Contents

Pref Aut	face hor			xxv xxvii			
1	0			a Dulaca			
1	Quest	ι τοι Απο	for Attosecond Optical Pulses 1				
	1.1	Ultrafast Optics 1					
		1.1.1	High-Power 1.1.1.1 1.1.1.2 1.1.1.3 1.1.1.4 1.1.1.5 1.1.1.6 1.1.1.7	Applications 1 Power, Peak Power, and Pulse Duration 1 Pulse Energy 2 Fluence 2 High-Power Lasers 2 Average Power and Repetition Rate 3 Intensity and Field Amplitude of CW Light 3 Peak Intensity and Beam Size 4			
			1.1.1.8 1.1.1.9 1.1.1.10	Gaussian Beams and Gaussian Pulses 5 Atomic Units 5 Nonlinear Optics and Strong Field Physics 6			
		1.1.2	High-Speed 1.1.2.1 1.1.2.2 1.1.2.3	Imaging 7 Framing Camera 8 Streak Camera 9 Pump-Probe Technique 10			
		1.1.3	Timescale of 1.1.3.1	f Electron Dynamics: The New Frontier 11 Atomic Unit of Time 11			
	1.2	Attosecon	d Light Pulses	s 12			
		1.2.1 1.2.2	Mathematica 1.2.1.1 1.2.1.2 1.2.1.3 1.2.1.4 Propagation	al Description of Attosecond Optical Pulses 13 Time Domain 13 Temporal Phase and Chirp 14 Frequency Domain 15 Time-Bandwidth Product 16 of Attosecond Pulse in Linear Dispersive			
			Media 17 1.2.2.1 1.2.2.2 1.2.2.3 1.2.2.4 1.2.2.5 1.2.2.6 1.2.2.7 1.2.2.8	Index of Refraction and Scattering Factor 17 Photoabsorption Cross Section and Transmission 19 Gas Medium 19 Thin Film 19 Spectral Phase 20 Carrier-Envelope Phase 21 Group Velocity Dispersion and Group Delay Dispersion 22 Pulse Broadening and Compression 23			
			1.2.2.9	GVD of Filters 23			

1.3 Overview of Attosecond Pulse Generation 26

- 1.3.1 Pulse Compression by Perturbative Harmonic Generation 27
 - 1.3.2 High-Order Harmonic Generation 29
 - 1.3.2.1 Attosecond Pulse Train 29
 - 1.3.2.2 Three-Step Model 31
 - 1.3.2.3 Singe Isolated Attosecond Pulses 32
 - 1.3.3 Measurement of Attosecond Pulse Duration 34
 - 1.3.3.1 Response of the Gas Photocathode 34
 - 1.3.3.2 Momentum Streaking 34
 - 1.3.3.3 Time to Momentum Conversion 35
 - 1.3.3.4 Time Resolution 37
- 1.4 Properties of Attosecond XUV Pulses 38
 - 1.4.1 Pulse Energy 38
 - 1.4.2 Divergence Angle 39
 - 1.4.2.1 XUV Mirrors at Glancing Incidences 39
 - 1.4.2.2 Multilayer XUV Mirrors 40
 - 1.4.3 Challenges and Opportunities in Attosecond Optics 40

Problems 43

References 45

Review Articles 45

- Textbooks 45
- Ultrafast High-Power Laser 45
- Ultrafast Imaging 45
- Attosecond Pulse and High-Order Harmonic Generation 46
- Attosecond Streak Camera 46
 - XUV Filters and Attosecond Pulse Compression 46

2 Femtosecond Driving Lasers 47

- 2.1 Introduction 47
- 2.2 Laser Beam Propagation 49
 - 2.2.1 Gaussian Beam in Free Space 49
 - 2.2.2 Gaussian Beam Focusing 51
 - 2.2.3 Aberration of Focusing Mirrors 52
 - 2.2.4 Spherical Aberration of Focusing Lenses 53
 - 2.2.5 Nonlinear Medium 54
 - 2.2.5.1 Optical Kerr Effect 54
 - 2.2.5.2 *B* Integral 54
 - 2.2.5.3 Kerr Lens and Self Focusing 54
 - 2.2.5.4 Optical Damage 55
- 2.3 Laser Pulse Propagation 56
 - 2.3.1 Wavelength Bandwidth 56
 - 2.3.2 Propagation in Linear Dispersive Medium 56
 - 2.3.2.1 Sellmeier Equation 57
 - 2.3.2.2 Second-Order Approximation 58
 - 2.3.2.3 Group Velocity Dispersion 58
 - 2.3.2.4 High-Order Dispersions 59
- 2.4 Mirrors 59
 - 2.4.1 Metal Mirrors 60
 - 2.4.2 Dielectric Mirrors 60

