

INDEX

- ABCD* matrices, 21, 71–72, 110
- Aberration, *see also* Astigmatism
chromatic, 175, 177
phase, 375, 414
- Absorber:
multilevel, 469, 475
saturable:
defined, 33
fast, 48, 58, 66–67, 337
slow, 48, 434
passive mode-locking using, 44–57, 75–77,
79, 81, 85
semiconductor, 54, 330, 335
soliton mode-locking using:
artificial fast, 316–328, 337
slow, 328–337
- Absorption:
coefficient, 110, 435–436, 453, 528
resonance, 136, 152, 200, 297, 433, 468, 470,
473, 475, 492
spectrum, 14–15, 47, 441, 443–444, 465–466,
470, 472, 474–477, 480–481, 486,
490–491, 493, 496, 498, 506, 529
ultrafast spectroscopy, 423–448, 482–483,
497–498
- Achromatic lenses, *see* Lenses, achromatic
- Acoustic:
shock, 306
- signals, 116
waves, 199, 390–394
- Acousto-optic(s):
modulator, 33, 336
programmable dispersive filter (AOPDF),
390–394, 414, 421
pulse shaping, 369, 390–394
- Active mode-locking:
characteristics of, 33–34
defined, 33
harmonic, 44, 328–330
jitter, 139–143
noise, 139–143
using phase modulator, 83
pulse shortening velocity, 81, 83
soliton lasers, 328–337
theory, 34–43, 331–334
variations of, 43–44
- Additive pulse mode-locking (APM), 58, 60–64,
81–82, 178
- Amplification, *see also* Amplifiers; Gain
parametric, 237–238, 245–253
of solitons, 324
ultrashort-pulse:
chirped pulse, 412–414
gain narrowing, 414–416
nonlinear beam propagation,
411–412

- Amplified spontaneous emission (ASE), 189, 409–410. *See also* Superluminescent diode
- Amplifier(s), *see also* Amplification; Gain
 basics, 406–411
 chirped pulse (CPA), 149, 166, 375–376, 393–394, 412–415
 femtosecond, 408–409
 fiber, 317, 328
 lock-in, 108, 424, 513, 530
 multipass, 409–410
 regenerative, 380, 410–411, 416, 421
- Angular dispersion:
 gratings, 162, 165–166, 364, 380
 lenses, 173
 parametric amplifier, 250–252, 255
 prisms, 167–170
 temporal dispersion, relationship with, 155–159
 tilted intensity fronts, 159–161, 196, 255, 379, 388
- Anharmonic:
 oscillator, 199
 potential, 466, 497
- Anomalous dispersion:
 angular dispersion, based on, 159
 atomic vapor, 278
 characteristics of, 60, 152–153, 167, 172
 gratings, 161–162, 166
 in lasers, 79, 316–337
 material, 153
 and nonlinear pulse propagation, 283–291, 411
 prisms, 170–172
 temporal, 170
- Antennas, photoconductive, 517–522, 527–528, 532
- Anti-reflection (AR) coatings, 185–186
- Astigmatism, 74–75, 168, 381, 420
- Atom:
 four-level, 15–16, 47–49, 441–442
 two-level, 453–454, 457, 459, 475, 477–478, 483
- Attosecond, 1–2, 201, 405
- Autocorrelation:
 electric field, 89–91, 95, 97–98, 107, 430, 442, 490
 data, 97–98
 electrical, 512–513
 intensity, 99–111, 233–236, 429–431, 441–442
 data, 104–105, 233, 277–279, 289–290, 312–313, 335, 338, 344
 fringe-averaged, 100–104, 112
 interferometric (fringe-resolved), 104–107, 112, 344, 351
 pulse duration related to autocorrelation width, 102–104
- B* integral, 411
- Back-scattered, 96–99
- Bacteriorhodopsin, 3
- Bandwidth, 2, 24, 32. *See also* Time-bandwidth product
 full-width at half-maximum (FWHM), 86–87
 of mode-locked solid-state laser pulses, 80
 root-mean-square, 86–87
- Bandwidth limited, 87, 104–105, 114, 122–123, 139, 236, 267–268, 348, 398, 430–431
- Beam(s), *see also* Terahertz beams
 Gaussian, 17–22, 30, 420, 523, 532
 with gratings and pulse shapers, 164, 378–379, 381, 385, 387–388
 in Kerr lens mode-locking, 66–67, 71–72, 74–75
 in pulse measurement, 109–110, 516
 in second harmonic generation, 215–217, 220, 228
 propagation method, 270. *See also* Split-step Fourier method
- Beamsplitter, 89, 92, 187, 524
 polarizing, 328, 352, 525
- Biomedical imaging, 4. *See also* Optical coherence tomography
- Birefringence:
 electro-optic sampling, 513–515, 525
 fiber lasers, 317, 328–329
 phase matching, 209, 213–214
 pulse shaping, 371–373, 390
 spatial walk-off, 210–214, 253–254
 ultrafast-pulse measurements, 119–121
 ultrafast spectroscopy, 423–424
- Bleaching, 442–443, 496, 498–499
- Boltzmann distribution, 449, 456, 458
- Born-Oppenheimer approximation, 297–298, 440–441, 462–463, 465
- Bound electron(s), 2, 199–200, 359, 405, 524
- Bragg wavelength, 180, 183–186
- Brewster angle:
 cut laser rod, 74
 prisms, arrangement of, 54, 168–171
- Carrier(s), charge:
 dynamics and ultrafast spectroscopy, 425, 439, 444–450, 486–487
 quantum confinement, 461
 in ultrafast electromagnetics, 508–510, 512–513, 517–518, 523–524

- Carrier, optical, 23–24, 27, 148, 202–203, 260, 470, 472. *See also* Frequency combs velocity, 37, 148
- Cavity, laser, *see* Resonator
- CCD camera, 109, 119, 121, 190
- Cesium clock, 356–358
- Characteristic impedance, *see* Impedance
- Chemistry, laser-controlled, 3, 376
- Chirp(ed):
 defined, 87, 112–115
 linear, 113–114, 125, 274, 277
 negative, 162. *See also* Down-chirp
 processing, ultrashort pulse manipulation, 397–400
 pulse(s):
 compression of, *see* Pulse, compression
 Gaussian, 112–114, 117, 121, 125, 150–151, 333, 342
 measurement of, *see also* Ultrafast-pulse measurement methods
 interferometric autocorrelation, 105–106
 frequency-resolved optical gating (FROG), 121–125
 self-referencing interferometry, time-domain, 135–137
 root-mean-square (rms), 104
 up-chirp, 59, 76, 78–79, 113, 122, 271, 274–276, 284
- Chirp-free, 76–77, 79–80, 87. *See also* Bandwidth-limited
- Chirped mirrors, 182–186
- Chirped pulse amplification (CPA), 149, 166, 375–376, 393–394, 412–415
- Chromatic aberrations, 175, 177
- Chromophore(s), 434, 456
- Coating technology, 184. *See also* Mirror structures
- Coherence:
 gating, optical coherence tomography (OCT), 97
 peak, intensity autocorrelation, 102
 time, 97, 106, 176, 187, 431. *See also* correlation time
- Coherent:
 control, *see* Chemistry, laser-controlled
 coupling, ultrafast spectroscopy, 429–431, 433–434, 438–439, 441–442
 demodulation, optical coherence tomography (OCT), 98–99
 motion, impulsive stimulated Raman scattering (ISRS), 499–503
 polarization, *see* Polarization
- Colliding pulse mode-locked (CPM) ring dye laser, 50, 53–54, 279–281, 31, 430
- Collisions:
 dephasing, 458, 480–481, 486–487, 491–492
 soliton, 290
- Comb, *see* Frequency combs
- Completing the square, 27
- Complexation process, 498
- Complex conjugate, 10, 89
- Complex notation, 8, 10, 30
- Compression, *see* Pulse, compression
- Conduction band(s), 445–449, 461–462
- Confocal microscopy, 4
- Conservation of energy. *See* Energy conservation
- Continuous-wave (CW):
 lasers, 4, 10–17, 42, 81, 323, 356–358
 light, stability of, 283, 411
 mode-locked laser systems, 108, 121, 124, 357
 noise or incoherent light, 91, 102–103, 187
 saturation, 15–17, 81
 second harmonic generation (SHG), *see* Second harmonic generation
 three-wave interactions, 238, 245–246, 251
- Continuum generation, 248–249, 265, 307, 310–313, 354–355
 ultrafast spectroscopy, 425, 446, 468
- Convergence, FROG algorithm, 127–128, 130
- Conversion efficiency, *see* Second-order nonlinear optics
- Convolution formula, 26
- Coplanar transmission line, 512–514, 516–519
- Co-polarization, *see* Third-order nonlinear optics, self-phase modulation; Ultrafast time-resolved spectroscopy, pump-probe, degenerate
- Correlation time, 24, 82, 90–91, 102, 143. *See also* Coherence time
 ultrafast spectroscopy, 480, 488, 491, 493
- Coulomb field *or* force, 199, 405, 461, 463
- Counterpropagating fields *or* pulses, 54, 64, 111, 320–322
- Coupled cavity mode-locked laser, 60–61
- Coupling, 2D spectroscopy, 495–498
- Coupling-of-modes equations, 184
- Cross-correlation:
 electric field, 91–93, 188–189, 495–496. *See also* Spectral interferometry
 optical coherence tomography (OCT), 96–99
 intensity, 108, 350–351
- Cross-peaks, 2D spectroscopy, 497–499
- Cross-phase modulation (XPM), 126, 275–276, 285–286, 318, 321
- Cross-relaxation, spectral, 491–493, 497, 499

