Contents

Preface xiii

1 Electromagnetic radiation 1

1.1 Brief history of the interaction of light and matter 3
1.2 Light in vacuum 3
1.2.1 The electromagnetic spectrum 6
1.2.2 Wave equation in vacuum 26
1.2.3 Propagation of one component in one dimension 30
1.2.4 Phase and group velocity of a light pulse 34
1.2.5 Amplitude modulation 38
1.2.6 Frequency and phase modulation 38
1.2.7 Energy, momentum and angular momentum of electromagnetic waves 41
1.2.8 Polarized light 50
1.2.9 Diffraction 60
1.2.10 Interference 66
1.2.11 Temporal and spatial coherence 72
1.2.12 Photons: quantization of the electromagnetic field 75
1.3 Matter–source of light 79
1.3.1 Classical expressions for the charge density and current 79
1.3.2 The wave equation with source terms: Lienard–Wiechert potentials 80

2 Phenomenology of light propagation in matter 87

2.1 Absorption of light 88
2.1.1 Color of materials 91
2.1.2 An aside on Einstein absorption and emission coefficients 93
2.2 Nonlinear absorption 94
2.2.1 Saturable absorption 95
2.2.2 Reverse saturable absorption 97
2.2.3 Two-photon absorption 99
2.3 Index of refraction 100
2.3.1 Reflection and refraction at a boundary interface 101
2.3.2 Relationship between refractive index and absorption: Kramers–Kronig relation 105
2.3.3 Dispersion 107
2.3.4 Refractive index temperature dependence: thermal lensing 112
2.4 Optical phenomena in nonisotropic media 113
2.4.1 Introduction to crystallography and optics in crystals 113
2.4.2 Dichroism 122
2.4.3 Birefringence 122
2.4.4 Optical activity, optical rotatory dispersion and circular dichroism 140
2.5 Electric field effects 143
2.5.1 Kerr effect 143

2.5.2 Pockels effect 144
2.5.3 Piezoelectricity 149
2.5.4 Pyroelectric effect 151
2.5.5 Ferroelectric effect 152
2.5.6 Electrostriction 158
2.5.7 Photorefractive effect 161
2.6 Acousto-optic effects 163
2.6.1 Diffraction by acoustic waves: Brillouin scattering 163
2.6.2 Photoelastic effect (stress-birefringence) 168
2.6.3 Acousto-optic detection of light 169
2.7 Magnetic field effects 171
2.7.1 Faraday effect 173
2.7.2 Voigt and Cotton–Mouton effects 175
2.7.3 Magnetic circular birefringence and dichroism 176
2.7.4 Magnetostriction and magnetoelasticity 176

3 The interaction of light and matter 177

3.1 Lorentz force law 178
3.2 Motion of a charged particle in static electric and magnetic fields 178
3.2.1 Motion in a magnetic field – the cyclotron frequency 178
3.2.2 Crossed electric and magnetic fields 179
3.2.3 Conductivity, magnetoconductivity and Hall effect 180
3.3 Motion of a bound electron in an electromagnetic field 184
3.3.1 Linewidth due to spontaneous emission 184
3.3.2 Rayleigh scattering, Thomson scattering, and resonant line scattering limits 186
3.3.3 Polarization of a medium 193
3.3.4 Polarization of a medium in a static magnetic field 202
3.3.5 Electromagnetic field and a static electric field 206
3.3.6 Nonlinear polarization of a medium 207
3.4 Radiation due to acceleration of charges 210
3.4.1 Radiation from relativistically moving charges 211
3.4.2 Synchrotron emission 214
3.4.3 Radiative damping force revisited 215
3.4.4 Cherenkov radiation 217
3.5 Multipole radiation 217
3.5.1 Scattering of long wavelength electromagnetic radiation from small particles 221
3.6 Scattering of a light wavepacket 224
3.7 Cooling and trapping of atoms 225
3.7.1 Far off-resonance trapping, atom mirrors and optical tweezers 226
3.7.2 Doppler cooling 228
3.7.3 Polarization gradient cooling (Sisyphus cooling) of atoms 230

4 Magnetic phenomena, constitutive relations and plasmas 235

4.1 Magnetic moments 237
4.2 Magnetization 242
4.2.1 Diamagnetism 243
4.2.2 Paramagnetism 244
4.2.3 Ferromagnetism 247
4.2.4 Ferrimagnetism 250
4.2.5 Antiferromagnetism 251

