

Contents

Preface	xiii	2 Phenomenology of light propagation in matter	87
1 Electromagnetic radiation	1	2.1 Absorption of light	88
1.1 Brief history of the interaction of light and matter	3	2.1.1 Color of materials	91
1.2 Light in vacuum	3	2.1.2 An aside on Einstein absorption and emission coefficients	93
1.2.1 The electromagnetic spectrum	6	2.2 Nonlinear absorption	94
1.2.2 Wave equation in vacuum	26	2.2.1 Saturable absorption	95
1.2.3 Propagation of one component in one dimension	30	2.2.2 Reverse saturable absorption	97
1.2.4 Phase and group velocity of a light pulse	34	2.2.3 Two-photon absorption	99
1.2.5 Amplitude modulation	38	2.3 Index of refraction	100
1.2.6 Frequency and phase modulation	38	2.3.1 Reflection and refraction at a boundary interface	101
1.2.7 Energy, momentum and angular momentum of electromagnetic waves	41	2.3.2 Relationship between refractive index and absorption: Kramers–Kronig relation	105
1.2.8 Polarized light	50	2.3.3 Dispersion	107
1.2.9 Diffraction	60	2.3.4 Refractive index temperature dependence: thermal lensing	112
1.2.10 Interference	66	2.4 Optical phenomena in nonisotropic media	113
1.2.11 Temporal and spatial coherence	72	2.4.1 Introduction to crystallography and optics in crystals	113
1.2.12 Photons: quantization of the electromagnetic field	75	2.4.2 Dichroism	122
1.3 Matter–source of light	79	2.4.3 Birefringence	122
1.3.1 Classical expressions for the charge density and current	79	2.4.4 Optical activity, optical rotatory dispersion and circular dichroism	140
1.3.2 The wave equation with source terms: Lienard–Wiechert potentials	80	2.5 Electric field effects	143
		2.5.1 Kerr effect	143

2.5.2	Pockels effect	144	3.3.3	Polarization of a medium	193
2.5.3	Piezoelectricity	149	3.3.4	Polarization of a medium in a static magnetic field	202
2.5.4	Pyroelectric effect	151	3.3.5	Electromagnetic field and a static electric field	206
2.5.5	Ferroelectric effect	152	3.3.6	Nonlinear polarization of a medium	207
2.5.6	Electrostriction	158	3.4	Radiation due to acceleration of charges	210
2.5.7	Photorefractive effect	161	3.4.1	Radiation from relativistically moving charges	211
2.6	Acousto-optic effects	163	3.4.2	Synchrotron emission	214
2.6.1	Diffraction by acoustic waves: Brillouin scattering	163	3.4.3	Radiative damping force revisited	215
2.6.2	Photoelastic effect (stress-birefringence)	168	3.4.4	Cherenkov radiation	217
2.6.3	Acousto-optic detection of light	169	3.5	Multipole radiation	217
2.7	Magnetic field effects	171	3.5.1	Scattering of long wavelength electromagnetic radiation from small particles	221
2.7.1	Faraday effect	173	3.6	Scattering of a light wavepacket	224
2.7.2	Voigt and Cotton-Mouton effects	175	3.7	Cooling and trapping of atoms	225
2.7.3	Magnetic circular birefringence and dichroism	176	3.7.1	Far off-resonance trapping, atom mirrors and optical tweezers	226
2.7.4	Magnetostriction and magnetoelasticity	176	3.7.2	Doppler cooling	228
			3.7.3	Polarization gradient cooling (Sisyphus cooling) of atoms	230
3	The interaction of light and matter	177	4	Magnetic phenomena, constitutive relations and plasmas	235
3.1	Lorentz force law	178	4.1	Magnetic moments	237
3.2	Motion of a charged particle in static electric and magnetic fields	178	4.2	Magnetization	242
3.2.1	Motion in a magnetic field – the cyclotron frequency	178	4.2.1	Diamagnetism	243
3.2.2	Crossed electric and magnetic fields	179	4.2.2	Paramagnetism	244
3.2.3	Conductivity, magnetoconductivity and Hall effect	180	4.2.3	Ferromagnetism	247
3.3	Motion of a bound electron in an electromagnetic field	184	4.2.4	Ferrimagnetism	250
3.3.1	Linewidth due to spontaneous emission	184	4.2.5	Antiferromagnetism	251
3.3.2	Rayleigh scattering, Thomson scattering, and resonant line scattering limits	186			

