CONTENTS

Introduction to the Nonineer Susceptibility.

Friedive Norlingants and d.

Preface to the First Edition Preface to the Second Edition Authors

xv xvii xix

5

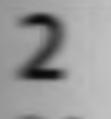
7

1 Introduction

- 1.1 Historical Background
- 1.2 Unifying Themes
- 3 Overview of Nonlinear Effects Covered in This Book

ter information of the state of

1.4 Labeling Conventions and Terminology
 1.5 Units
 Problems
 Peferences
 Further Reading

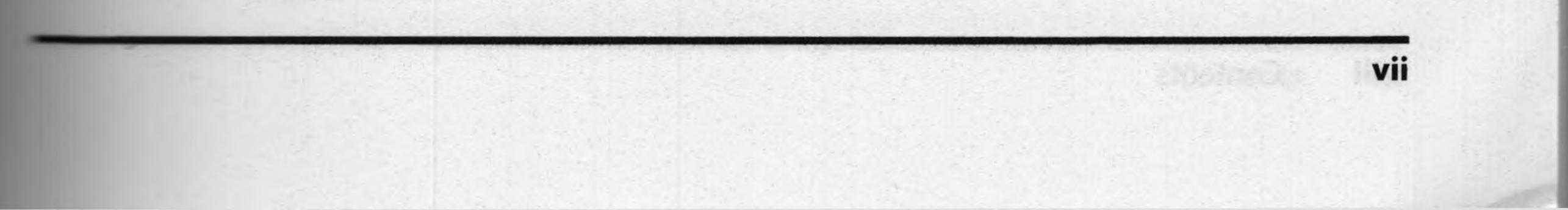


Linear Optics

- 1 Introduction
 - 2.1.1 Linearity
 - 2.1.2 Maxwell's Equations
 - 2.1.3 Poynting's Theorem
 - 2.1.4 Intensity
 - 2.1.5 Linear Polarization
 - 2.1.6 Complex Representation of Polarization
 - 2.1.7 Energy Exchange between a Field and Polarization

192

22	Tenso	r Properties of Materials	25
	2.2.1	Tensors	26
23	Wave	Equation	28
	2.3.1	Constitutive Relationships for Complex Amplitudes	29
	2.3.2	Wave Equation in Homogeneous Isotropic Materials	30
	2.3.3	Dispersion	32
	2.3.4	Wave Equation in Crystals	34
	2.3.5	Fresnel's Equation	37
	2.3.6	o-Waves and e-Waves	37
	2.3.7	Poynting Vector Walk-Off	39
	Deter	mining e-Waves and o-Waves in Crystals	41
	2.4.1	Homogeneous Isotropic	41
	2.4.2	Uniaxial Crystal	41
	2.4.3	Biaxial Crystals	42
	Index	Ellipsoid	43



85

95

97

99

101

102

103

107

110

116

116

119

119

120

122

Applications 2.6

- Slowly Varying Envelope Approximation and Gaussian Beams 2.6.1
- Gaussian Beam Propagation Using the q-Parameter 2.6.2
- M² Propagation Factor 2.6.3
- Example of Formatting a Beam for SHG 2.6.4

Problems

References

Further Reading

- Introduction to the Nonlinear Susceptibility 3
- Introduction 3.1
 - Nonlinear Polarization 3.1.1
 - 3.1.2 Parametric Processes
- Classical Origin of the Nonlinearity 3.2
 - **One-Dimensional Linear Harmonic Oscillator** 3.2.1
 - **One-Dimensional Anharmonic Oscillator** 3.2.2
 - Third-Order Effects in Centrosymmetric Media 3.2.3
- 3.3 Details of the Nonlinear Susceptibility, $\chi^{(2)}$
 - Degeneracy and Subtleties of Squaring the Field 3.3.1
 - **Tensor Properties of Susceptibility** 3.3.2
 - Permuting the Electric Fields in the Nonlinear Polarization 3.3.3
 - Full Permutation Symmetry in Lossless Media 3.3.4
 - Kleinman's Symmetry 3.3.5
 - Contracting the Indices in $\chi_{iik}^{(2)}$ 3.3.6
 - Effective Nonlinearity and deff 3.3.7
 - Example Calculation of deff 3.3.8
- Connection between Crystal Symmetry and the d-Matrix 3.4 Centrosymmetric Crystals 3.4.1