- 2.4.2.1 High-Energy Mirrors 60
- 2.4.2.2 Broadband Mirrors 61
- 2.4.2.3 Broadband High-Energy Mirrors 61
- 2.4.3 Chirped Mirrors with Negative GDD 62
- 2.5 Prism Pairs 62
 - 2.5.1 Phase Delay 63
 - 2.5.2 Group Delay Dispersion 64
 - 2.5.3 Single Glass Slab 64
 - 2.5.4 Two Slabs and Prism Pairs 65
 - 2.5.5 Brewster's Angle Configuration 66
 - 2.5.6 Effects of the Second Prism 67
 - 2.5.7 Double Pass Configuration 67
- 2.6 Grating Pairs 68
 - 2.6.1 Phase Matching 69
 - 2.6.2 Phase 70
 - 2.6.3 Group Delay Dispersion 70
 - 2.6.4 Optical Pulse Compressor 70
 - 2.6.5 Optical Pulse Stretcher 71
- 2.7 Laser Pulse Propagation in Nonlinear Media 71
 - 2.7.1 Self-Phase Modulation 71
 - 2.7.2 Photonic Crystal Fiber 73
 - 2.7.2.1 Highly Nonlinear Fiber 73
 - 2.7.3 Hollow-Core Fibers 74
- 2.8 Femtosecond Oscillator 75
 - 2.8.1 Ti:Sapphire Crystals 76
 - 2.8.2 Principle of Mode Locking 76
 - 2.8.2.1 Longitudinal Modes 76
 - 2.8.2.2 Mode Locking 77
 - 2.8.2.3 Pulse Picker 77
 - 2.8.3 Kerr Lens Mode Locking 78
 - 2.8.3.1 Stability Range of a Laser Cavity 79
- 2.9 Chirped Pulse Amplifiers 79
 - 2.9.1 Configurations 79
 - 2.9.1.1 Multipass Amplifier 79
 - 2.9.1.2 Regenerative Amplifier 80
 - 2.9.2 Gain Narrowing 80
 - 2.9.2.1 Gain Cross Section 80
 - 2.9.2.2 Gain Narrowing 81
 - 2.9.2.3 Effects of the Seed Pulse Bandwidth 82
 - 2.9.3 Gain Narrowing Compensation 83
 - 2.9.3.1 Spectral Shaping 83
 - 2.9.3.2 Optical Parametric Chirped Pulse Amplification 84
- 2.10 Pulse Characterization 84
 - 2.10.1 FROG 84
 - 2.10.1.1 Autocorrelators 84
 - 2.10.1.2 FROG Trace 85
 - 2.10.1.3 Phase Retrieval 86
 - 2.10.1.4 Principal Component Generalized Projection
 - Algorithm 87

- 2.10.2 Multiphoton Intrapulse Interference Phase Scan 87
 - 2.10.2.1 Setup 88
 - 2.10.2.2 Principle 88
 - 2.10.2.3 Experimental Approach 89
 - 2.10.2.4 High-Order Phases 90
- 2.11 Few-Cycle Pulses 90
 - 2.11.1 Chirped Mirror Compressor 90
 - 2.11.2 Adaptive Phase Modulator 91
 - 2.11.2.1 Zero-Dispersion Stretcher 91
 - 2.11.2.2 Spatial Light Modulator 91
 - 2.11.2.3 MIIPS for Compressing Pulses from Hollow-Core Fibers 92
 - 2.11.2.4 White-Light Chirp Compensation 93
 - 2.11.2.5 FROG Measurements 94
- 2.12 Summary 95
- Problems 96

References 98

Stretching and Compressing Optical Pulses 98 Chirped Pulse Amplification 99 Gain Narrowing Compensation 99 Femtosecond Oscillators 99 Hollow-Core Fiber Pulse Compressor 99 Adaptive Pulse Compression 100 Femtosecond Pulse Characterization 100 Properties of Ti:Sapphire 100 Textbooks 100

3.1 Introduction 101

- 3.1.1 Definition of Carrier-Envelope Phase 101
 - 3.1.1.1 Linearly Polarized Field 101
 - 3.1.1.2 Circularly Polarized Field 103
 - 3.1.1.3 Elliptically Polarized Field 103
- 3.1.2 Physics Processes Sensitive to Carrier-Envelope Phase 103
 - 3.1.2.1 Sub-Cycle Field Strength Variation 103
 - 3.1.2.2 Sub-Cycle Gating 104
- 3.2 Carrier-Envelope Phase and Dispersion 104
 - 3.2.1 Effects of Group and Phase Velocity Difference 104
 - 3.2.1.1 Group and Phase Velocity 104
 - 3.2.1.2 Gouy Phase and Carrier-Envelope Phase 105
 - 3.2.1.3 Index of Refraction 106
 - 3.2.2 Prism-Based Compressor 107
- 3.3 Carrier-Envelope Phase in Laser Oscillators 108
 - 3.3.1 Carrier-Envelope Phase Offset Frequency 109
 - 3.3.1.1 Carrier-Envelope Phase Change Rate 109
 - 3.3.1.2 Carrier-Envelope Offset Frequency 109
 - 3.3.2 Stabilization of Offset Frequency 111
 - 3.3.2.1 Measuring f₀ by f-to-2f Interferometers 111