4.2.6 Permeability resonances 251
4.3 Magnetic resonance 252
4.3.1 Nuclear magnetic resonance 256
4.4 Polarization and magnetization as source terms 259
4.5 Atomistic derivation of macroscopic electromagnetism and the constitutive relations 261
4.6 Microscopic polarizability and macroscopic polarization 264
4.6.1 Clausius–Mossotti equation and the Lorentz–Lorenz correction factor 265
4.6.2 Microscopic magnetic moment and macroscopic magnetization 267
4.7 Dielectric relaxation 267
4.7.1 Molecular orientation (and re-orientation) in an applied field 270
4.7.2 Dispersion relations for light in dielectric crystals 272
4.8 Plasmas 275
4.8.1 Plasma parameters 277
4.8.2 Constitutive equations in a plasma 280
4.8.3 Kinetic theory 282
4.8.4 Hydrodynamic model of plasmas 284
4.8.5 Waves in a plasma 289

5 Quantum description of absorption, emission and light scattering 293

5.1 Charged particle in an electromagnetic field 294
5.1.1 Electron spin coupling 297
5.1.2 Landau levels in a static magnetic field 300
5.2 Absorption and emission 301
5.2.1 Time-dependent perturbation theory 301
5.2.2 Spontaneous emission 304
5.2.3 Stimulated emission and absorption 309
5.2.4 Finite lifetime considerations for stimulated emission and absorption 309
5.2.5 Finite duration pulses 311
5.3 Rayleigh and Raman scattering 312
5.3.1 Why is the sky blue, the setting sun red and clouds white? 316
5.4 Thomson scattering 317

6 Spectroscopy 319

6.1 Atoms 320
6.1.1 The hydrogen atom 327
6.1.2 Multielectron atomic systems 337
6.1.3 Atomic selection rules 347
6.1.4 Broadening due to lifetime and collisions 347
6.2 Molecules 348
6.2.1 Hamiltonian for molecular systems 348
6.2.2 The Born–Oppenheimer approximation and potential energy surfaces 349
6.2.3 Molecular orbitals 350
6.3 Diatomic molecules 353
6.3.1 Diatomic rotational and vibrational states and transitions 354
6.3.2 Electric dipole transitions 360
6.3.3 The Franck–Condon principle 361
6.3.4 More about rotational states and transitions: microwave spectroscopy 363
6.3.5 H_2^+ ion 364
6.3.6 H_2 molecule 366
6.4 Polyatomic molecules 367

6.4.1 Multidimensional Born–Oppenheimer potential surfaces 367
6.4.2 The nuclear Hamiltonian for molecular systems 369
6.4.3 Rotational degrees of freedom 370
6.4.4 Large molecules 377
6.5 Condensed-phase materials 381
6.5.1 Crystals doped with metal ions 381
6.5.2 Metals 392
6.5.3 Semiconductor materials 397

7 Lasers 409

7.1 Laser dynamics 410
7.1.1 Three- and four-level lasers 410
7.1.2 Laser rate equations 412
7.2 Threshold 414
7.3 Steady state 416
7.3.1 Small signal gain and gain saturation 417
7.3.2 Circulating intracavity intensity 417
7.3.3 cw output vs input 419
7.4 Pulsed laser operation 420
7.4.1 Relaxation oscillations 420
7.4.2 Q-switching 422
7.4.3 Mode-locking 426
7.4.4 Extra-cavity pulse compressor 429
7.4.5 Chirped pulse amplifiers 429
7.5 Cavity modes 430
7.5.1 Longitudinal modes 430
7.5.2 Transverse modes 432
7.6 Amplified spontaneous emission 435
7.7 Laser linewidth 437
7.8 Laser coherence 437
7.9 Specific laser systems 437
7.9.1 He–Ne laser 438
7.9.2 Ar ion and Kr ion lasers 439
7.9.3 CO_2 laser 441
7.9.4 Nitrogen laser 443
7.9.5 Excimer and exciplex lasers 444
7.9.6 Dye lasers 444
7.9.7 Solid-state lasers 445
7.9.8 Semiconductor diode lasers: GaAs, AlGaAs heterostructures 451

8 Nonlinear optics 455

8.1 Expansion of the polarization in the electric field 456
8.1.1 Symmetry relations of the nonlinear susceptibilities 460
8.1.2 Electromagnetic energy density in a nonlinear medium 462
8.1.3 Local field corrections to nonlinear susceptibilities 464
8.1.4 The nonlinear wave equation for the slowly varying envelope 465
8.1.5 Manley–Rowe relations 469
8.2 Phase-matching 470
8.2.1 Collinear phase-matching 471
8.2.2 Noncollinear phase-matching 472
8.3 Second harmonic generation 473
8.3.1 Second harmonic generation with multimode light 473
8.3.2 Short-pulse second harmonic generation 476
8.4 Three-wave mixing 478
8.4.1 Sum frequency generation 478
8.4.2 Difference frequency generation 484

