

Contents

<i>Preface to the Fourth Edition</i>	<i>xv</i>
<i>Preface to the Third Edition</i>	<i>xvii</i>
<i>Preface to the Second Edition</i>	<i>xix</i>
<i>Preface to the First Edition</i>	<i>xxi</i>
Chapter 1: The Nonlinear Optical Susceptibility	1
1.1 Introduction to Nonlinear Optics	1
1.2 Descriptions of Nonlinear Optical Processes	4
1.2.1 Second-Harmonic Generation	4
1.2.2 Sum- and Difference-Frequency Generation	6
1.2.3 Sum-Frequency Generation	7
1.2.4 Difference-Frequency Generation	8
1.2.5 Optical Parametric Oscillation	9
1.2.6 Third-Order Nonlinear Optical Processes	10
1.2.7 Third-Harmonic Generation	10
1.2.8 Intensity-Dependent Refractive Index	11
1.2.9 Third-Order Interactions (General Case)	11
1.2.10 Parametric versus Nonparametric Processes	13
1.2.11 Saturable Absorption	14
1.2.12 Two-Photon Absorption	15
1.2.13 Stimulated Raman Scattering	16
1.3 Formal Definition of the Nonlinear Susceptibility	16
1.4 Nonlinear Susceptibility of a Classical Anharmonic Oscillator	20
1.4.1 Noncentrosymmetric Media	21
1.4.2 Miller's Rule	26
1.4.3 Centrosymmetric Media	27

1.5	Properties of the Nonlinear Susceptibility	32
1.5.1	Reality of the Fields.....	33
1.5.2	Intrinsic Permutation Symmetry	34
1.5.3	Symmetries for Lossless Media	34
1.5.4	Field Energy Density for a Nonlinear Medium.....	35
1.5.5	Kleinman's Symmetry	37
1.5.6	Contracted Notation.....	38
1.5.7	Effective Value of d (d_{eff})	40
1.5.8	Spatial Symmetry of the Nonlinear Medium	41
1.5.9	Influence of Spatial Symmetry on the Linear Optical Properties of a Material Medium.....	41
1.5.10	Influence of Inversion Symmetry on the Second-Order Nonlinear Response	42
1.5.11	Influence of Spatial Symmetry on the Second-Order Susceptibility ...	44
1.5.12	Number of Independent Elements of $\chi_{ijk}^{(2)}(\omega_3, \omega_2, \omega_1)$	45
1.5.13	Distinction between Noncentrosymmetric and Cubic Crystal Classes .	45
1.5.14	Distinction between Noncentrosymmetric and Polar Crystal Classes..	50
1.5.15	Influence of Spatial Symmetry on the Third-Order Nonlinear Response	50
1.6	Time-Domain Description of Optical Nonlinearities.....	50
1.7	Kramers–Kronig Relations in Linear and Nonlinear Optics	56
1.7.1	Kramers–Kronig Relations in Linear Optics	56
1.7.2	Kramers–Kronig Relations in Nonlinear Optics.....	59
	Problems	61
	References	63
	Chapter 2: Wave-Equation Description of Nonlinear Optical Interactions	65
2.1	The Wave Equation for Nonlinear Optical Media	65
2.2	The Coupled-Wave Equations for Sum-Frequency Generation.....	70
2.2.1	Phase-Matching Considerations.....	72
2.3	Phase Matching	74
2.4	Quasi-Phase-Matching (QPM)	79
2.5	The Manley–Rowe Relations.....	83
2.6	Sum-Frequency Generation.....	86
2.7	Second-Harmonic Generation	91
2.7.1	Applications of Second-Harmonic Generation	98
2.8	Difference-Frequency Generation and Parametric Amplification	100
2.9	Optical Parametric Oscillators.....	102
2.9.1	Influence of Cavity Mode Structure on OPO Tuning	105
2.10	Nonlinear Optical Interactions with Focused Gaussian Beams	109
2.10.1	Paraxial Wave Equation.....	109
2.10.2	Gaussian Beams.....	110