- Cubic (*or* third-order):
 dispersion, 150–151, 163, 170–172, 326
 spectral phase, 149–150, 180, 277, 279–280, 344, 374, 413
 implications of, 114–115
 frequency-resolved optical gating (FROG), 121–122, 124–125
- Current dynamics, 529. *See also* Carrier(s), charge, dynamics and ultrafast spectroscopy
- Damping, 153, 478, 494, 500. *See also* Relaxation
- Dark solitons, 286
- Decay, in ultrafast spectroscopy, *see* Ultrafast time-resolved spectroscopy
- Deconvolution, 93, 103, 108, 429
- Delay(s):
 frequency-dependent, *see* Group velocity dispersion
 in compressors, amplifiers, and pulse shapers, 279–280, 373, 414
 implications of, 113–115
 measurements of, 118, 121, 124, 132, 145, 187
 mirror structures, 178–179, 183, 185, 196–197
 prisms, 172
 in quasi-phase matching, 233
 marginal, 117
 transverse effects, in noncollinear measurements, 109, 119
- Delayed nonlinear response, Raman effect and, 296–305
- Delta function, 26, 92, 144, 240–241, 244, 363, 430, 460, 464, 484–485
- Density matrix, 455–460, 462, 469, 478
- Density-of-states, 446–447, 477
- Dephasing:
 defined, 459
 impulsive stimulated Raman scattering (ISRS), 502
 measurement of, 460
 linear spectroscopies, 469–475
 transient gratings, 481–494
 two-dimensional spectroscopy, 494–499
 models of:
 dynamics, Markovian *or* non-Markovian, 481, 487, 493
 homogeneous broadening, 469, 475
 inhomogeneous broadening, 444, 475–476, 480–481, 483–491, 493–494, 496–497
 multilevel systems, 476
 stochastic oscillator treatment, 477–481, 493–494
 wave packets, 462, 467
- Depopulation, 442–443
- Dichroic mirror, 64, 352
- Dichroism, 423, 436–438
- Dielectric:
 constant, 6
 tensor, 210–212
- Dielectric mirrors, *see* Mirror structures
- Difference frequency generation, 237–238, 244–246, 394, 471, 524, 526
- Diffraction:
 Bragg, 424
 frequency-dependent, terahertz beams, 523
 Fresnel, 377, 395, 402, 416–418
 Fraunhofer, 396. *See also* Far field
 grating, *see* Grating, diffraction
 self-diffraction, frequency-resolved optical gating (FROG), 122–124
- Dipole antenna, 517–520, 522
- Dipole moment, 452–453, 460, 464, 477
- Dirac notation, 452, 454
- Direct bandgap semiconductors, 444, 446
- Direct optical spectral phase measurement (DOSPM), 134–135
- Direct space-to-time (DST) pulse shaping, 386–390
- Discrete Fourier transform, 28–29
- Dispersion:
 angular, *see* Angular dispersion
 anomalous, *see* Anomalous dispersion
 cubic, 150–151, 163, 170–172, 326
 group velocity, *see* Group velocity dispersion
 lenses, properties of, 165, 173–177
 map, 340–341, 345–347
 material, 149, 151–155, 158–159, 161–163, 170–172, 175–177, 180, 183, 414
 negative, *see* Negative dispersion
 normal, *see* Normal dispersion
 positive, *see* Normal dispersion
 quadratic, 149–151, 163, 171–172
 slope, 151
 wave packet, 469
- Dispersion-compensating fiber (DCF), 326, 328–329, 374–375
- Dispersion-managed soliton(s), 340–342, 345–347
- Dispersive ray tracing, 172–173
- Divergence theorem, 8–9, 262
- DODCI, 54
- Doppler:
 broadening, 475, 486
 OCT, 99

- Double-chirped mirrors (DCMs), 183–185, 344–346
- Double-pass grating pair, 165, 276, 278, 280, 314, 413
- Double-quantum-well, 461
- Double-sided spectrum, 27–28
- Down-chirp, 60, 76, 79, 122, 275, 279. *See also* Chirp(ed)
- Dye(s):
- amplifiers, 408–409
 - lasers, 11. *See also* Colliding pulse mode-locked (CPM) ring dye laser
 - passively mode-locked, 45, 50–54, 57
 - synchronously pumped, 44, 281
 - saturation of, 15, 47, 49
 - ultrafast spectroscopy of, 431, 434–444, 466–467, 477, 490–491, 493
- Eigenfunctions, 452, 454, 458, 465
- Eigenstates, 452–454, 457, 460, 462, 464
- Eigenvalues, 263, 452
- Electrical testing, high-speed, 3. *See also* Ultrafast electromagnetics
- Electrical transit time, electro-optic sampling, 516
- Electric dipole approximation, 452
- Electric field, *see also* Beams, Gaussian
 - Maxwell's equations, 4–10
 - measurements, *see also* Ultrafast-pulse measurement methods
 - autocorrelation, 89–91, 97–98, 107, 430, 442, 490
 - cross-correlation, 91–93, 188–189, 495–496
 - power spectrum, 88–91
 - spectral interferometry, 93–96
- Electric flux density, 5, 198–199
- Electro-optic(s), *see also* Optical rectification
 - modulator, 33, 400, 404, 410
 - sampling, 245, 472, 513–516, 524–528, 530
- Electromagnetics:
- Maxwell's equations, 4–6
 - Poynting's vector and power flow, 8–10
 - ultrafast, *see* Ultrafast electromagnetics
 - wave equation and plane waves, 6–8
- Electronic absorption resonances, 152, 200, 297
- Electronic-vibrational coupling, 493–494
- Electronic wave function, 57, 434, 441, 445, 462–464, 501
- Emitters, terahertz:
- built-in fields at semiconductor surfaces, 523
 - dipole antennas, 517–520
 - large-aperture, 520–523
 - optical rectification, 523–524
- Energy:
- conservation, 9, 222, 237, 239, 391
 - quantization, in soliton lasers, 322–324
 - relaxation, 426, 440, 459
 - splitting, 462
- Envelope equation, nonlinear, 270, 292–296, 308–309, 311, 313, 350
- Envelope function, *see* Rotating wave approximation
 - definition and implications of, 23, 27, 34, 348, 358–359
 - group velocity, 148
 - nonlinear optics equations, 202–204, 292–294
 - spatial, 18, 395. *See also* Paraxial wave equation
- Equilibrium, thermal *or* thermodynamic, 11, 301, 443, 445, 458
- Erbium-doped fiber, 49, 317, 338, 340
- Ergodic process, 89, 478
- Excited-state wave function, 462, 464–465
- Expectation value, 453, 456–457
- Extraordinary wave (e-wave), 212–214, 222, 237, 250, 254–255
- Extreme ultraviolet (XUV), 2, 405
- Fabry-Perot laser cavity, 11, 22
- Far field *or* Far-field, 72–74, 110, 396, 517, 522–523
- Faraday mirror *or* rotator, 328–329, 410
- Fast Fourier transform (FFT), 28, 130, 268
- Femtosecond, defined, 1–2
- Femtosecond amplifiers, *see* Amplifier(s)
- Ferroelectric nonlinear materials, 230–231
- Few-cycle lasers or pulses, 139, 344–348, 351, 359, 375–376, 504
- Fiber lasers, 44, 64, 81, 316–330, 336–340, 347
- Fiber optic(s), *see* Optical fibers
- Field autocorrelation, 89–91, 97–98, 107, 430, 442, 490
- Figure-eight laser (F8L), 317–319
 - energy quantization, 322–323
 - nonlinear loop mirrors, switching behavior of, 319–322
 - soliton sidebands, 324–327
- Filters/filtering:
- acousto-optic dispersive, 390–394
 - birefringent, 64–65
 - in continuous-wave lasers, 13
 - linear, 93, 362–363
 - in mode-locked lasers, 22, 32, 45–46, 75, 79, 328, 330–335, 345
 - phase-only, 367–368
 - pulse shaping, 362–369, 378, 380, 382–383, 386
 - second harmonic generation, due to phase matching, 223–224, 231–233, 234–237