- 3.4 Stabilization of the Carrier-Envelope Phase of Oscillators 112
 - 3.4.1 Oscillator Configuration 112
 - 3.4.2 *f*-to-2*f* Interferometer 113
 - 3.4.2.1 White-Light Generation 113
 - 3.4.2.2 Setup 114
 - 3.4.2.3 Beat Signal 115
 - 3.4.3 Locking the Offset Frequency 115
 - 3.4.3.1 Phase Detector and Proportional Integral Control 115
 - 3.4.3.2 Stability of the Locked f_0 116
 - 3.4.4 Noise of the Interferometer 117
 - 3.4.4.1 Error in Measuring f_0 117
 - 3.4.4.2 Interferometer Locking 118
 - 3.4.4.3 Noise Spectrum 119
- 3.5 Measurement of the Carrier-Envelope Phase of Amplified Pulses 119
 - 3.5.1 Single Shot f-to-2f Interferometry 121
 - 3.5.1.1 Interferometer Setup 121
 - 3.5.1.2 Fourier Transform Spectral Interferometry 122
 - 3.5.2 Precisions of the Carrier-Envelope Phase Measurement 123
 - 3.5.2.1 Experimental Determination of the Carrier-Envelope Phase–Energy Coupling Coefficient 123
 - 3.5.2.2 Explanation of the Carrier-Envelope Phase–Energy Coupling 125
 - 3.5.3 Two-Step Model 126
 - 3.5.3.1 Filamentation in Sapphire Plate 126
 - 3.5.3.2 White-Light Generation 128
 - 3.5.3.3 Frequency Phase of White Light, Nonlinear Phase, and Carrier-Envelope Phase 129
 - 3.5.3.4 Group Delay 130
 - 3.5.3.5 Carrier-Envelope Phase Measurement Error 130
- 3.6 Carrier-Envelope Phase Shift in Stretchers and Compressors 132
 - 3.6.1 Carrier-Envelope Phase Shift Introduced by Grating-Based Compressors 132
 - 3.6.1.1 Carrier-Envelope Phase 132
 - 3.6.1.2 Beam Pointing 134
 - 3.6.1.3 Grating Separation 134
 - 3.6.2 Carrier-Envelope Phase Shift Introduced by Grating-Based Stretcher 135
 - 3.6.2.1 Pulse Duration 136
- 3.7 Stabilization of the Carrier-Envelope Phase in CPA 137
 - 3.7.1 Using the Compressor 137
 - 3.7.1.1 Frequency Response of the PZT Mount 138
 - 3.7.1.2 Frequency Response of the *f*-to-*2f* Interferometer and of the PZT 139
 - 3.7.1.3 Carrier-Envelope Phase Locking 140
 - 3.7.2 Using the Stretcher 140
 - 3.7.2.1 Dependence of Carrier-Envelope Phase on the Effective Grating Separation 142

- 3.7.2.2 Compensation of Slow Carrier-Envelope Phase Drift 143
- 3.7.2.3 Effects of the Oscillator *f*-to-2*f* Stability 143
- 3.8 Controlling of the Stabilized Carrier-Envelope Phase 145 3.8.1 Carrier-Envelope Phase Staircase 145
 - 3.8.2 Phase Sweeping 145
- 3.9 Carrier-Envelope Phase Measurements after Hollow-Core Fibers 146 3.9.1 Experimental Setup 147
 - 3.9.2 Carrier-Envelope Phase Stability 150
 - 3.9.3 Energy to Carrier-Envelope Phase Coupling Coefficient 151
- 3.10 Stabilizing Carrier-Envelope Phase of Pulses from Adaptive Phase Modulators 152
 - 3.10.1 Carrier-Envelope Phase Stability 152
 - 3.10.2 Carrier-Envelope Phase Error Introduced by the Zero-Dispersion Stretcher 153
 - 3.10.3 Compensate the Carrier-Envelope Phase Shift Introduced by the 4*f* System 154
- 3.11 Power Locking for Improving Carrier-Envelope Phase Stability 156
 - 3.11.1 Feedback Loop 156
 - 3.11.2 Pockels Cell 157
 - 3.11.3 Power Stability 158
 - 3.11.4 Carrier-Envelope Phase Stability 158
- 3.12 Carrier-Envelope Phase Measurements with Above-Threshold lonization 160