2.10.3	Harmonic Generation Using Focused Gaussian Beams	112
2.11	Nonlinear Optics at an Interface	116
2.12	Advanced Phase Matching Methods	121
	Problems	130
	References	134
Chapter 3: Quantum-Mechanical Theory of the Nonlinear Optical Susceptibility ..		137
3.1	Introduction	137
3.2	Schrödinger Equation Calculation of the Nonlinear Optical Susceptibility .	138
3.2.1	Energy Eigenstates	139
3.2.2	Perturbation Solution to Schrödinger's Equation	140
3.2.3	Linear Susceptibility	142
3.2.4	Second-Order Susceptibility	144
3.2.5	Third-Order Susceptibility	146
3.2.6	Third-Harmonic Generation in Alkali Metal Vapors	148
3.3	Density Matrix Formulation of Quantum Mechanics	151
3.3.1	Example: Two-Level Atom	158
3.4	Perturbation Solution of the Density Matrix Equation of Motion	159
3.5	Density Matrix Calculation of the Linear Susceptibility	161
3.5.1	Linear Response Theory	164
3.6	Density Matrix Calculation of the Second-Order Susceptibility	169
3.6.1	$\chi^{(2)}$ in the Limit of Nonresonant Excitation	178
3.7	Density Matrix Calculation of the Third-Order Susceptibility	179
3.8	Electromagnetically Induced Transparency	184
3.9	Local-Field Effects in the Nonlinear Optics	192
3.9.1	Local-Field Effects in Linear Optics	192
3.9.2	Local-Field Effects in Nonlinear Optics	194
	Problems	198
	References	201
Chapter 4: The Intensity-Dependent Refractive Index		203
4.1	Descriptions of the Intensity-Dependent Refractive Index	203
4.2	Tensor Nature of the Third-Order Susceptibility	209
4.2.1	Propagation through Isotropic Nonlinear Media	213
4.3	Nonresonant Electronic Nonlinearities	217
4.3.1	Classical, Anharmonic Oscillator Model of Electronic Nonlinearities .	218
4.3.2	Quantum-Mechanical Model of Nonresonant Electronic Nonlinearities	218
4.3.3	$\chi^{(3)}$ in the Low-Frequency Limit	222
4.4	Nonlinearities Due to Molecular Orientation	223
4.4.1	Tensor Properties of $\chi^{(3)}$ for the Molecular Orientation Effect	229

Contents

4.5	Thermal Nonlinear Optical Effects	231
4.5.1	Thermal Nonlinearities with Continuous-Wave Laser Beams	233
4.5.2	Thermal Nonlinearities with Pulsed Laser Beams.....	234
4.6	Semiconductor Nonlinearities	235
4.6.1	Nonlinearities Resulting from Band-to-Band Transitions.....	235
4.6.2	Nonlinearities Involving Virtual Transitions.....	241
4.7	Concluding Remarks	243
	Problems	245
	References	247
Chapter 5: Molecular Origin of the Nonlinear Optical Response		249
5.1	Nonlinear Susceptibilities Calculated Using Time-Independent Perturbation Theory	249
5.1.1	Hydrogen Atom	250
5.1.2	General Expression for the Nonlinear Susceptibility in the Quasi-Static Limit	251
5.2	Semiempirical Models of the Nonlinear Optical Susceptibility	255
	Model of Boling, Glass, and Owyong.....	256
5.3	Nonlinear Optical Properties of Conjugated Polymers.....	257
5.4	Bond-Charge Model of Nonlinear Optical Properties	259
5.5	Nonlinear Optics of Chiral Media	264
5.6	Nonlinear Optics of Liquid Crystals	266
	Problems	269
	References	269
Chapter 6: Nonlinear Optics in the Two-Level Approximation.....		273
6.1	Introduction	273
6.2	Density Matrix Equations of Motion for a Two-Level Atom	274
6.2.1	Closed Two-Level Atom.....	276
6.2.2	Open Two-Level Atom	279
6.2.3	Two-Level Atom with a Non-Radiatively Coupled Third Level.....	279
6.3	Steady-State Response of a Two-Level Atom to a Monochromatic Field ...	280
6.4	Optical Bloch Equations	288
6.4.1	Harmonic Oscillator Form of the Density Matrix Equations	291
6.4.2	Adiabatic-Following Limit	293
6.5	Rabi Oscillations and Dressed Atomic States	295
6.5.1	Rabi Solution of the Schrödinger Equation	296
6.5.2	Solution for an Atom Initially in the Ground State.....	298
6.5.3	Dressed States	302
6.5.4	Inclusion of Relaxation Phenomena	305