- Filters/filtering (*Continued*)
 ultrafast-pulse measurement, 93, 116–117, 130–136, 234–237
- Finite-duration noise burst, *see* Noise
- Finite-size electromagnetic beams, 523
- First-order, generally:
 correlation, 89–90
 dispersion, 151
 perturbation, 455, 460, 464, 470, 472
 polarization, *see* Polarization, first-order
 spectroscopy, 475, 477
- Fluence:
 defined, 221
 saturation, 408–409, 412–413
 second-order nonlinear processes, 221, 226, 241–242, 244
- Fluorescence:
 spectrum, 441
 two-photon, 110–111
 ultrafast spectroscopy, 241, 423, 425–426, 448–450, 468
- Focusing, *see also* Self-focusing
 effects, in second harmonic generation (SHG):
 continuous-wave, 215–220
 pulsed, 226–228
 of femtosecond pulses, 173–178
 space-time, *see* Space-time, generally
- Focusing effects, continuous-wave SHG:
 overview of, 215–217
 strong focusing:
 negligible walk-off, 218
 phase-matching effects, 219–220
 with walk-off, 219
 weak focusing:
 negligible walk-off, 217–218
 with walk-off, 218–219
- Forced wave equation, 201–204, 223, 524
- Four-level atom, 15–16, 47–49, 441–442
- Four-prism sequence, 54, 167, 169
- Four-wave mixing,
 in fibers, 275, 285, 340
 ultrafast spectroscopy, 460, 481–497
- Fourier series:
 analytical aspects, 25–28
 computational aspects, 28–29
- Fourier transform:
 analytical aspects, 25–28, 43, 86, 102
 computational aspects, 28–29, 130
 algorithms:
 fast (FFT), 28, 268–269
 iterative, for phase retrieval, 127–128
 split-step, 268–270
 electric field correlation measurements, 91–92, 94–95, 188
 optical coherence tomography, 97–99
 of Gaussian functions, 27
 in mode-locking theory, 37, 43, 45–46, 60
 spatial, 72, 177
 by a lens 416–418
 pulse shaping, *see* Pulse shaping
 relationship:
 lineshape and phase relaxation, 465, 474–477, 480, 486
 power spectrum and correlation function, 91, 97–98, 140–141
- Franck-Condon principle, 441, 443, 464, 466
- Fraunhofer diffraction, 396. *See also* Far field
- Free induction decay, 136, 471–473, 477, 529
- Frequency comb(s):
 applications:
 extreme nonlinear optics, 358–359
 optical clocks, 357–358
 optical frequency metrology, 3, 356–357
 basics, 347–350
 measurement techniques, 350–354
 stabilization, 354–356
- Frequency-dependent:
 delays, *see* Delay(s), frequency-dependent
 phase, *see* Cubic, spectral phase; Dispersion;
 Spectral phase
- Frequency-domain intracavity dispersion
 measurements, 190–191
- Frequency fluctuations, dephasing, 479–480
- Frequency metrology, 3, 356–357
- Frequency-mixing processes, 200. *See also*
 Second-order nonlinear optics;
 Three-wave interactions
- Frequency modulation:
 chirp processing and time lenses, 403–405
 defined, 87
 in direct space-to-time pulse shaping, 389–390
 self-phase modulation, 271
- Frequency-resolved optical gating (FROG):
 defined, 118–119
 error, 128–129
 polarization-gating (PG), 119–122, 515
 second harmonic generation (SHG), 124–125, 129, 233–234, 237
 self-diffraction, 122–124
 signal recovery from FROG traces, 126–130
 temporal phase modulation and, 125–126
- Frequency response, electro-optic, 526–527
- Frequency-to-time mapping, 397–398
- Fresnel diffraction, 377, 395, 402, 416–418
- Fresnel reflection, 179, 520

- Fringe-averaged autocorrelation, 100–104, 112
- Fringe-resolved autocorrelation, *see*
Interferometric autocorrelation
- Fringe contour shift dispersion measurement,
187–188
- f -to- $2f$ interferometer, 351–355
- Full width at half maximum (FWHM), *see also*
Root-mean-square (rms)
pulse duration and bandwidth, generally, 86–88
pulse duration related to autocorrelation width,
102–104
- Fundamental soliton, 286–287, 290. *See also*
Solitons
- Gain, *see also* Amplification; Amplifier(s)
in actively mode-locked lasers, 35–39
coefficient, 16, 68, 406–407
narrowing effect, 414–416
Raman, 299–300
saturation, 12–17, 49, 406, 415
spectrum, modulational instability, 284–285
in steady-state lasers, 10–12
- Gallium arsenide (GaAs):
ultrafast electronics, 514, 516, 531
ultrafast spectroscopy:
pump-probe spectroscopic studies, 444–451
semiconductor quantum wells studies,
461–462, 471–472
two-pulse scattering, 486–487
- Gas lasers, 11
- Gating:
coherence gating, 97
frequency-resolved optical gating (FROG),
119–130
spectrograms, 115–118
fluorescence spectroscopy, via upconversion
gating, 450–451
- Gaussian beams, *see* Beams, Gaussian
- Gaussian frequency fluctuations, 478–480
- Gaussian, defined, 27, 87
pulse, chirped, 112–114, 117, 121, 125,
150–151, 333, 342
- Gaussian random:
field, 102
process, 478–480
- Gauss's law, 201
- Generalized projections algorithm, 128–129
- Gires-Tournois interferometer (GTI), 178–180,
182–185
- Grating, diffraction:
pairs:
chirped pulse amplification, 413–414
dispersion of, 155, 161–166, 171–172
double-pass, 413
pulse compression, 276–281, 283
pulse shaping, 363–364, 376–386
spectrometer, 378–379
wave optics model, 418–420
- Grating, generally:
quasi-phase matching (QPM), 230–233, 242
transient grating experiments:
frequency-resolved optical gating, 122–123
ultrafast spectroscopy, 423, 429–430, 438,
481–494
- Gray-level phase control, 371, 373–375
- Group delay, *see also* Group velocity dispersion
mirror structures, 179, 184–185
lenses, 175
prism pair, 172, 189
ultrashort-pulse SHG, 224–226
- Group velocity:
defined, 147–151
dispersion, *see* Group velocity dispersion
(GVD)
mismatch (GVM), second-order nonlinear
optics, 223–228, 231–239, 242, 245,
250, 252
solitons, 290
third-order nonlinear optics, 266, 295, 306, 309
- Group velocity dispersion (GVD):
angular dispersion, relationship to, 155–161
defined and general relations, 58–60, 147–151
gratings, 155, 161–166, 171–172
material dispersion, 149, 151–155, 158–159,
161–163, 170–172, 175–177, 180, 183,
414
measurements of:
frequency-domain intracavity dispersion,
190–191
interferometric methods, 91–96, 187–190
mirror structures, 177–186
in mode-locked lasers:
passively mode-locked, 54
solid-state lasers, 58–60, 76, 78–79, 344–347
soliton fiber lasers, 321–328
soliton mode-locking, 330–334
stretched pulse mode-locking, 337–343
prisms, 54, 167–170
and pulse compression, 277–282
and self-phase modulation, 267–271, 274–275
- Guiding center soliton, 324
- Hamiltonian operator, 451–452, 456, 463
- Hard-aperture KLM, 67–68, 73
- Harmonically mode-locked lasers:
active, 40–41, 44
soliton, 328–330
- Harmonic potential *or* well, 41–43, 466–467