References 162

Review Articles 162

Physics Processes Sensitive to CE Phase 163 Carrier-Envelope Offset Frequency of Oscillators 163 Stabilizing the CE Phase Chirped Pulse Amplifiers 164 CE Phase of Hollow-Fiber Compressor 164 *f*-to-2*f* Measurements 164 Power Locking 164

4 Semiclassical Model 165

- 4.1 Three-Step Model 165
 - 4.1.1 Recombination Time 168
 - 4.1.1.1 Graphic Solutions and Kramers–Henneberger Frame 168
 - 4.1.1.2 Numerical Solutions and Fitting
 - Functions 169
 - 4.1.2 Return Energy 170
 - 4.1.3 Long and Short Trajectories 171
 - 4.1.4 Chirp of Attosecond Pulses 172
 - 4.1.4.1 Short Trajectory 174
 - 4.1.4.2 Long Trajectory 174
 - 4.1.4.3 The General Case 175
 - 4.1.4.4 High-Order Chirp 175

- 4.2 Tunneling Ionization and Multiphoton Ionization 175
 - 4.2.1 The Keldysh Theory 176
 - 4.2.1.1 Volkov States 176
 - 4.2.1.2 Fermi's Golden Rule and Photoionization Rate 177
 - 4.2.1.3 Keldysh Parameter 178
 - 4.2.2 PPT Model 180
 - 4.2.3 ADK Model 183
 - 4.2.3.1 Cycle-Averaged Rate 184
 - 4.2.3.2 Cycle-Averaged Rate of an Elliptically Polarized Field 184
 - 4.2.3.3 Saturation Inization Intensity 185
 - 4.2.4 Attosecond Electron and Photon Pulses 185
 - 4.2.4.1 Returning Electron Pulse 185
 - 4.2.4.2 Attosecond Pulse Train and High-Order Harmonics 186
- 4.3 Cutoff Photon Energy 186
 - 4.3.1 Saturation Field and Intensity 187
 - 4.3.1.1 Sech Square Pulse 188
 - 4.3.1.2 Definition of Ionization Saturation 188
 - 4.3.1.3 ADK Rate 189
 - 4.3.1.4 Circularly Polarized Pulses 189
 - 4.3.1.5 Linearly Polarized Fields 191
 - 4.3.1.6 Saturation Intensity for Linearly Polarized Field 192
 - 4.3.1.7 Ionization Probability 193
 - 4.3.2 Cutoff due to Depletion of the Ground State 194
 - 4.3.2.1 Ionization Potential 195
 - 4.3.2.2 Pulse Width 196
 - 4.3.2.3 Wavelength of the Driving Laser 197
- 4.4 Free Electrons in Two-Color Laser Fields 199
 - 4.4.1 Equation of Motion 199
 - 4.4.1.1 Return Time 201
 - 4.4.2 Return Energy 202
 - 4.4.3 Two-Color Gating 203
- 4.5 Polarization Gating 204
 - 4.5.1 Electrons in Elliptically Polarized Laser Fields 205
 - 4.5.1.1 Laser Field 205
 - 4.5.1.2 Equations of Motion 206
 - 4.5.1.3 Transverse Displacement 207
 - 4.5.1.4 Quantum Diffusion 208
 - 4.5.2 Isolated Attosecond Pulse Generation 208
 - 4.5.2.1 Principle of the Polarization Gating 208
 - 4.5.2.2 Laser Field 210
 - 4.5.2.3 Fields inside the Polarization Gate 211
 - 4.5.2.4 Electron Trajectories 213
 - 4.5.2.5 Polarization Gate Width 214
 - 4.5.2.6 Optics for Creating Laser Pulse for Polarization Gating 215
 - 4.5.2.7 Upper Limit of Laser-Pulse Duration 217