6.6	Optical Wave Mixing in Two-Level Systems	307
6.6.1	Solution of the Density Matrix Equations for a Two-Level Atom in the Presence of Pump and Probe Fields	308
6.6.2	Nonlinear Susceptibility and Coupled-Amplitude Equations	315
	Problems	319
	References	320
Chapter 7: Processes Resulting from the Intensity-Dependent Refractive Index		321
7.1	Self-Focusing of Light and Other Self-Action Effects	321
7.1.1	Self-Trapping of Light	324
7.1.2	Mathematical Description of Self-Action Effects	327
7.1.3	Laser Beam Breakup into Many Filaments	328
7.1.4	Self-Action Effects with Pulsed Laser Beams	333
7.2	Optical Phase Conjugation.....	334
7.2.1	Aberration Correction by Phase Conjugation.....	336
7.2.2	Phase Conjugation by Degenerate Four-Wave Mixing.....	338
7.2.3	Polarization Properties of Phase Conjugation	345
7.3	Optical Bistability and Optical Switching	349
7.3.1	Absorptive Bistability.....	351
7.3.2	Refractive Bistability	354
7.3.3	Optical Switching	356
7.4	Two-Beam Coupling	359
7.5	Pulse Propagation and Temporal Solitons	365
7.5.1	Self-Phase Modulation.....	365
7.5.2	Pulse Propagation Equation	368
7.5.3	Temporal Optical Solitons	372
	Problems	374
	References	379
Chapter 8: Spontaneous Light Scattering and Acoustooptics		381
8.1	Features of Spontaneous Light Scattering	381
8.1.1	Fluctuations as the Origin of Light Scattering.....	382
8.1.2	Scattering Coefficient	384
8.1.3	Scattering Cross Section.....	385
8.2	Microscopic Theory of Light Scattering	386
8.3	Thermodynamic Theory of Scalar Light Scattering	392
8.3.1	Ideal Gas.....	394
8.3.2	Spectrum of the Scattered Light.....	395
8.3.3	Brillouin Scattering	395
8.3.4	Stokes Scattering (First Term in Eq. (8.3.36))	398

8.3.5	Anti-Stokes Scattering (Second Term in Eq. (8.3.36))	400
8.3.6	Rayleigh Center Scattering	402
8.4	Acoustooptics	403
8.4.1	Bragg Scattering of Light by Sound Waves	403
8.4.2	Raman–Nath Effect	412
	Problems	416
	References	417
Chapter 9: Stimulated Brillouin and Stimulated Rayleigh Scattering		419
9.1	Stimulated Scattering Processes	419
9.2	Electrostriction	421
9.3	Stimulated Brillouin Scattering (Induced by Electrostriction)	425
9.3.1	Pump Depletion Effects in SBS	431
9.3.2	SBS Generator	433
9.3.3	Transient and Dynamical Features of SBS	436
9.4	Phase Conjugation by Stimulated Brillouin Scattering	437
9.5	Stimulated Brillouin Scattering in Gases	441
9.6	General Theory of Stimulated Brillouin and Stimulated Rayleigh Scattering	443
9.6.1	Appendix: Definition of the Viscosity Coefficients	454
	Problems	456
	References	457
Chapter 10: Stimulated Raman Scattering and Stimulated Rayleigh-Wing Scattering		459
10.1	The Spontaneous Raman Effect	459
10.2	Spontaneous versus Stimulated Raman Scattering	460
10.3	Stimulated Raman Scattering Described by the Nonlinear Polarization	465
10.4	Stokes–Anti-Stokes Coupling in Stimulated Raman Scattering	474
10.4.1	Dispersionless, Nonlinear Medium without Gain or Loss	478
10.4.2	Medium without a Nonlinearity	479
10.4.3	Stokes–Anti-Stokes Coupling in Stimulated Raman Scattering	480
10.5	Coherent Anti-Stokes Raman Scattering	483
10.6	Stimulated Rayleigh-Wing Scattering	486
10.6.1	Polarization Properties of Stimulated Rayleigh-Wing Scattering	490
	Problems	492
	References	492
Chapter 11: The Electrooptic and Photorefractive Effects		495
11.1	Introduction to the Electrooptic Effect	495
11.2	Linear Electrooptic Effect	496
11.3	Electrooptic Modulators	500