- Heavy hole bands, 445
- Hermite Gaussians *or* polynomials, 19–20, 42, 465–466
- Hermitian operators, 453
- Higher-order solitons, 288, 303–305
- High-reflectivity quarter-wave stack, 181–182
- Hollow-core fibers, 265, 276, 281
- Homogeneous broadening, 13–15, 47, 407, 427, 469, 481, 484–486, 488–492, 496
- Hot carriers, 445, 448
- Hybrid mode-locking, 44
- Ideal compressor, 277, 282
- Idler wave, 247–248, 250–256
- Imaging, 2, 4
 - optical coherence tomography, 96–99
 - temporal, 400–405
 - terahertz, 530–531
- Impedance:
 - characteristic *or* wave, 9, 193–195, 509, 511, 521
 - matching, 184
 - transformation, 180, 192–195
- Impulsive stimulated Raman scattering (ISRS), 499–505
- Impurity-doped crystals, 11
- Indium phosphide (InP), 449
- Infrared absorption, 152
- Inhomogeneous broadening, 14–15, 301, 444, 475–477, 484–493, 496–497
- Instantaneous frequency, 59, 113–116, 118, 138–139, 271–275, 278–279, 300–301
- Integrated-circuit, 508, 522, 531
- Intensity:
 - correlations:
 - autocorrelation, 99–111, 233–236, 429–431, 441–442
 - data, 104–105, 233, 277–279, 289–290, 312–313, 335, 338, 344
 - interferometric (fringe-resolved), 104–107, 112, 344
 - cross-correlation, 108, 350–351
 - higher-order correlation techniques, 111–112
 - definition, 9–10
 - fronts, tilted, 159–161, 196, 255, 379, 388
 - profile(s), *see also* Beam(s), Gaussian defined, 87
 - mode-locked lasers, 23–24
- Interference:
 - dispersion, due to, 151, 176–178, 183
 - in mode-locked lasers, 54, 58, 60, 64
 - optical coherence tomography, 96–98
 - for pulse and dispersion measurement, 122, 134–137, 176, 187, 190, 353–354
 - spectral, 273, 275, 313, 527. *See also* Interferometry, spectral
 - in ultrafast spectroscopy, 429–430, 462, 465, 477, 482, 485
- Interferogram, 97–99, 495
- Interferometer(s):
 - calibration of, 93, 188
 - f*-to-2*f*, 351–355
 - Gires-Tournois (GTI), 178–180, 182–185
 - ultrafast-pulse measurements, 88, 90, 94, 96–100, 135–136, 138, 176, 187–190, 350–351
- Interferometric autocorrelation, 104–107, 112, 344
- Interferometry, *see also* Interference
 - self-referencing:
 - mode-locked frequency combs, 351–354
 - spectral (SPIDER), 137–139
 - time-domain, of chirped pulses, 135–137
 - spatial-spectral, 189–190
 - spectral, 93–96, 189–190, 495
 - white light, 171, 187
- International Conference on Ultrafast Phenomenon, 426
- Inverse discrete Fourier transform, 28. *See also* Fast Fourier transform (FFT)
- Inverse Fourier transform, 116, 137, 204, 224, 232, 269, 369, 391, 484
- Inverse scattering method, 286
- Inversion symmetry, 200, 453
- Ion implantation, 508
- Ionization, multiphoton, 201, 265, 313, 405
- Iterative Fourier transform algorithm, 127–128
- Jitter, timing, 139–144, 358, 400
- k*-vector, 8, 210–211, 250–251, 254
- Kerr effect, *see* Optical Kerr effect
- Kerr lens mode-locking (KLM):
 - few-cycle regime, 344–347
 - general description of, 57–58, 64–67, 344
 - initiation of, 81–82
 - resonator properties and self-amplitude modulation coefficient, 67–75
- Kinetic energy, 405, 442, 450, 452, 463
- Laser(s), *see specific types of lasers*
 - gain saturation, 14–17
 - Gaussian beams, 17–22
 - longitudinal modes, 12–13
 - multimode, 22–24
 - resonator *or* cavity, *see* Resonator
 - steady-steady operation, 10–15
 - transverse modes, 17–22

- Lattice(s):
 resonances, in electro-optic crystals, 524, 526–527
 scattering with and vibrations of, in ultrafast spectroscopy, 424, 445–447, 450, 456, 494
- Lenses:
 achromatic, 175–177
 dispersive properties of, 173–177
- Light hole bands, 445
- Linear chirp, 113–114, 125, 274, 277
- Linear medium, 5–6, 9, 199, 394
- Line-shape, 15, 35, 474, 480; *see also*
 Homogeneous broadening;
 Inhomogeneous broadening
- Liquid-crystal modulator (LCM) arrays, for pulse shaping, 369–375, 384
- Longitudinal modes, 12–13, 22, 25, 33, 37, 40, 43, 81. *See also* Frequency comb(s)
- Longitudinal optical (LO) phonon, 493–494
- Longitudinal relaxation time, 459
- Loop mirror:
 defined, 320
 nonlinear, 317, 319–322
- Lorentzian, 35–36, 75, 152, 415, 470
- Loss coefficient, 40, 58, 260
- Loss line, 13, 43, 50, 77
- Loss modulation, 33, 45
- Luminescence, *see* Fluorescence
- Magnetic field, 5–6, 195
- Magnetization, 5–6
- Manley-Rowe relation, 238–239, 246
- Marginal delay distribution, 117, 234
- Marginal frequency distribution, 117, 125, 236
- Markovian dynamics, 481, 487
- Master equation, 46, 54, 74, 331, 336–337
- Material dispersion, 149, 151–155, 158–159, 161–163, 170–172, 175–177, 180, 183, 414
- Material processing, 4
- Mathematical form constraint, 126–128
- Maxwell's equation, 4–6, 198, 521
- Measurement of:
 dephasing, *see* Dephasing
 dispersion, *see* Group velocity dispersion (GVD)
 frequency combs, 350–354
 frequency dependent delay, *see* Delay(s)
 terahertz beams, 517–527
 ultrafast physical processes, *see* Ultrafast time-resolved spectroscopy
 ultrashort pulses, *see* Ultrafast-pulse measurement methods
- Melting, 424
- Metrology, optical frequency, 3, 356–357
- Michelson interferometer, 88, 99, 138, 176
- Microolithography, 230–232, 365
- Microscope(s) *and* microscopy, 2, 4, 97, 362
 time, 403–404
- Microstrip transmission line, 508, 513, 516
- Microstructured fibers, 265, 310, 313
- Midinfrared, 238, 244–245, 471–472, 526
- Minimum deviation, 168, 170–171. *See also*
 Prism pairs
- Mirror structures:
 chirped mirrors, 182–186, 344–346
 classified, 177–178
 dichroic, 64, 352
 in few-cycle lasers, 344–346
 Gires-Tournois interferometer (GTI), 178–180
 loop mirrors, 317, 319–322
 metal, 181–182
 output coupler, 10–12, 53, 65, 74, 248, 318, 339, 344–345
 quarter-wave stacks, 180–182
 impedance analysis methods, 192–195, 509
- Mixed state, 456
- Mode-locking:
 active, *see* Active mode-locking
 few cycle lasers, 344–347
 frequency comb, *see* Frequency comb(s)
 frequency-domain intracavity dispersion measurements, 190–191
 initiation of, 81–82
 introduction to, 22–24
 passive, using saturable absorbers, 44–56, 330–337
 colliding pulse mode-locked dye laser, 50, 53–54, 279–281, 310, 430
 processes involved in, 32–33
 regenerative, 43–44
 self-starting, 57, 65, 74, 81–82, 331
 solid-state lasers, using optical Kerr effect, 57–81. *See also* Kerr lens mode-locking
 additive pulse mode-locking (APM), 58, 60–64, 81–82, 178
 self-amplitude modulation, *see*
 Self-amplitude modulation (SAM)
 self-phase modulation, *see* Self-phase modulation (SPM)
- soliton lasers:
 artificial fast saturable absorbers, using, 316–328, 337
 fiber, 316–330
 net gain window, 330–337
 stretched pulse fiber lasers, 337–344