xv

	4.6 Proble	Summary	217			
	Refere	210	2			
	Neiele	lonization	, by Lacor Field	4 210		
			Dy Laser Fleit			
		Cutoff of	piniouei 220 Ligh Harmani	Concretion 220		
			nigii nariiloille Coting 220	C Generation 220		
		Two-Color Delerization	Gating 220	0		
		FUIdrizatio	on Gating 22	20		
5	Stron	g Field A	pproximatio	n 223		
	5.1	Analytical	Solution of th	e Schrödinger Equation 223		
		5.1.1	Approximati	ons 223		
			5.1.1.1	Dipole Radiation and Dipole Moment 223		
			5.1.1.2	Single Active Electron Approximation 224		
			5.1.1.3	Electric Dipole Approximation 225		
			5.1.1.4	Strong Field Approximation 225		
			5.1.1.5	Continuum-State Wave Function 226		
			5.1.1.6	Total Wave Function 226		
			5.1.1.7	Dipole Moment 226		
		5.1.2	Continuum \	Nave Packet 227		
			5.1.2.1	Analytical Approach to Solve the Schrödinger		
				Equation 228		
			5.1.2.2	Solution of the Differential Equation 229		
			5.1.2.3	Conservation of Canonical Momentum 230		
		5.1.3	Saddle-Poin	t Approach 231		
			5.1.3.1	One-Dimensional Saddle Point		
				Approximation 232		
			5.1.3.2	3D Saddle-Point Method 233		
		5.1.4	Dipole Mom	ent for Linearly Polarized Driving Laser 236		
			5.1.4.1	Laser Field 236		
			5.1.4.2	Momentum and Action 237		
		5.1.5	Dipole Trans	ition Matrix Element 238		
		5.1.6 Coulomb Corrections 240		rrections 240		
			5.1.6.1	Correction to the Recombination Term 240		
			5.1.6.2	Correction to the Ionization Step 241		
			5.1.6.3	Matrix Element 241		
	5.2	Temporal Phase of Harmonic Pulses 242				
		5.2.1	Intrinsic Dip	ole Phase 243		
		5.2.2	Gaussian An	alysis of the Temporal Phase 244		
			5.2.2.1	Laser Pulses 244		
			5.2.2.2	High Harmonic Pulses 245		
			5.2.2.3	High Harmonic Spectrum 247		
		5.2.3	Experimenta	l Results 247		
			5.2.3.1	Using 40 fs Lasers 247		
			5.2.3.2	Numerical Simulation Results 248		
			5.2.3.3	Few-Cycle Driving Laser 248		
	53	Effects of Molecular Orbital Symmetry 250				
	0.0	5.3.1	Experimenta	l Results 251		

5.3.1.1 Ellipticity Control 251

- 5.3.1.2 High Harmonic Cutoff 252
- 5.3.1.3 Ellipticity Dependence 253
- 5.3.2 Numerical Simulations 253
 - 5.3.2.1 Bonding Orbital and Antibonding Orbital 254
 - 5.3.2.2 Simulation Results 256
 - 5.3.2.3 Role of Interference 256
- 5.4 Polarization Gating Revisit 258
 - 5.4.1 SFA for Polarization Gating 258
 - 5.4.1.1 Single Atom Response 258
 - 5.4.1.2 Propagation Effects 260
 - 5.4.2 Results of Simulations 261
 - 5.4.2.1 Double Attosecond Pulses Generated with Multicycle NIR Lasers 261
 - 5.4.2.2 Isolated Attosecond Pulse Generated with Few-Cycle NIR Lasers 262
 - 5.4.2.3 Effects of Carrier-Envelope Phase 265
- 5.5 Complete Reconstruction of Attosecond Burst 267
 - 5.5.1 Approximations 267
 - 5.5.1.1 Strong Field Approximation 267
 - 5.5.1.2 Single Active-Electron Approximation 268
 - 5.5.2 Ionization in Two-Color Field 268
 - 5.5.2.1 XUV Field 268
 - 5.5.2.2 Photoelectron Wave Packet 269
 - 5.5.2.3 Effects of Dipole Matrix Elements 270
 - 5.5.2.4 Photoelectron Wave Packet Produced by the Two-Color Field 271
 - 5.5.2.5 Time Delay between the Two Fields 272
 - 5.5.3 Saddle Point Approximation 273
 - 5.5.4 FROG-CRAB Trace 275
 - 5.5.4.1 Electron Phase Modulator 275
 - 5.5.4.2 FROG-CRAB Trace 275
 - 5.5.4.3 Dipole Correction 276
 - 5.5.4.4 Central Momentum Approximation 277
- 5.6 Summary 277

References 278

Review Articles 278

Strong Field Approximation for High Harmonic Generation 278

Intrinsic Dipole Phase 278

- Ellipticity Dependence of High Harmonic Generation 278
- Polarization Gating 279

