CONTENTS

2.4 Solid-State Laser Mode-Locking Using the Optical Kerr Effect, 57
  2.4.1 Nonlinear Refractive Index Changes, 57
  2.4.2 Self-Amplitude Modulation, Self-Phase Modulation, and Group Velocity Dispersion, 58
  2.4.3 Additive Pulse Mode-Locking, 60
  2.4.4 Kerr Lens Mode-Locking, 64
  2.4.5 Mode-Locking Solutions, 75
  2.4.6 Initiation of Mode-Locking, 81

Problems, 83

3 Ultrafast-pulse Measurement Methods 85
  3.1 Terminology and Definitions, 85
  3.2 Electric Field Autocorrelation Measurements and the Power Spectrum, 88
  3.3 Electric Field Cross-Correlation Measurements and Spectral Interferometry, 91
    3.3.1 Electric Field Cross-Correlation, 92
    3.3.2 Spectral Interferometry, 93
    3.3.3 Application: Optical Coherence Tomography, 96
  3.4 Intensity Correlation Measurements, 99
    3.4.1 Correlation Measurements Using Second-Harmonic Generation, 99
    3.4.2 Experimental Procedures, 108
    3.4.3 Correlation Measurements Using Two-Photon absorption, 110
    3.4.4 Higher-Order Correlation Techniques, 111
  3.5 Chirped Pulses and Measurements in the Time–Frequency Domain, 112
  3.6 Frequency-Resolved Optical Gating, 118
    3.6.1 Polarization-Gating FROG, 119
    3.6.2 Self-Diffraction FROG, 122
    3.6.3 Second-Harmonic-Generation FROG, 124
    3.6.4 Frequency-Resolved Optical Gating Using Temporal Phase Modulation, 125
    3.6.5 Signal Recovery from FROG Traces, 126
  3.7 Pulse Measurements Based on Frequency Filtering, 130
    3.7.1 Single-Slit Approaches, 131
    3.7.2 Double-Slit Approach, 134
  3.8 Self-Referencing Interferometry, 135
    3.8.1 Time-Domain Interferometry of Chirped Pulses, 135
    3.8.2 Self-Referencing Spectral Interferometry, 137
  3.9 Characterization of Noise and Jitter, 139

Problems, 144

4 Dispersion and Dispersion Compensation 147
  4.1 Group Velocity Dispersion, 147
    4.1.1 Group Velocity Definition and General Dispersion Relations, 147
    4.1.2 General Aspects of Material Dispersion, 151
  4.2 Temporal Dispersion Based on Angular Dispersion, 155
    4.2.1 Relation Between Angular and Temporal Dispersion, 155
    4.2.2 Angular Dispersion and Tilted Intensity Fronts, 159
  4.3 Dispersion of Grating Pairs, 161
4.4 Dispersion of Prism Pairs, 166
4.5 Dispersive Properties of Lenses, 173
4.6 Dispersion of Mirror Structures, 177
  4.6.1 The Gires–Tournois Interferometer, 178
  4.6.2 Quarter-Wave Stack High Reflectors, 180
  4.6.3 Chirped Mirrors, 182
4.7 Measurements of Group Velocity Dispersion, 186
  4.7.1 Interferometric Methods, 187
  4.7.2 Frequency-Domain Intracavity Dispersion Measurements, 190
4.8 Appendix, 191
  4.8.1 Frequency-Dependent Phase Due to Propagation Through a Slab: Alternative Derivation, 191
  4.8.2 Impedance Method for Analysis of Dielectric Mirror Stacks, 192
4.8 Problems, 195

5 Ultrafast Nonlinear Optics: Second Order 198
5.1 Introduction to Nonlinear Optics, 198
5.2 The Forced Wave Equation, 201
  5.2.1 Frequency-Domain Formulation, 202
  5.2.2 Time-Domain Formulation, 203
5.3 Summary of Continuous-Wave Second-Harmonic Generation, 204
  5.3.1 Effect of Phase Matching, 207
  5.3.2 Phase Matching in Birefringent Media, 209
  5.3.3 Focusing Effects in Continuous-Wave SHG, 215
5.4 Second-Harmonic Generation with Pulses, 220
  5.4.1 SHG in the Quasi-Continuous-Wave Limit, 220
  5.4.2 Ultrashort-Pulse SHG, 221
  5.4.3 Quasi-Phase Matching, 228
  5.4.4 Effect of Group Velocity Walk-off on SHG-Based Pulse Measurements, 233
5.5 Three-Wave Interactions, 237
  5.5.1 Sum Frequency Generation, 240
  5.5.2 Difference Frequency Generation, 244
  5.5.3 Optical Parametric Amplification, 245
5.6 Appendix, 253
  5.6.1 Spatial Walk-off and Pulse Fronts in Anisotropic Media, 253
  5.6.2 Velocity Matching in Broadband Noncollinear Three-Wave Mixing, 254
5.6 Problems, 256