- Modulation, in mode-locking:
 active loss, 38–39, 41, 43–44, 328–334, 336–337
 active phase, 33, 43, 83
 classified, 33, 43–44
 self-amplitude, *see* Self-amplitude modulation (SAM)
 self-phase, *see* Self-phase modulation (SAM)
- Modulational instability, 283–286, 411–412
- Molecular modulators, impulsive stimulated Raman scattering (ISRS), 503–505
- Monochromator, *see* Spectrometer
- Monte Carlo simulations, 450
- Motion, types of:
 bound electron, 2, 199, 359
 coherent, 499–503
 nuclear *or* vibrational, 3, 152, 199, 296–299, 301–302, 440–443, 462–469, 494, 499–503. *See also* Born-Oppenheimer approximation
 orientational, 199, 431–439
 wave packet, 461–469, 494
- Multimode lasers, 13, 22–24
- Multipass amplifiers, 409–410
- NaI, dissociation reaction, 468
- Nanocrystals, three-pulse scattering, 493–494
- Nanosecond, defined, 1
- Nd:glass lasers, 11, 336, 413
- Nd:YAG, 11, 44, 49, 61, 278, 281
- Negative dispersion, 79–80, 153, 180, 183, 336, 338–340, 345–347. *See also* Anomalous dispersion
- Negative uniaxial media, 211
- Net gain window *or* curve, 50–52, 55–56, 80, 330–337
- Nobel Prize, 347, 469
- Noise, 354. *See also* Timing jitter
 amplitude *or* intensity, 82, 98, 141–143
 field, 89, 91, 102–103, 106
 burst, 102–103, 367
- Noncollinear:
 optical parametric amplifier (NOPA), 248–250
 three-wave mixing, 249–252, 254–256, 404
- Nonlinear amplifying loop mirror (NALM), 317–322, 324
- Nonlinear envelope equation (NEE), 350
 in uniform media, 292–295, 308–309, 311
 in waveguides, 295–296, 313
- Nonlinear optical loop mirror (NOLM), 317–320, 322, 324
- Nonlinear optics:
 extreme, 201, 358–359
 in lasers, *see* Mode-locking
 second-order, *see* Second-order nonlinear optics
 third-order, *see* Third-order nonlinear optics
 in waveguides, 261–264
- Nonlinear refractive index, *see also* Optical Kerr effect
 propagation equations, 258–264, 292–296
- Nonlinear Schrödinger equation (NLSE), 266–270, 280, 286, 290–291, 296, 303, 305–307, 331
- Non-Markovian dynamics, 481, 487, 493
- Normal dispersion, 60, 77, 80, 152–153, 159, 166–167, 171–2, 177, 338–343
 and self-phase modulation, 274–275. *See also* Pulse, compression
- n th order susceptibilities, 199
- Nuclear magnetic resonance (NMR), 495
- Nuclear motion, *see* Motion, types of
- Nuclear wave function, 462–465, 467
- Nyquist criterion, 29. *See also* Sampling theorem
- Odd parity, 453
- Off-diagonal elements, 457–458, 478
- Offset frequency, of frequency comb, 349–357
- Ohm's law, 522
- Optical carrier frequency, 24, 27
- Optical clocks, 3, 357–358
- Optical code-division multiple-access (O-CDMA), 367, 382
- Optical coherence tomography (OCT), 96–99
- Optical communications, 4, 44, 79, 265, 288, 311, 324, 330, 340–341, 367, 382
- Optical fibers:
 characteristics of, 4, 264–265
 group velocity dispersion (GVD), 150–151, 374–375
 Raman spectrum, 301–302
 dispersion-compensating, 326, 328–329, 374–375
 erbium-doped, 49, 317, 338, 340
 hollow-core, 265, 276, 281
 microstructured, 265, 310, 313
 nonlinear optics in, *see* Third-order nonlinear optics
 polarization maintaining, 328–329
- Optical Kerr effect, 57–58, 120, 261. *See also* Third-order nonlinear optics
 gating, 119–121
 lensing, 64–66, 411
 solid-state laser mode-locking, using, 57–81, 344–347
- Optical parametric interactions, 237–240. *See also* Three-wave interactions
 amplification *or* amplifiers (OPAs), 245–252, 406

- generators (OPGs), 247–248
- oscillators (OPOs), 111, 247–248, 251
- Optical path length, definition, 11–12, 35
- Optical power spectrum, *see* Power spectrum
- Optical pumping, 11, 16, 44
- Optical rectification, 523–524
- Optical shock, 305–307, 312
- Optical transit time, electro-optic sampling, 516
- Optical wave breaking, 275
- Ordinary wave (o-wave), 212–214, 242–243, 254–256
- Oriental relaxation, 431–439
- Output coupler, 10–12, 53, 65, 74, 248, 318, 339, 344–345

- Parametric amplification, *see* Optical parametric interactions
- Paraxial:
 - propagation, 308–309, 377, 395, 416–418
 - wave equation, 17–18, 215–216
- Parseval's theorem, 26, 234
- Passive mode-locking:
 - defined, 33
 - few cycle lasers, 344–347
 - jitter, 144
 - using saturable absorbers, 44–56, 330–337
 - colliding pulse mode-locked dye laser, 50, 53–54, 279–281, 310, 430
 - solid-state lasers, using optical Kerr effect, 57–81. *See also* Kerr lens mode-locking
 - additive pulse mode-locking (APM), 58, 60–64, 81–82, 178
- Path-averaged soliton, 324
- Permeability, 5
- Permittivity, 5
- Permutation symmetry, 432
- Perturbation(s):
 - growth *or* decay of:
 - modulational instability, 283–286
 - soliton mode-locking, 331, 333, 335–337
 - soliton sidebands, 324–328, 339
 - perturbative nonlinear optics, 201, 203, 258, 261, 263, 405
 - perturbation theory, quantum mechanics, 452–455, 458–460, 464–465
 - in ultrafast spectroscopy, *see* Ultrafast time-resolved spectroscopy
- Petawatt, unit of measurement, 2
- Phase, generally:
 - absolute, 358–359
 - cubic spectral, *see* Cubic (or third-order) second-order spectral, 149–151, 163, 171–172
 - spectral, *see* Spectral phase
- Phase front(s):
 - Gaussian beams, 18–19
 - lenses, 173–174
 - and tilted intensity fronts, 159–161, 252–253
- Phase matching:
 - acousto-optic programmable dispersive filter, 390–392
 - angle tuning, 213–214
 - birefringent, 209–214, 229, 231
 - effect of, continuous-wave SHG, 206–209, 219–220
 - effect of, pulsed SHG, 221–223, 225–226, 228
 - effect of, ultrafast pulse measurements, 100–101, 233–237
 - electro-optic sampling, 525–526
 - quasi-phase matching, 228–233
 - three-wave mixing, 237, 239, 241, 247–256
 - noncollinear, 248–253
 - third-order nonlinear optics, 285–286, 325–327
- Phase modulation, *see also* Self-phase modulation (SPM):
 - active mode-locking, 33, 43, 83
 - liquid crystal arrays, pulse shaping, 399–401, 403–404
 - pulse measurement, 87, 120–121, 125–126
 - time lens, 399–405
- Phase relaxation time, 459. *See also* Dephasing
- Phase retrieval, 107, 126–128, 130, 132
- Phase velocity, *see also* Group velocity
 - defined, 37, 148, 152
 - frequency combs, 348
 - group velocity, compared with, 154
 - nonlinear envelope equation, 293–294
- Phonon motion, 494. *See also* Motion, types of, nuclear *or* vibrational
- Photoconductors, electrical generation and sampling:
 - side-gap correlation geometry, 512, 519
 - sliding contact, 512–513, 518
- terahertz:
 - beams, 517–523
 - time-domain spectroscopy and imaging, 527–528, 530
 - transmission lines, 507–513
- Photocurrent power spectrum, *see* Radio frequency (RF), power spectrum
- Photodetectors (PDs), two- *or* three-photon absorption, 111, 112, 132
- Photodissociation, 3, 469
- Photoexcitation, ultrafast spectroscopy, *see also* Ultrafast time-resolved spectroscopy
 - charge carriers, 444–450, 461–462, 486
 - molecules, 440–442, 468