8.5 Third harmonic generation 485
8.5.1 Third harmonic generation in rare gas mixtures 487
8.5.2 Effects of self-phase modulation on third harmonic generation 487
8.6 Self-focusing and self-phase modulation 488
8.6.1 The nonlinear Schrödinger equation 490
8.6.2 Optical solitons 492
8.7 Four-wave mixing 495
8.8 Stimulated Raman processes 496
8.8.1 Coherent anti-Stokes and Stokes Raman spectroscopy 498
8.9 Stimulated Brillouin processes 498
8.10 Nonlinear matter-wave optics 501

9 Quantum-optical processes 503

9.1 Interaction of a two-level system with an electromagnetic field 504
9.1.1 Rotating wave approximation 505
9.1.2 Rabi oscillations 506
9.1.3 Dressed states 508
9.1.4 Adiabatic passage and the adiabatic theorem 512
9.2 Liouville–von Neumann equation for the density matrix 514
9.2.1 The density matrix description of matter 515
9.2.2 The steady-state density matrix solution 524
9.2.3 Rate equation limit 526
9.2.4 Atom cooling and trapping revisited 527
9.2.5 The adiabatic theorem for density matrix dynamics 528
9.2.6 Inhomogeneous broadening 529
9.2.7 Optical coherent transient processes 530
9.3 Three-level system 536
9.3.1 Wavefunction treatment of a three-level system 537
9.3.2 Population transfer using stimulated Raman adiabatic passage 539
9.3.3 Coherent trapping: dark states 541
9.3.4 Density matrix treatment of a three-level system 541
9.4 Coherent states and squeezed states 543
9.4.1 Position-momentum squeezing 547
9.4.2 Number and phase squeezing and the phase operator 549
9.4.3 Generation of squeezed states: parametric down-conversion 551
9.4.4 Homodyne detection of squeezed states 552
9.4.5 Application of squeezed states: sub-shot-noise phase measurements 553
9.5 The Jaynes–Cummings model 554
9.6 Interaction between modes of a quantum field 556
9.6.1 Interaction representation 557
9.6.2 Quantum-field two-mode Rabi problem 558
9.6.3 Parametric oscillation 559

10 Light propagation in optical fibers and introduction to optical communication systems 561

10.1 Fiber characteristics 562
10.1.1 Attenuation in fibers 564
10.1.2 Dispersion in fibers 565

10.1.3 Polarization-maintenance and single-polarization fibers 565
10.1.4 Gain in doped fibers 566
10.2 Transverse modes of an optical fiber 567
10.2.1 Single-mode fiber 572
10.2.2 Imperfections in the fiber 572
10.2.3 Coupling between fiber modes 572
10.2.4 Fiber–Bragg gratings 572
10.3 Nonlinear processes in fibers 573
10.3.1 Optical solitons in fibers 573
10.3.2 Stimulated Raman amplification in fibers 574
10.3.3 Higher-order nonlinear effects 575
10.3.4 Parametric processes 576
10.4 Fiber-optic communication systems 576
10.4.1 Analogue communication 577
10.4.2 Coherent optical communication 577
10.4.3 Digital communication 579
10.4.4 Multiplexing techniques 581

Appendices 583

Appendix A: vector analysis 583
A.1 Scalar and vector products 583
A.2 Differential operators 583
A.3 Divergence and Stokes theorems 585
A.4 Curvilinear coordinates 586
Appendix B: Electromagnetism and Maxwell's equations 588
B.1 The laws of electromagnetism 588
B.2 Electromagnetic units 589
B.3 Maxwell's equations 590
Appendix C: Quantum mechanics and the Schrödinger equation 595
C.1 Time-dependent and time-independent Schrödinger equations 595
C.2 Spherical harmonics 597
C.3 The radial Schrödinger equation 598
C.4 The free particle 600
C.5 The spherical top and the distorted spherical top 601
C.6 The Coulomb potential 602
C.7 Atomic units 603
C.8 The Morse potential 606
C.9 The harmonic oscillator potential 606
Appendix D: perturbation theory 609
D.1 Nondegenerate time-independent perturbation theory 609
D.2 Degenerate time-independent perturbation theory 611
D.3 Time-dependent perturbation theory 612
Appendix E: Fundamental constants 613

References 615

Bibliography 619

Index 623