 - Example Calculation of *d*-Matrix for 3m Crystals 3.4.2
- **Electro-Optic Effect** 3.5
 - EO Effects and the r-Matrix 3.5.1
 - Example Calculation of EO Effect in KH₂DPO₄ 3.5.2
 - **EO Wave Plates** 3.5.3
 - EO Sampling: Terahertz Detection 3.5.4
 - Connection between d and r 3.5.5
- Problems References
- Further Reading

Three-Wave Processes in the Small-Signal Regime 4

Introduction to the Wave Equation for Three Fields 4.1 Wave Equation for a Three-Wave Process 4.1.1 Slowly Varying Envelope Approximation Extended 4.1.2



	4.1.3	Introduction to Phase Matching	124
	4.1.4	First Solution to the Coupled Amplitude Equations	125
	4.1.5	k-Vector Picture	129
4.2	Birefri	ingent Phase Matching	130
	4.2.1	Birefringent Phase-Matching Types	130
	4.2.2	Example: Phase-Matching Problem	200 vol 133
	4.2.3	Phase-Matching SHG	136
4.3	Tunin	g Curves and Phase-Matching Tolerances	137
	4.3.1	Phase-Matching Bandwidth and Angular Acceptance	139
4.4	Taylor	Series Expansion Techniques for Determining Bandwidth	141
	4.4.1	Temperature Bandwidth	143
	4.4.2	Phase-Matching Bandwidth and Acceptance Bandwidth	144

Angular Acceptance and Noncritical Phase Matching 146 4.4.3 147 Noncollinear Phase Matching Optical Parameters OptioO 4.5 148 **Off-Axis Propagation SVEA Equations** 4.5.1 CHROMENTER CHIEFERING 150 Noncollinear Application 4.5.2 Doubly Research OPOs 152 Problems 12090 Incourse I vinnik 160 Feference Further Reading 160 161 **Quasi-Phase Matching** Introduction to Quasi-Phase Matching 161 5.1 Linear and Nonlinear Material Considerations 161 5.2 164 **QPM** with Periodic Structures 53 **QPM** Calculation: An Example 167 5.4 168 Fourier Transform Treatment of QPM 5.5 5.6 Tolerances

- Fabricating Quasi-Phase-Matched Structures 57 Problems
- Feference
- Further Reading

172
173
176
181
181
183
183
183
184
185

186

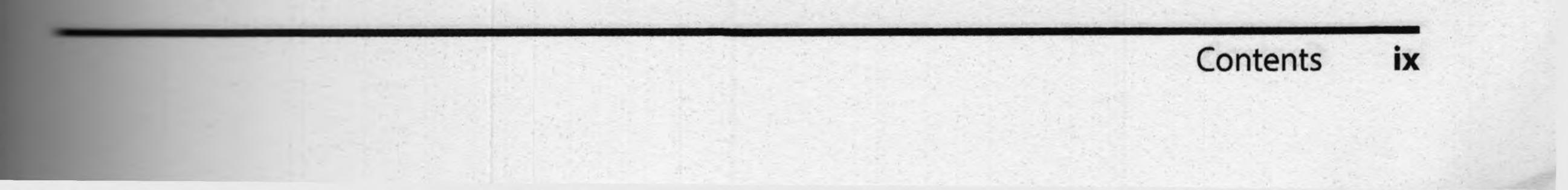
189

193

193

195

5	Three	-Wave Mixing beyond the Small-Signal Limit
	Introd	luction
12	DFG v	vith a Single Strong Pump
	6.2.1	Defining Equations for the Undepleted Pump Approximation
	6.2.2	Solution for Difference-Frequency Output
	6.2.3	Solution with Specific Boundary Conditions
	DFG v	vith Strong Pump and Loss
	Soluti	ons for All Three Coupled Amplitude Equations
	6.4.1	Manley–Rowe Relations
	647	Analytic Solution for Three Plane Waves