- Photon echo, 485, 488. *See also* Scattering, ultrafast spectroscopy; Dephasing
- Picosecond, as unit of measurement, 1, 3
- Planck's constant, 451
- Plane wave(s):
 characteristics of, 6–10
 nonlinear propagation equation, third-order nonlinear optics, 260–261
 reflection of, analysis, 192–195
- Plasma generation, 3, 201, 313
- Pockels cell, 410
- Polarization:
 coherent, 471, 476–477, 481–485, 494. *See also* Free induction decay; Dephasing
 effects, in ultrafast spectroscopy, *see* Ultrafast time-resolved spectroscopy
 in electro-optic sampling, change of, 514–515, 524–525
 first-order, 5–6, 201, 259, 297, 455, 469–470, 474, 477, 484
 gating, 119–122, 410, 515
 nonlinear, 199, 201–204, 208, 258–260, 292–297, 358–359, 405
 second-order, 513, 523. *See also* Second-order nonlinear optics
 third-order, *see* Third-order nonlinear optics; Ultrafast time-resolved spectroscopy
 nonlinear polarization evolution, 318–319, 324, 330, 337
 in quantum mechanics, 453, 455, 457
- Polarization-gating FROG (PG-FROG), 119–124, 515
- Polarizing beamsplitter (PBS), *see* Beamsplitter, polarizing
- Population, generally:
 four-level atoms, 15–16, 47–49, 441–442
 inversion *or* difference, 11, 14, 36, 406–407, 409
 ultrafast dynamics, *see* Ultrafast time-resolved spectroscopy
- Positive dispersion, *see* Normal dispersion
- Potential energy surface, 440, 442, 463–469
- Power, average:
 in electromagnetics, 10
 in lasers, 39, 49, 77, 323, 330
- Power flow, Poynting's theorem, 8–10, 208, 432
- Power spectral density, 26, 358
- Power spectrum:
 defined, 86–87
 electric field autocorrelation, relation to, 88–91
 radio-frequency, 139, 141–144, 353–354
 two-dimensional, 126
- Poynting's theorem, 8–10, 208, 432
- Prism pairs *or* sequences:
 dispersion, 166–173
 in lasers, 54, 65, 69, 76, 336, 344–345, 347, 355–356
- Propagation:
 angle-dependent, 155–157, 160–161
 frequency-dependent, 523
 nonlinear, equation:
 forced wave, *see* Forced wave equation
 nonlinear envelope, *see* Nonlinear envelope equation (NEE)
 nonlinear Schrödinger, *see* Nonlinear Schrödinger equation (NLSE)
 characteristic propagation regimes, 268
 nonlinear, generally:
 beam propagation (spatial), 411–412
 third-order, *see* Third-order nonlinear optics
 higher-order effects, 291–310
 paraxial, *see* Paraxial
 soliton, 286–291. *See also* Soliton(s)
 velocity, *see* Group velocity
- Pseudonoise burst, 367
- Pulse, generally:
 chirped Gaussian, 112–114, 117, 121, 125, 150–151, 333, 342
 compression, *see also* Chirped pulse amplification (CPA)
 fiber and grating, 271, 276–283
 molecular modulator, impulsive stimulated Raman scattering, 504
 soliton, 288, 290–291
 fronts, 159–161. *See also* Intensity, fronts, tilted lenses, 176–177
 measurements, *see* Ultrafast-pulse measurement methods
 processing:
 chirp, 397–400
 time lens, 400–405
 propagation velocity, *see* Group velocity
 shape:
 asymmetric, 53, 107, 114, 149
 defined, 85–88
 shaping, *see* Pulse shaping
 square, 365–366
 width, defined, 85–88
- Pulse shaping:
 acousto-optic programmable dispersive filter (AOPDF), 390–394, 414, 421
 applications of, 130–135, 280, 356, 367–368, 374–375, 397, 502
 direct space-to-time (DST), 386–390
 Fourier transform, 362–364
 using fixed masks, examples of, 364–369
 programmable, 369–376
 theory, 376–386
 second-order nonlinear optics:

- quasi-phase matching, 232–233
- sum frequency generation, 242
- Pulse-shortening velocity, 81
- Pump-probe, *see* Ultrafast time-resolved spectroscopy
- Q-switching, 54
- Quadratic dispersion, 149–151, 163, 171–172. *See also* Group velocity dispersion
- Quantum confinement, 461, 493
- Quantum mechanics:
 - basics of, 451–455
 - density matrix, 456–460
 - dephasing phenomena, 469–471, 475–477
 - harmonic potential, 41–42
 - Raman scattering, 297–298, 301
 - wave packets, 461–469
- Quantum noise, 247
- Quantum well(s), 461–462
- Quasi-phase matching (QPM), 228–233
- Radio frequency (RF):
 - arbitrary waveform generation, 397
 - power spectrum, 139, 141–144, 353–354
 - spectrum analyzer, 82, 141
- Raman gain spectroscopy, 301
- Raman scattering:
 - delayed nonlinear response, 296–298
 - impulsive stimulated Raman scattering (ISRS), 499–505
 - response function, and relation to Raman gain, 298–303
 - soliton effects:
 - soliton fission, 304–305
 - soliton self-frequency shift, 303–304
 - vibrational modes, revealed by, 443, 467
- Random process *or* variable:
 - ergodic, 89, 478
 - Gaussian, 102, 478–480
 - random walk, 143
 - time-stationary, 89
- Ray optics, 21
- Ray tracing, dispersive, 172–173
- Reflectors, *see* Mirror structures
- Refractive index:
 - birefringence, *see* Birefringence
 - defined and characteristics of, 6–7, 12, 151–154, 157
 - nonlinear, 57–58, 258–259. *See also* Optical Kerr effect; Third-order nonlinear optics
 - propagation equations, 258–264, 292–296
 - prism pairs and, 168
 - resonant, actively mode-locked lasers, 35–36
 - ultrafast spectroscopy, 423
 - impulsive stimulated Raman scattering (ISRS), 499, 501–504
- Regenerative mode-locking, 43–44
- Relaxation:
 - density matrix treatment, 455–459
 - function, stochastic oscillator, 478–479
 - time, saturable absorption and gain, 15–16, 47–48, 50, 54
 - ultrafast spectroscopy, 440, 444, 455, 459
 - dephasing, *see* Dephasing
 - orientational, 436–439, 441
 - semiconductors, 444–448
 - vibrational, 440–444
- Resonance:
 - absorption and gain, 35, 470–471, 473–474. *See also* Dephasing
 - dispersion and, 151–154
 - electro-optic crystals, 515, 524, 526–527
- Resonator *or* cavity:
 - Gires-Tournois interferometer, 178–179, 184–185
 - laser, 10–14, 18–21
 - coupled-cavity, additive pulse mode-locking, 60
 - intracavity dispersion measurement, 189–191
 - Kerr lens mode-locking, 67–75, 345–347
 - mode-locked, generally, 22–23, 35, 37, 39–40
- Response function:
 - acousto-optic programmable dispersive filter (AOPDF), 391–393
 - pulse shaping, 362–363, 380, 383–390
 - Raman, and relation to Raman gain, 296–305
 - ultrafast spectroscopy, 423–424, 427, 429–430, 432, 434, 437–439, 442, 474
- RF (radio-frequency) spectrum analyzer, 82, 141
- Ring laser, 11, 54
- Root-mean-square (rms):
 - chirp, 104
 - pulse width, 86–87, 104, 117
- Rotating wave approximation, 454, 459
- Round trip time, actively mode-locked lasers, 33–35, 37–38, 40, 44
- Sampling:
 - electro-optic, 513–516, 526–527
 - photoconductive, 511–513
 - theorem, 138. *See also* Nyquist criterion
- Saturable absorber, *see* Absorber, saturable
- Saturation:
 - absorption, *see* Absorber, saturable
 - fluence, 408–409, 412–413
 - gain, 12–17, 35, 49, 55–56, 406, 415