TDSE for High Harmonic Generation 279

High Harmonic Generation in Molecules 279

Textbooks 279 FROG-CRAB 279

6 Phase Matching 281

6.1 Wave-Propagation Equation 2826.1.1 Wave Equations for the Total Fields 282

- 6.1.1.1 Maxwell Equations 282
- 6.1.1.2 Wave Equation for Electric Field 283
- 6.1.2 Wave Equations for High-Harmonic Fields 283
 - 6.1.2.1 Monochromatic Driving Laser 284
- 6.1.3 Linearly Polarized Fields 284
 - 6.1.3.1 Paraxial Approximation 285
- 6.2 Phase Matching for Plane Waves 285
 - 6.2.1 Perfect Phase Matching in Lossless Media 286
 - 6.2.1.1 Plasma Dispersion 287
 - 6.2.1.2 Pressure (Plasma) Gradient Gas Target 289
 - 6.2.2 Effect of Absorption 290
 - 6.2.2.1 Absorption Limit 290
 - 6.2.3 Maker Fringes 292
 - 6.2.4 Rule of Thumb for Optimizing XUV Photon Flux 293
 - 6.2.5 Effects of Intensity Distribution in the Propagation Direction 294 6.2.5.1 Quasiphase Matching 296
- 6.3 Phase Matching for Gaussian Beams 296
 - 6.3.1 On-Axis Phase Matching without Plasma and Gas Dispersion 297
 - 6.3.2 On-Axis Phase Matching without Neutral Gas Dispersion 299
 - 6.3.3 Off-Axis Phase Matching 300
- 6.4 Phase Matching for Pulsed Lasers 301
 - 6.4.1 Wave Equation 301
 - 6.4.1.1 Beams with Axial symmetry 302
 - 6.4.1.2 Retarded Coordinate 303
 - 6.4.1.3 Plane Waves 303
 - 6.4.2 Paraxial Wave Equation in the Frequency Domain 304
 - 6.4.3 Carrier-Envelope Phase 305
 - 6.4.4 Propagation of Few-Cycle Pulses 305
 - 6.4.5 Integral Approach 307
 - 6.4.6 Calculating the Electric Field in the Far-Field 309
- 6.5 Compensating the Chirp of Attosecond Pulses 310
 - 6.5.1 Numerical Simulation Method 311
 - 6.5.1.1 NIR Laser Field 311
 - 6.5.1.2 Single-Atom Response 312
 - 6.5.1.3 Macroscopic Attosecond Signal 313
 - 6.5.2 Simulation Results 314
 - 6.5.2.1 Ground-State Depletion 314
 - 6.5.2.2 Gated XUV Spectrum 314
 - 6.5.2.3 Modulation in the Single-Atom Spectrum 315
 - 6.5.2.4 Comparison with the Semiclassical Results 316
 - 6.5.2.5 Chirp of Attosecond Pulses 316
 - 6.5.2.6 Chirp Compensation 318
- 6.6 Phase Matching in Double-Optical Gating 320
 - 6.6.1 Principle of Double-Optical Gating 321
 - 6.6.2 Major Factors 322
 - 6.6.2.1 Intrinsic Phase of Isolated Attosecond Pulses 323
 - 6.6.2.2 On-Axis Phase Matching 324
 - 6.6.2.3 Pressure Gradient 326

		6.6.3	Experimental Results 327 6.3.3.1 Experimental Setup 327 6.3.3.2 Gating Optics 327				
		6.6.4	Gas-Target Location 329 6.6.4.1 Argon Gas 329 6.6.4.2 Neon Gas 329				
		6.6.5	Gas Pressure 330 6.6.5.1 Argon Gas 330 6.6.5.2 Neon Gas 333				
	6.7	Summarv	333				
	Proble	ms 333					
	Refere	nces 334					
		Review Articles 334					
		Phase Matching 334					
		Polarization Gating 335					
		Double-Op Dipole Pha	tical Gating 335 Ise 336				
7	Attosecond Pulse Trains 337						
	7.1	Truncated	Gaussian Beam 338				
		7.1.1	Electric Field 338				
			7.1.1.1 Bessel Functions 340				
			7.1.1.2 Narrow Annular Aperture 342				
		710	7.1.1.3 On Axis 343				
		7.1.2 7.1.2	Field Distribution in the Propagation Direction 344				
		7.1.5	7.1.3.1 Gouy Phase 345				
	7.2	Detection	Detection Gas 346				
		7.2.1	Effects of Spin–Orbit Coupling and Inner Shells 346				
		7.2.2	Maximum Pressure 346				
	7.3	Electron T	ime-of-Flight Spectrometer 349				
		7.3.1	Field-Free TOF 350				
			7.3.1.1 Energy Resolution 351				
			7.3.1.2 Retarding Potential 351 7.2.1.2 Time Resolution Measurement 252				
		732	Magnetic Bottle 353				
		7.3.2	7.3.2.1 Parallelization of the Trajectories 353				
			7.3.2.2 Acceptance Angle 355				
			7.3.2.3 Energy Resolution 355				
			7.3.2.4 Adiabaticity Parameter 355				
			7.3.2.5 Transition Region 356				
			7.3.2.6 Transverse Magnification 356				
			7.3.2.7 Overall Considerations 356				
			7.3.2.8 Construction of the Magnetic Bottle 357				
			7.3.2.9 Experimental Energy Resolution 358				
		733	Position-Sensitive Detector 358				