11.4	Introduction to the Photorefractive Effect.....	507
11.5	Photorefractive Equations of Kukhtarev et al.	508
11.6	Two-Beam Coupling in Photorefractive Materials	511
11.7	Four-Wave Mixing in Photorefractive Materials	518
11.7.1	Externally Self-Pumped Phase-Conjugate Mirror	519
11.7.2	Internally Self-Pumped Phase-Conjugate Mirror.....	519
11.7.3	Double Phase-Conjugate Mirror	520
11.7.4	Other Applications of Photorefractive Nonlinear Optics.....	521
	Problems	521
	References	521
Chapter 12: Optically Induced Damage and Multiphoton Absorption		523
12.1	Introduction to Optical Damage	523
12.2	Avalanche-Breakdown Model	524
12.3	Influence of Laser Pulse Duration	526
12.4	Direct Photoionization	528
12.5	Multiphoton Absorption and Multiphoton Ionization	528
12.5.1	Theory of Single- and Multiphoton Absorption and Fermi's Golden Rule	530
12.5.2	Linear (One-Photon) Absorption	532
12.5.3	Two-Photon Absorption	535
12.5.4	Multiphoton Absorption	538
	Problems	538
	References	538
Chapter 13: Ultrafast and Intense-Field Nonlinear Optics		541
13.1	Introduction	541
13.2	Ultrashort-Pulse Propagation Equation	541
13.3	Interpretation of the Ultrashort-Pulse Propagation Equation	547
13.3.1	Self-Steepening	548
13.3.2	Space-Time Coupling	550
13.3.3	Supercontinuum Generation	551
13.4	Intense-Field Nonlinear Optics	552
13.5	Motion of a Free Electron in a Laser Field	553
13.6	High-Harmonic Generation.....	555
13.7	Tunnel Ionization and the Keldysh Model	559
13.8	Nonlinear Optics of Plasmas and Relativistic Nonlinear Optics	560
13.9	Nonlinear Quantum Electrodynamics	565
	Problem	567
	References	567

Chapter 14: Nonlinear Optics of Plasmonic Systems	569
14.1 Introduction to Plasmonics	569
14.2 Simple Derivation of the Plasma Frequency	569
14.3 The Drude Model	571
14.4 Optical Properties of Gold	574
14.5 Surface Plasmon Polaritons	576
14.6 Electric Field Enhancement in Plasmonic Systems	579
Problems	581
References	581
Appendices	583
Appendix A The SI System of Units	583
A.1 Energy Relations and Poynting's Theorem	586
A.2 The Wave Equation	586
A.3 Boundary Conditions	588
Appendix B The Gaussian System of Units	590
Appendix C Systems of Units in Nonlinear Optics	594
C.1 Conversion between the Systems	595
Appendix D Relationship between Intensity and Field Strength	596
Appendix E Physical Constants	597
References	599
Index	601