- Saturation (*Continued*)
 in passive mode-locking, *see* Mode-locking,
 passive, using saturable absorbers
 ultrafast spectroscopy, 433–439, 442, 446, 481
- Scalar wave equation, 259
- Scattering:
 impulsive stimulated Raman (ISRS), 499–505
 inverse, 286
 matrix, 62, 178, 319
 Raman, *see* Raman scattering
 in semiconductors, 444, 447–450
 ultrafast spectroscopy:
 three-pulse, 481–484, 488–494
 two-pulse, 481–488
- Schrödinger equation, 41, 451–452, 454, 458,
 463, 465
 nonlinear (NLSE), 266–270, 280, 286,
 290–291, 296, 303, 305–307, 331
- Second harmonic generation (SHG):
 additive pulse mode-locked lasers, 61–62
 continuous-wave (CW):
 focusing effects, 215–220
 phase matching effects, 207–214, 219–220
 summary of, 204–207
 FROG (SHG-FROG), 124–125, 129–130,
 233–234, 236
 intensity correlation measurement:
 autocorrelations, 99–107, 233–236
 cross-correlations, 108
 transverse delay effects, noncollinear
 measurements, 109–110
 with pulses:
 quasi-continuous-wave limit, 220–221,
 227–228
 ultrashort-pulse, 221–228
 quasi-phase matching (QPM), 228–233
 continuous-wave, 229–231
 with pulses, 231–233
- Second-order dispersion, 149–151, 163, 171–172.
See also Group velocity dispersion
- Second-order nonlinear optics:
 conversion efficiency, 206, 224, 228, 242–243
 focusing effects, 215–220, 226–228
 forced wave equation, 201–204, 216, 223, 238,
 524
 introduction to, 198–201
 phase matching, 207–214
 birefringent, 209–214, 229, 231
 effect of, ultrafast pulse measurements,
 100–101, 233–237
 electro-optic sampling, 525–526
 second harmonic generation, 206–209,
 219–223, 225–226, 228
 three-wave mixing, 237, 239, 241, 247–256
 quasi-phase matching (QPM), 228–233
 second harmonic generation, *see* Second
 harmonic generation (SHG)
 spatial walk-off, 212–214, 218–219, 227,
 253–254
 three-wave interactions, *see* Three-wave
 interactions
- Second-order spectral phase, 149–151, 163,
 171–172. *See also* Group velocity
 dispersion
- Self-amplitude modulation (SAM):
 defined and characteristics of, 33, 44, 57–58
 in solid-state lasers:
 additive pulse mode-locking, 61–64
 initiation of mode-locking, 81–82
 Kerr lens mode-locking, 67–75
 mode-locking solutions, 77–78, 80
 soliton lasers, 317–318 321–322, 330
 stretched pulse mode-locking, 337–339,
 342–344
- Self-defocusing, 405
- Self-diffraction FROG (SD-FROG), 122–124
- Self-focusing:
 aberrationless approximation, 71–72
 definition and theory, 66–67, 71–72
 in high-power amplifiers, 405, 411–412
 Kerr lens mode-locking, 64, 66–75
 third-order ultrafast nonlinear optics, 261, 277,
 309, 311–313
- Self-lensing, *see* Self-focusing
- Self-phase modulation (SPM), 33, 58–59,
 270–274. *See also* Soliton(s)
 continuum generation, 310–313
 cross-phase modulation, 275–276, 285, 321
 delayed nonlinear response and the Raman
 effect, 299–300
 with normal dispersion, 78–80, 274–279
 pulse compression, 276–279, 281
 in solid-state lasers:
 additive pulse mode-locking, 61–64
 Kerr lens mode-locking, 69, 74–76, 345
 mode-locking solutions, 77–80
 in soliton lasers, 318, 320, 322, 331, 336
 in stretched pulse mode-locking, 342–343
 in ultrafast-pulse measurements, 121,
 125–126
- Self-starting, mode-locking, 57, 65, 74, 81–82,
 331
- Self-steepening, 306–308, 312, 355
- Sellmeier equation, 153–154
- Semiconductor(s), *see also* Gallium arsenide
 (GaAs)
 built-in fields, 523
 diode lasers, 11, 43–44, 97–98

- optical spectroscopy, 439, 444–451, 471–472, 486–487
 - quantum wells, 461–462
 - saturable absorbers, 54, 330, 335
- Semiconductor-doped glasses, 153
- Shock, optical, 305–307, 312
- Sidebands, spectral:
 - in actively mode-locked lasers, 41–43
 - in impulsive stimulated Raman scattering (ISRS), 503–505
 - soliton, 324–328, 339–340, 343
- Side-gap correlation geometry, photoconductive sampling, 512, 519
- Sigma configuration, mode-locked fiber laser, 328–329
- Signal-to-noise ratio, 143, 357–358, 450–451, 527
- Silica optical fibers, 301–302
- Simulated photon echo, 488
- Single-mode fiber (SMF), 264, 278, 289, 317–318, 374, 377, 397. *See also* Optical fibers
- Single-shot measurements, 108–109, 119, 121, 132, 404
- Sliding contact, photoconductive generation and sampling, 512–513, 518
- Slowly varying:
 - envelope, 18, 27, 394–395
 - envelope approximation (SVEA), 202–204, 245, 260, 263, 293–294, 307–308, 311
- Small-signal:
 - absorption coefficient, 435–436
 - gain, 13–14, 17, 42, 49, 51, 68, 406–409, 414–415
- Snell's law, 167, 172, 178–179, 192, 195
- Soft-aperture KLM, 67–68
- Solid-state lasers, mode-locking, *see* Mode-locking
- Soliton(s), 33, 79, 286–292
 - collisions, 290
 - dark, 286
 - dispersion-managed, 340–342, 345–347
 - effects, in mode-locking:
 - using artificial fast saturable absorbers, 61, 79, 316–328, 337
 - fiber lasers, 316–330
 - net gain window, 330–337
 - fission of, 304–305, 308
 - fundamental, 286–287, 290
 - self-frequency shift, 303–304
 - self-steepening, 307–308
 - sidebands, 324–328, 339–340, 343
- Sonograms, 116–118
 - ultrafast-pulse measurement methods, based on, 130–135, 187
- Space-time, generally:
 - coupling:
 - dispersive lenses, 177
 - Kerr lens mode-locking, 347
 - pulse shaping, 385
 - third-order nonlinear optics, 308–310, 312
 - duality, 394–397, 400–401
- Spatial light modulator (SLM), 363–364, 369–373, 375–376, 384–385
- Spatial resolution:
 - electro-optic sampling, 513
 - microscopy and imaging, 2, 4, 98, 403
- Spatial-spectral interferometry, 190
- Spatial walk-off, in second harmonic generation, 212–214, 218–219, 227, 253–254
- Spectral broadening:
 - continuum generation, 311–313
 - impulsive stimulated Raman scattering, 503–504
 - in mode-locked lasers, 76, 330, 340
 - self-phase modulation, 59, 271–274, 276–277, 300
- Spectral diffusion, *see* Cross-relaxation, spectral
- Spectral filtering, *see* Filters/filtering
- Spectral hole, 14–15, 442–444, 448, 467, 481
- Spectral interferometry, 93–96, 189–190, 372, 495
 - self-referencing (SPIDER), 137–139, 145–146
- Spectrally and temporally resolved upconversion technique (STRUT), 132–134
- Spectral phase, 60, 87, 104, 113–115. *See also* Group velocity dispersion (GVD)
 - cubic, *see* Cubic (or third-order)
 - interferometry for direct electric field reconstruction (SPIDER), 137–139
 - measurement, 91, 93–95, 104, 122, 125, 131–135, 189–190
 - pulse compression, 277, 279–281
 - pulse shaping, 365, 367–369, 372–375
 - second-order, 149–151, 163, 171–172
- Spectral shear *or* shift, 137
- Spectral windowing, 278–279
- Spectrogram, 115–118, 280
 - frequency-resolved optical gating (FROG), 119, 121–122, 124
- Spectrometer, 131, 378–379, 382, 386, 388–390
 - in pulse measurement, 91, 93, 119, 121, 124, 131–133, 138, 190
- Spectroscopy. *See specific types of spectroscopies*
 - ultrafast time-resolved, *see* Ultrafast time-resolved spectroscopy
- SPIDER (spectral phase interferometry for direct electric field reconstruction), 137–139
- Split-off bands, 445, 448

