Vector transmission line 182
8.2.3 Reflection and transmission coefficients 185
8.2.4 Axial propagation 188
8.3 More general media 189
References 191

9 Electromagnetic waves in spiral structures 193
9.1 Cholesteric liquid crystals 193
9.2 Conservation laws 194
9.3 Diffraction of light in cholesteric liquid crystals 198

9.4 Dielectrically isotropic crystals with spiral symmetry . . 201
9.5 Macro-chirality in dielectric and magnetic structures . . 205
9.6 Bi-anisotropic spiral structures and micro-chirality . . . 211
9.6.1 Chiral superlattices 212
9.6.2 Numerical example 216
9.7 Extraordinary waves in media with helical structure . . 218
References 224

10 Chiral media under external fields 227
10.1 Optical Kerr effect in dispersive chiral media 227
10.2 Formation of spiral structure in chiral crystals at the influence of ultrasound 231
10.3 Diffraction of electromagnetic waves by ultrasound in chiral crystals and measurements of acoustic rotational ability 234
10.4 Weakening of optical absorption at diffraction of light by ultrasound 236
References 241

11 Nonlinear effects 245
11.1 Spiral molecule model of nonlinear gyrotropy 245
11.2 Thermal mechanism of nonlinear gyrotropy 249
11.3 Second harmonic generation in media with spiral structure 253
11.4 Non-linear gyrotropy in liquid crystals 258
11.5 Nonlinear transmission through liquid crystals 264
References 267

II Applications of bi-anisotropic media 271

12 Antennas and shields 273
12.1 Antenna techniques 273
12.1.1 Polarization correction in lens and reflector antennas 273
12.1.2 Accelerating lenses 275
12.2 Polarization transformation 277
12.2.1 Transmission polarizators 277
12.2.2 Reflection polarizators 278
12.3 Stealth technology problems 279
12.3.1 Conventional radar absorbers 280
12.3.2 Chiral absorbers 286
12.3.3 Omega materials 289
12.3.4 Artificial magnetics 293
References 296

13 Microwave applications **299**
13.1 Chiral waveguide mode transformers 299
13.1.1 Eigenmodes in the soft and hard surface chiral waveguide 300
13.1.2 Mode transformation 300
13.1.3 Impedance transformation 301
13.2 Electrical control of wave propagation 302
References 306

14 Applications to optics **307**
14.1 Superlattices as artificial anisotropic chiral media with required properties 307
14.2 Chiral superlattices with magnetic and dielectric structure311
14.3 Frequency modulation and polarization transformation . 314
14.4 Wave front reversal in the microwave frequency range . 318
14.5 Polarization plane rotation in nonstationary media . . . 321
References 323