7.3.3.1	Experimental Determination of the Energy			
	Resolution	361		

- 7.3.3.2 Setup 361
- 7.3.3.3 Energy Resolution Calibration 362
- 7.3.4 Velocity Map Imaging 363
- 7.4 Measurement of Temporal Width of a Single Harmonic Pulse 364 7.4.1 Sidebands 366
- 7.5 Reconstruction of Attosecond Beating by Interference of Two-Photon Transition 368
 - 7.5.1 Reconstruction of Attosecond Beating by Interference of Two-Photon Transition Experiments 368
 - 7.5.1.1 Spectral Phase and Harmonic Emission Time 370
 - 7.5.2 Transition-Matrix Element in XUV Field 371
 - 7.5.2.1 Fermi's Golden Rule 371
 - 7.5.2.2 First-Order Approximation 371
 - 7.5.2.3 Dipole Approximation 372
 - 7.5.2.4 Absorption Cross Section 372
 - 7.5.2.5 Neon Atom 372
 - 7.5.3 Transitions in XUV and IR Fields 373
 - 7.5.3.1 Attosecond Pulse Train Generated with One-Color Driving Field 373
 - 7.5.3.2 Sideband Intensity Oscillation 374
 - 7.5.3.3 Two-Color Driving Field 375
- 7.6 Complete Reconstruction of Attosecond Bursts 376
 - 7.6.1 CRAB Trace 377
 - 7.6.1.1 Temporal-Phase Gate 379
 - 7.6.1.2 Reconstruction Algorithm 379
 - 7.6.2 Linearly Polarized Dressing Laser Field 380
 - 7.6.2.1 Energy Shift 381
 - 7.6.2.2 Phase and Laser Field 381
 - 7.6.2.3 Ponderomotive Shift 381
 - 7.6.2.4 NIR Laser Intensity 382
 - 7.6.2.5 Observation Angle 383
 - 7.6.3 Attosecond Pulse Train 384
 - 7.6.3.1 $T_m = 2T_{tr}$ 384
 - 7.6.3.2 Attosecond Pulses near the Cutoff Region 3847.6.4 Perturbative Regime of CRAB 384
 - 7.6.4.1 Attosecond Pulse Train Generated with One-Color Lasers 385
 - 7.6.4.2 Attosecond Pulse Train Generated with Two-Color Lasers 386
- 7.7 Summary 389
- Problems 389
- References 390
 - Magnetic Bottle TOF 390 Velocity Map Imaging 390 Laser Assisted Photoelectric Effect 390 FROG-CRAB and RABITT 391 Truncated Gaussian Beams 391

8 Single Isolated Attosecond Pulses 393

- 8.1 Phase Retrieval by Omega Oscillation Filtering 393
 - 8.1.1 Introduction 394
 - 8.1.2 Phase Encoding in Electron Spectrogram 396
 - 8.1.2.1 Dressing Laser 397
 - 8.1.2.2 ω_1 Component of Electron Spectrogram 398
 - 8.1.2.3 Perturbative Regime 400
 - 8.1.2.4 Flat Spectrum 401
 - 8.1.2.5 Arbitrary Spectrum 402
 - 8.1.2.6 Modulation Depth 404
 - 8.1.2.7 Phase Angle of the Filtered Spectrogram 405
 - 8.1.2.8 Comparison with Attosecond Streak Camera 408
 - 8.1.3 Modulation Depth for Gaussian Pulses 409 8.1.3.1 High-Order Effects 410
 - 8.1.4 Effect of Dipole Transition Element 412
- 8.2 Complete Reconstruction of Attosecond Bursts for Isolated Attosecond Pulses 414
 - 8.2.1 Central Momentum Approximation 414
 - 8.2.1.1 Effects of Experimental Conditions 415
 - 8.2.1.2 Shot Noise 416
 - 8.2.1.3 Array Dimension of CRAB Trace 416
 - 8.2.2 Simulation of Shot Noise in CRAB Traces 417
 - 8.2.3 Effects of Shot Noise on XUV Pulse Retrieval 418
 - 8.2.4 Dressing Laser Intensity 420
 - 8.2.4.1 NIR Intensity and Streaking Speed 420
 - 8.2.4.2 Dependence of Minimum NIR Intensity on XUV Chirp 421
 - 8.2.4.3 Comparison between PROOF and CRAB 422
- 8.3 Amplitude Gating 422
- 8.4 Polarization Gating 426
 - 8.4.1 Setup for Measuring Polarization Gated XUV Spectrum 427
 - 8.4.2 Effects of Laser Pulse Duration 428
- 8.5 Double Optical Gating 430
 - 8.5.1 Principle of Double Optical Gating 430
 - 8.5.2 Gate Width 431
 - 8.5.3 Upper Limit of NIR Laser Pulse Duration 433
 - 8.5.4 Creating the Gating Laser Field 435
 - 8.5.4.1 Controlling the Delay by the Whole Wave Plate 436
 - 8.5.4.2 Controlling the Ellipticity by Brewster Window 436
 - 8.5.4.3 BBO Crystal 437
 - 8.5.5 Numerical Simulations 438
 - 8.5.5.1 One-Color Linearly Polarized NIR Laser 439
 - 8.5.5.2 One-Color Polarization Gating 439
 - 8.5.5.3 Two-Color Gating 439
 - 8.5.5.4 Double Optical Gating 439
 - 8.5.5.5 Effects of CE Phase 441