6.5 Spontaneous Parametric Scattering (Optical Parametric Generation)
 Problems
 References
 Further Reading

Ball the Statistic testing and the Statistics

medicine only and the stander all ma

Chief and the second second

150 DITORIA SCALEBOR

edit bring being and the

SUDER STRUCTURE TRUCKE-FREGUE

And Sold Drive sold the Light of the

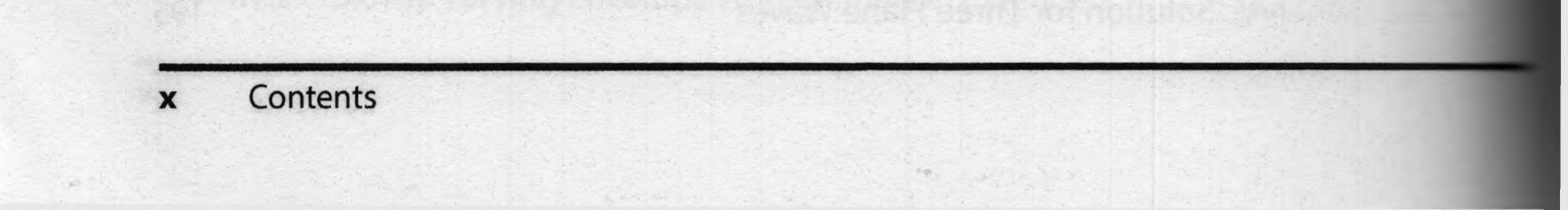
7 $\chi^{(2)}$ Devices

- 7.1 Introduction
- 7.2 Optimizing Device Performance: Focusing
 - 7.2.1 Overlap of Gaussian Beams with Nonlinear Polarization
 - 7.2.2 Parametric Interactions with Focused Gaussian Beams
 - 7.2.3 Optimizing Gaussian Beam Interactions
- 7.3 Resonator Devices
 - 7.3.1 Resonant SHG
 - 7.3.2 Optical Parametric Oscillator
 - 7.3.3 OPO with Gaussian Beams
 - 7.3.4 Doubly Resonant OPOs
 - 7.3.5 Singly Resonant OPOs
 - 7.3.6 Cavity Design
 - 7.3.7 Pulsed OPOs
 - 7.3.8 Backward OPOs

Problems References Further Reading

8 χ⁽³⁾ Processes

- 8.1 Introduction
- 8.2 Nonlinear Polarization for $\chi^{(3)}$ Processes
 - 8.2.1 Defining Relationships
 - 8.2.2 Permutation Symmetries for $\chi^{(3)}$
 - 8.2.3 Symmetry Considerations for Centrosymmetric Media
- 8.3 Wave Equation for $\chi^{(3)}$ Interactions
 - 8.3.1 Four Distinct Frequencies
 - 8.3.2 Manley–Rowe Relations
- 8.4 Self-Induced Effects
 - 8.4.1 Nonlinear Index of Refraction
 - 8.4.2 Nonlinear Absorption
 - 8.4.3 Cross-Phase Shifts
 - 8.4.4 Self-Focusing
 - 8.4.5 Optical Bistability
- 8.5 Parametric Amplifiers
 - 8.5.1 Introduction
 - 8.5.2 Two Undepleted Inputs



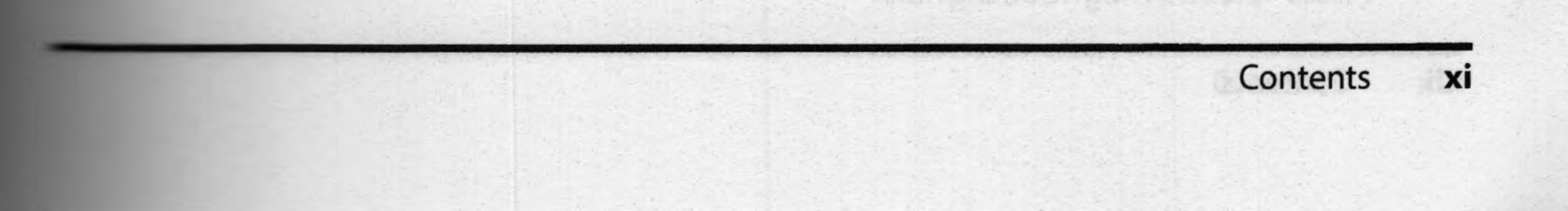
	8.5.3	One Undepleted Input	266
	8.5.4	Pump Depletion	267
8.6	Nonco	ollinear Processes	268
8.7	Deger	nerate Four-Wave Mixing	270
	8.7.1	Introduction	270
	8.7.2	Pump Phase Shifts	271
	8.7.3	Probe and Signal Fields	272
	8.7.4	Optical-Phase Conjugation	275
8.8	z-SCA	N	277
	8.8.1	Introduction	277
	8.8.2	Measuring the Nonlinear Index of Refraction	278
	8.8.3	Nonlinear Absorption	283