4.2.6	Permeability resonances	251	5.2.2	Spontaneous emission	304
4.3	Magnetic resonance	252	5.2.3	Stimulated emission and absorption	309
4.3.1	Nuclear magnetic resonance	256	5.2.4	Finite lifetime considerations for stimulated emission and absorption	309
4.4	Polarization and magnetization as source terms	259	5.2.5	Finite duration pulses	311
4.5	Atomistic derivation of macroscopic electromagnetism and the constitutive relations	261	5.3	Rayleigh and Raman scattering	312
4.6	Microscopic polarizability and macroscopic polarization	264	5.3.1	Why is the sky blue, the setting sun red and clouds white?	316
4.6.1	Clausius–Mossotti equation and the Lorentz–Lorenz correction factor	265	5.4	Thomson scattering	317
4.6.2	Microscopic magnetic moment and macroscopic magnetization	267	6 Spectroscopy	319	
4.7	Dielectric relaxation	267	6.1	Atoms	320
4.7.1	Molecular orientation (and re-orientation) in an applied field	270	6.1.1	The hydrogen atom	327
4.7.2	Dispersion relations for light in dielectric crystals	272	6.1.2	Multielectron atomic systems	337
4.8	Plasmas	275	6.1.3	Atomic selection rules	347
4.8.1	Plasma parameters	277	6.1.4	Broadening due to lifetime and collisions	348
4.8.2	Constitutive equations in a plasma	280	6.2	Molecules	348
4.8.3	Kinetic theory	282	6.2.1	Hamiltonian for molecular systems	348
4.8.4	Hydrodynamic model of plasmas	284	6.2.2	The Born–Oppenheimer approximation and potential energy surfaces	349
4.8.5	Waves in a plasma	289	6.2.3	Molecular orbitals	350
5 Quantum description of absorption, emission and light scattering	293		6.3	Diatomic molecules	353
5.1	Charged particle in an electromagnetic field	294	6.3.1	Diatomic rotational and vibrational states and transitions	354
5.1.1	Electron spin coupling	297	6.3.2	Electric dipole transitions	360
5.1.2	Landau levels in a static magnetic field	300	6.3.3	The Franck–Condon principle	361
5.2	Absorption and emission	301	6.3.4	More about rotational states and transitions: microwave spectroscopy	363
5.2.1	Time-dependent perturbation theory	301	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	7.9.2	Ar ion and Kr ion lasers	439
6.4.2	The nuclear Hamiltonian for molecular systems	369	7.9.3	CO ₂ laser	441
6.4.3	Rotational degrees of freedom	370	7.9.4	Nitrogen laser	443
6.4.4	Large molecules	377	7.9.5	Excimer and exciplex lasers	444
6.5	Condensed-phase materials	381	7.9.6	Dye lasers	444
6.5.1	Crystals doped with metal ions	381	7.9.7	Solid-state lasers	445
6.5.2	Metals	392	7.9.8	Semiconductor diode lasers: GaAs, AlGaAs heterostructures	451
6.5.3	Semiconductor materials	397			
7	Lasers	409	8	Nonlinear optics	455
7.1	Laser dynamics	410	8.1	Expansion of the polarization in the electric field	456
7.1.1	Three- and four-level lasers	410	8.1.1	Symmetry relations of the nonlinear susceptibilities	460
7.1.2	Laser rate equations	412	8.1.2	Electromagnetic energy density in a nonlinear medium	462
7.2	Threshold	414	8.1.3	Local field corrections to nonlinear susceptibilities	464
7.3	Steady state	416	8.1.4	The nonlinear wave equation for the slowly varying envelope	465
7.3.1	Small signal gain and gain saturation	417	8.1.5	Manley–Rowe relations	469
7.3.2	Circulating intracavity intensity	417	8.2	Phase-matching	470
7.3.3	cw output vs input	419	8.2.1	Collinear phase-matching	471
7.4	Pulsed laser operation	420	8.2.2	Noncollinear phase-matching	472
7.4.1	Relaxation oscillations	420	8.3	Second harmonic generation	473
7.4.2	<i>Q</i> -switching	422	8.3.1	Second harmonic generation with multimode light	473
7.4.3	Mode-locking	426	8.3.2	Short-pulse second harmonic generation	476
7.4.4	Extra-cavity pulse compressor	429	8.4	Three-wave mixing	478
7.4.5	Chirped pulse amplifiers	429	8.4.1	Sum frequency generation	478
7.5	Cavity modes	430	8.4.2	Difference frequency generation	484
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			