- 8.6 Measurement of the XUV Pulse Duration 442
 - 8.6.1 Experimental Setup 442
 - 8.6.1.1 Chirped Pulse Amplification with Spectral Shaping 442
 - 8.6.1.2 Femtosecond FROG 444
 - 8.6.1.3 Attosecond Streak Camera 445
 - 8.6.2 Dependence of Attosecond Electron Spectrum on CE Phase 447
 - 8.6.3 Reconstruction of the Attosecond Pulse 448
- 8.7 XUV Pulses with One Atomic Unit of Time Duration and keV X-Ray Pulses 449
 - 8.7.1 Generation of Pulse with 25 as Duration 449
 - 8.7.2 keV Attosecond Pulses 450
- 8.8 Summary 454

References 454

Attosecond Streak Camera and FROG-CRAB 454 Amplitude Gating 455 Polarization Gating 455 Two-Color Gating 456 Double Optical Gating 456 Field Ionization 456 IR Femtosecond Laser 456 PROOF 456

9 Applications of Attosecond Pulses...... 457

- 9.1 Introduction 457
 - 9.1.1 Attosecond Pump–Probe Experiments 457
 - 9.1.2 Requirement on the Attosecond Pulse Energy 460
- 9.2 Direct Measurement of the Temporal Oscillation of Light 460
 - 9.2.1 Direct Measurement of Low-Frequency Electric Field 461
 - 9.2.2 Direct Measurement of Light-Field Oscillation 461
 - 9.2.2.1 Definition of Electric Field 462
 - 9.2.2.2 Definition of Force 462
 - 9.2.2.3 The Retarded Frame 463
 - 9.2.2.4 Measurement Demonstration 464

9.3 Direct Measurement of Spatial Variation of Field in Bessel Beams 466

- 9.3.1 Bessel Beam 466
 - 9.3.1.1 Electric Field of an Ideal Bessel Beam 466
 - 9.3.1.2 Field in Experimental Setup 467
- 9.3.2 Measurement Scheme 468
 - 9.3.2.1 Experimental Demonstration 470

9.4 Controlling Two-Electron Dynamics in Helium Atoms 474

- 9.4.1 Double Excitation of Helium 475
 - 9.4.1.1 Shell Model 475
 - 9.4.1.2 Coupled Pendulum Model 477
 - 9.4.2 Energy Domain Description of Fano Resonance 478
 - 9.4.2.1 Zero-Order Approximation 479
 - 9.4.2.2 Configuration Interaction 480

- 9.4.2.3 Position of Resonance and Modified Bound State 481
- 9.4.2.4 Resonance Linewidth 482
- 9.4.2.5 Fano Profile and *q* Parameter 482
- 9.4.3 Time-Domain Description of Fano Resonance 485
 - 9.4.3.1 Lorentzian Lineshape 485
- 9.4.4 Strong-Field Approximation on XUV Photoionization in Laser Fields 487
 - 9.4.4.1 Direct Ionization from the Ground State 487
 - 9.4.4.2 Autoionization from an Excited State 487
 - 9.4.4.3 Fano Profile 488
- 9.4.5 TDSE Simulations 488
 - 9.4.5.1 XUV Photoionization with and without the Laser Field 488
 - 9.4.5.2 Laser-Intensity Dependence 489
 - 9.4.5.3 TDSE Simulations on Studying Two-Electron Dynamics by Attosecond Pump–Probe 490
- 9.4.6 Experiments on Autoionization of Helium in NIR Laser Fields 490
 - 9.4.6.1 Experimental Setup 492
 - 9.4.6.2 Calculations under the Strong-Field Approximation 495
 - 9.4.6.3 Discussion 497

References 498

Direct Measurement of Light Fields 498 Bessel Beams 499 Fano Resonance 499 Autoionization in Near Infrared Laser Fields 500 Time-Resolved Two-Electron Dynamics 500 Other Experiments on Attosecond Applications 500 X-Ray Transient Absorption 500

Appendix A: Solutions to Selected Problems	501
Index	507