285

290 290

Pho	bl	en	ns			
Te	fer	en	ce			
	rth	er	Re	adi	ing	

9	Raman and Brillouin Scattering	291
	Introduction	291
92	Spontaneous Raman Scattering	292
	9.2.1 Classical Model of Spontaneous Raman Scattering	293
	9.2.2 Raman Scattering Cross Section	295
	9.2.3 Raman Microscope	298
	Stimulated Raman Scattering	299
	9.3.1 Introduction	299
	9.3.2 Classical Calculation for Inducing a Molecular Vibration	299
	9.3.3 Nonlinear Polarization for a Stimulated Raman Process	302
	9.3.4 Wave Equation for the Stokes Field	304
	9.3.5 Amplification of the Stokes Field Off Resonance	305
	9.3.6 Stokes Amplification with a Depleted Pump	306
	Anti-Stokes Generation	310
	9.4.1 Classical Derivation of the Anti-Stokes Nonlinear Polarizati	on 310
	9.4.2 Wave Equation for Stokes and Anti-Stokes in the Undeplet	ed
	Pump Approximation	312
	9.4.3 Stokes and Anti-Stokes Generation with Pump Depletion	314
	Faman Amplifiers	316
	Photoacoustic Effects: Raman-Nath Diffraction	317
	Erilouin Scattering	321
	97.1 Spontaneous Brillouin Scattering	321
	E72 Classical Model for the Stimulated Brillouin Scattering	323
	 Nonlinear Polarization for the Stimulated Brillouin Scatterin Coupled Intensity Equations and Solutions for the 	ng 325
	Stimulated Brillouin Scattering	327



Brillouin with Linear Absorption 9.7.5 Mitigating Brillouin Effects 9.7.6 Problems References

10 Nonlinear Optics Including Diffraction and Dispersion

329

331

331

335

337

337

338

338

341

345

347

348

348

350

352

353

357

358

360

361

363

364

365

367

369

371

372

374

376

379

379

381

381

384

384

389

391

393

395

396

10.1 Introduction

10.2 Spatial Effects

10.2.1 Diffraction and the Poynting Vector Walk-Off

10.2.2 Split-Step Technique

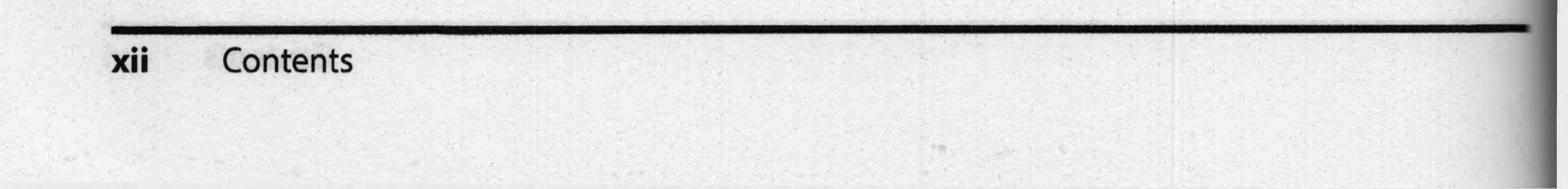
10.2.3 Linear Propagation: Beam Propagation Method