8.5	Third harmonic generation	485	9.3	Three-level system	536
8.5.1	Third harmonic generation in rare gas mixtures	487	9.3.1	Wavefunction treatment of a three-level system	537
8.5.2	Effects of self-phase modulation on third harmonic generation	487	9.3.2	Population transfer using stimulated Raman adiabatic passage	539
8.6	Self-focusing and self-phase modulation	488	9.3.3	Coherent trapping: dark states	541
8.6.1	The nonlinear Schrödinger equation	490	9.3.4	Density matrix treatment of a three-level system	541
8.6.2	Optical solitons	492	9.4	Coherent states and squeezed states	543
8.7	Four-wave mixing	495	9.4.1	Position-momentum squeezing	547
8.8	Stimulated Raman processes	496	9.4.2	Number and phase squeezing and the phase operator	549
8.8.1	Coherent anti-Stokes and Stokes Raman spectroscopy	498	9.4.3	Generation of squeezed states: parametric down-conversion	551
8.9	Stimulated Brillouin processes	498	9.4.4	Homodyne detection of squeezed states	552
8.10	Nonlinear matter-wave optics	501	9.4.5	Application of squeezed states: sub-shot-noise phase measurements	553
9	Quantum-optical processes	503	9.5	The Jaynes–Cummings model	554
9.1	Interaction of a two-level system with an electromagnetic field	504	9.6	Interaction between modes of a quantum field	556
9.1.1	Rotating wave approximation	505	9.6.1	Interaction representation	557
9.1.2	Rabi oscillations	506	9.6.2	Quantum-field two-mode Rabi problem	558
9.1.3	Dressed states	508	9.6.3	Parametric oscillation	559
9.1.4	Adiabatic passage and the adiabatic theorem	512	10	Light propagation in optical fibers and introduction to optical communication systems	561
9.2	Liouville–von Neumann equation for the density matrix	514	10.1	Fiber characteristics	562
9.2.1	The density matrix description of matter	515	10.1.1	Attenuation in fibers	564
9.2.2	The steady-state density matrix solution	524	10.1.2	Dispersion in fibers	564
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			

10.1.3	Polarization-maintenance and single-polarization fibers	566	B.1	The laws of electromagnetism	588
10.1.4	Gain in doped fibers	566	B.2	Electromagnetic units	589
10.2	Transverse modes of an optical fiber	567	B.3	Maxwell's equations	590
10.2.1	Single-mode fiber	571	Appendix C: Quantum mechanics and the Schrödinger equation		595
10.2.2	Imperfections in the fiber	572	C.1	Time-dependent and time-independent Schrödinger equations	595
10.2.3	Coupling between fiber modes	572	C.2	Spherical harmonics	597
10.2.4	Fiber-Bragg gratings	572	C.3	The radial Schrödinger equation	598
10.3	Nonlinear processes in fibers	573	C.4	The free particle	600
10.3.1	Optical solitons in fibers	574	C.5	The spherical top and the distorted spherical top	601
10.3.2	Stimulated Raman amplification in fibers	574	C.6	The Coulomb potential	602
10.3.3	Higher-order nonlinear effects	575	C.7	Atomic units	603
10.3.4	Parametric processes	576	C.8	The Morse potential	606
10.4	Fiber-optic communication systems	576	C.9	The harmonic oscillator potential	607
10.4.1	Analogue communication	577	Appendix D: perturbation theory		609
10.4.2	Coherent optical communication	577	D.1	Nondegenerate time-independent perturbation theory	609
10.4.3	Digital communication	579	D.2	Degenerate time-independent perturbation theory	611
10.4.4	Multiplexing techniques	581	D.3	Time-dependent perturbation theory	612
Appendices		583	Appendix E: Fundamental constants		613
Appendix A: vector analysis		583	References		615
A.1	Scalar and vector products	583	Bibliography		619
A.2	Differential operators	583	Index		623
A.3	Divergence and Stokes theorems	585			
A.4	Curvilinear coordinates	586			
Appendix B: Electromagnetism and Maxwell's equations		588			