6 Ultrafast Nonlinear Optics: Third Order 258
6.1 Propagation Equation for Nonlinear Refractive Index Media, 258
  6.1.1 Plane Waves in Uniform Media, 260
  6.1.2 Nonlinear Propagation in Waveguides, 261
  6.1.3 Optical Fiber Types, 264
6.2 The Nonlinear Schrödinger Equation, 266
6.3 Self-Phase Modulation, 270
  6.3.1 Dispersionless Self-Phase Modulation, 270
  6.3.2 Dispersionless Self-Phase Modulation with Loss, 273
CONTENTS

6.3.3 Self-Phase Modulation with Normal Dispersion, 274
6.3.4 Cross-Phase Modulation, 275
6.4 Pulse Compression, 276
6.5 Modulational Instability, 283
6.6 Solitons, 286
6.7 Higher-Order Propagation Effects, 291
   6.7.1 Nonlinear Envelope Equation in Uniform Media, 292
   6.7.2 Nonlinear Envelope Equation in Waveguides, 295
   6.7.3 Delayed Nonlinear Response and the Raman Effect, 296
   6.7.4 Self-Steepening, 306
   6.7.5 Space–Time Focusing, 308
6.8 Continuum Generation, 310
Problems, 313

7 Mode-Locking: Selected Advanced Topics 316

7.1 Soliton Fiber Lasers: Artificial Fast Saturable Absorbers, 316
   7.1.1 The Figure-Eight Laser, 317
   7.1.2 Energy Quantization, 322
   7.1.3 Soliton Sidebands, 324
7.2 Soliton Mode-Locking: Active Modulation and Slow Saturable Absorbers, 328
   7.2.1 Harmonically Mode-Locked Soliton Fiber Lasers, 328
   7.2.2 The Net Gain Window in Soliton Mode-Locking, 330
7.3 Stretched Pulse Mode-Locking, 337
   7.3.1 Stretched Pulse Mode-Locked Fiber Laser, 337
   7.3.2 Dispersion-Managed Solitons, 340
   7.3.3 Theoretical Issues, 342
7.4 Mode-Locked Lasers in the Few-Cycle Regime, 344
7.5 Mode-Locked Frequency Combs, 347
   7.5.1 Comb Basics, 347
   7.5.2 Measurement Techniques, 350
   7.5.3 Stabilization of Frequency Combs, 354
   7.5.4 Applications, 356
Problems, 360

8 Manipulation of Ultrashort Pulses 362

8.1 Fourier Transform Pulse Shaping, 362
   8.1.1 Examples of Pulse Shaping Using Fixed Masks, 364
   8.1.2 Programmable Pulse Shaping, 369
   8.1.3 Pulse-Shaping Theory, 376
8.2 Other Pulse-Shaping Techniques, 386
   8.2.1 Direct Space–Time Pulse Shaping, 386
   8.2.2 Acousto-optic Dispersive Filters, 390
8.3 Chirp Processing and Time Lenses, 394
   8.3.1 Space–Time Duality, 394
   8.3.2 Chirp Processing, 397
   8.3.3 Time Lens Processing, 399
CONTENTS xi

8.4 Ultrashort-Pulse Amplification, 405
  8.4.1 Amplification Basics, 406
  8.4.2 Special Issues in Femtosecond Amplifiers, 411
8.5 Appendix, 416
  8.5.1 Fresnel Diffraction and Fourier Transform Property of a Lens, 416
  8.5.2 Wave Optics Model of a Grating, 418
Problems, 420

9 Ultrafast Time-Resolved Spectroscopy 422
  9.1 Introduction to Ultrafast Spectroscopy, 422
  9.2 Degenerate Pump–Probe Transmission Measurements, 426
    9.2.1 Co-polarized Fields: Scalar Treatment, 426
    9.2.2 Vector Fields and Orientational Effects, 431
  9.3 Nondegenerate and Spectrally Resolved Pump–Probe: Case Studies, 439
    9.3.1 Femtosecond Pump–Probe Studies of Dye Molecules, 440
    9.3.2 Femtosecond Pump–Probe Studies of GaAs, 444
  9.4 Basic Quantum Mechanics for Coherent Short-Pulse Spectroscopies, 451
    9.4.1 Some Basic Quantum Mechanics, 451
    9.4.2 The Density Matrix, 456
  9.5 Wave Packets, 460
    9.5.1 Example: Semiconductor Quantum Wells, 461
    9.5.2 Molecules, 462
  9.6 Dephasing Phenomena, 469
    9.6.1 Linear Spectroscopies, 469
    9.6.2 Models of Dephasing, 475
    9.6.3 Measurement of Dephasing Using Transient Gratings, 481
    9.6.4 Two-Dimensional Spectroscopy, 494
  9.7 Impulsive Stimulated Raman Scattering, 499
Problems, 505

10 Terahertz Time-Domain Electromagnetics 507
  10.1 Ultrafast Electromagnetics: Transmission Lines, 507
    10.1.1 Photoconductive Generation and Sampling, 507
    10.1.2 Electro-optic Sampling, 513
  10.2 Ultrafast Electromagnetics: Terahertz Beams, 516
    10.2.1 Generation and Measurement of Terahertz Pulses, 517
    10.2.2 Terahertz Spectroscopy and Imaging, 527
Problems, 531

References 533

Index 563