10.2.4 Nonlinear Propagation for Three-Wave Mixing 10.3 Temporal Effects 10.3.1 Time-Dependent Field Definitions 10.3.2 Time-Dependent Linear Polarization 10.3.3 Time-Dependent Nonlinear Polarization 10.3.4 Wave Equation for Fields with a Time-Dependent Envelope 10.4 Dynamical Solutions to the Nonlinear Envelope Equation 10.4.1 Self-Phase Modulation 10.4.2 Numerical Solutions with Pulses 10.4.2.1 Dispersion Step 10.4.2.2 Nonlinear Step 10.4.3 Nonlinear Schrodinger Equation 10.4.4 Modulation Instability 10.4.5 Fundamental Soliton Solution 10.4.6 Spatial Solitons 10.4.7 Dark and Gray Solitons 10.5 Dynamical Stimulated Raman Scattering 10.5.1 Dynamical SRS Equations Solution Problems References Further Reading

Quantum Nonlinear Optics

- 11.1 Introduction
- 11.2 Quantizing Equations of Motion
 - 11.2.1 Classical to Quantum Equations of Motion
 - 11.2.2 Heisenberg Uncertainty Relations
- 11.3 Electromagnetic Field
 - 11.3.1 Coherent State Representation
 - 11.3.2 Electromagnetic Wave Function
 - 11.3.3 Electromagnetic Signals





11.4 Quantum Amplifiers and Attenuators	397
11.4.1 Quantum Attenuator Model	397
11.4.2 Quantum Amplifier Model	402
11.4.3 Quantum Initiation: Optical Parametric Generator	403
11.4.4 Schrödinger's Cat States	405
11.5 Quantum Detection	405
11.5.1 Direct Detection	405
11.5.2 Coherent Detection	407
11.5.2.1 Beam Splitter	407
11.5.2.2 Coherent Detection Signal to Noise	409
11.5.2.3 Balanced Homodyne Detection	409
11.6 Quantum Squeezed Light	411
11.6.1 Single-Mode Squeezed States	411
11.6.2 Squeezed Light Experiments	414
11.7 Multimode Quantum States	416
11.7.1 Entangled Quantum States	416
11.7.2 Entanglement via SPDC	418
11.7.2.1 Type I Phase Matching	420
11.7.2.2 Type II Phase Matching	422
11.7.3 Two-Mode Parametric Squeezing	424
11.7.4 Quantum Optical Phase Conjugation	425
11.7.5 HOM Interferometer	427
Problems	431
Feferences	436
Books	436
Selected Articles	436
Amplifiers and Attenuators	437
Sourcezed Light	437

437

439

443

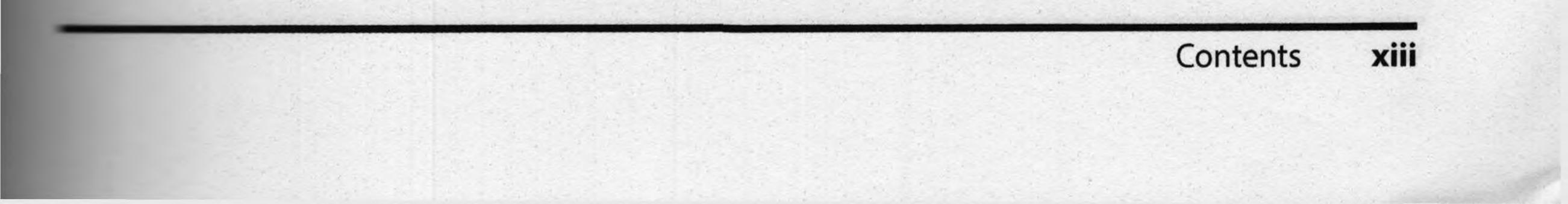
451

457

465

469

Squeezed Light PR and Tests of Quantum Mechanics Appendix A: Complex Notation Appendix B: Sellmeier Equations Appendix C: Programming Techniques Appendix D: Exact Solutions to the Coupled Amplitude Equations Appendix E: Optical Fibers—Slowly Varying Envelope Equations Index



and should be the space dence of plotting and should be able to

asset that to a slogic mothematical backage, testent, it grees general alec-

the second ble to the scientific graphical and programming out hag

a find the product of the control of the cost of chapter, here here all all all all and the