- Split-step Fourier method, 268–270
- Spontaneous emission, 10, 14, 441
amplified, 189, 409–410
- Spontaneous Raman scattering, 296–297,
301–302, 443, 467, 502
- Spread-spectrum communications, 367
- Square pulses, 365–366
- Stabilization, frequency combs, 354–356
- Stepper motor, 108
- Stretched pulse mode-locked fiber laser, 337–340
- Stochastic oscillator, 477–481, 493–494
- STRUT, *see* Spectrally and temporally resolved
upconversion technique (STRUT)
- Sum frequency generation, 200, 237, 240–244,
404, 423, 425
- Supercontinuum generation, *see* Continuum
generation
- Superluminescent diode (SLD), 97–98
- Switches, photoconductive, 507–513
- Switching, nonlinear loop mirrors, 319–322
- Synchronous pumping, mode-locking, 44, 61, 81,
248
- Telecommunications, *see* Optical communications
- Temporal imaging, 401–404
- Terahertz (THz):
beams, ultrafast electromagnetics, 516–531
emission spectroscopy, 529–530
radiation, 462
time-domain electromagnetics, defined, 507.
See also Ultrafast electromagnetics
time-domain spectroscopy, 527–530
as unit of measurement, 2
- Terahertz beams:
characteristics of, 516–517
generation and measurement of, 517–527
terahertz spectroscopy and imaging,
527–531
- Thermal distribution *or* equilibrium, 301, 443–445,
447, 456, 458
- Third-harmonic generation (THG), pulse
measurement, 111–112
- Third-order dispersion, *see* Cubic (*or* third-order),
dispersion
- Third-order nonlinear optics:
higher-order propagation effects:
continuum generation, 248–249, 265, 307,
310–313, 354–355
Raman effect and delayed nonlinear
response, 296–305
self-steepening, 306–308, 312, 355
space-time focusing, 308–310,
312
modulational instability, 283–286
nonlinear polarization, 258–260, 263, 292,
294–295, 297–299
propagation equations, nonlinear refractive
index media:
nonlinear envelope equation, 292–296
nonlinear Schrödinger equation, 266–270
uniform media, 260–261, 292–295
waveguides, 261–264, 295–296
pulse compression, 276–283
self-phase modulation, *see also* Self-phase
modulation
cross-phase modulation, 275–276, 285, 321
dispersionless, 58–59, 270–274
dispersionless with loss, 273
with normal dispersion, 78–80, 274–279
polarization dependence, 276
solitons, 33, 79, 286–292. *See also* Soliton(s)
used for time-resolved spectroscopy, *see*
Ultrafast time-resolved spectroscopy
- Third-order spectral phase, *see* Cubic (*or*
third-order), spectral phase
- Three-photon absorption (3PA), pulse
measurement, 111–112
- Three pulse scattering, 481–484, 488–494
- Three-wave interactions:
difference frequency generation, 237–238,
244–246, 394, 471, 524, 526
noncollinear geometry, velocity matching in,
254–256
optical parametric amplification, 245–253, 406
sum frequency generation, 200, 237, 240–244,
404, 423, 425
types of, 237–240
- Threshold:
damage, 265, 276, 411–412
laser, 14, 17, 42, 82
- Ti:sapphire (Ti:S), 15, 49
amplifier, 408–409, 411–413, 415
laser:
experiments with, 242, 248, 280–281, 310
mode-locking of, 64–67, 70, 74, 82,
190–191, 335, 344–347, 354, 404
pulses, measurements of, 97–98, 104–105,
280, 344
- Tilted intensity fronts, 159–161, 196, 255, 379,
388
- Time-bandwidth product, 87–88, 103–106, 121,
125, 336–337
acousto-optic programmable dispersive filter,
393–393
pulse shaping, 384
- Time-frequency distribution, 99, 115–116, 118.
See also Frequency-resolved optical
gating (FROG)

- Time lens, 399–405
- Time-resolved spectroscopy, *see* Ultrafast time-resolved spectroscopy
- Time-stationary process, 89
- Time-to-frequency mapping, 399
- Time units, defined, 1
- Timing jitter, 139–144, 358, 400
- Timing restoration, active mode-locking, 39
- Transient gratings:
 - frequency-resolved optical gating (FROG), 122–123
 - ultrafast spectroscopy, 423, 429–430, 438
 - dephasing measurements, 481–494
 - impulsive stimulated Raman scattering (ISRS), 501
- Transmission lines:
 - coplanar, 512–514, 516–519
 - electro-optic sampling, 513–516
 - inhomogeneous, relation to chirped mirrors, 185
 - microstrip, 508, 513, 516
 - photoconductive generation and sampling, 507–513
- Transverse delay, 109–110
- Transverse modes, laser resonator, 19–22, 65–66
- Transverse relaxation time, 459, 488. *See also* Dephasing
- Treacy grating pair, 161–162, 165
- Two-dimensional, generally:
 - optical spectroscopy, 494–499
 - phase-retrieval problem, 126
- Two-level atom, 453–454, 457, 459, 475, 477–478, 483
- Two-photon (TPA), absorption or fluorescence, 3, 110–111, 502
- Two-pulse scattering, 484–489
- Type I/Type II phase matching, in second harmonic generation, 213–214, 222, 233–234, 237, 239, 241–242, 253, 255
- Ultrafast electromagnetics, *see* Terahertz beams; Transmission lines
- Ultrafast-pulse measurement methods:
 - based on frequency filtering, *see also* Sonograms
 - double slit approach, 134–135
 - single slit approach, 131–132
 - spectrally and temporally resolved upconversion technique (STRUT), 132–134
 - electric field measurements:
 - autocorrelation and power spectrum, 89–91, 97–98, 107, 430, 442, 490
 - cross-correlation, 91–93, 188–189, 495–496
 - power spectrum, 88–91
 - spectral interferometry, 93–96
- frequency-resolved optical gating (FROG):
 - defined, 118–119
 - error, 128–129
 - polarization-gating (PG), 119–122, 515
 - second harmonic generation (SHG), 124–125, 129, 233–234, 237
 - self-diffraction, 122–124
 - signal recovery from FROG traces, 126–130
 - temporal phase modulation and, 125–126
- intensity autocorrelation, 99–111, 429–431, 441–442
- data, 104–105, 233, 277–279, 289–290, 312–313, 335, 338, 344
- experimental procedures, 108–110, 351
- higher-order correlation techniques, 111–112
- interferometric (fringe-resolved), 104–107, 112, 344
- using second harmonic generation (SHG), 99–108, 233–236
- using two-photon absorption, 110–111
- intensity cross-correlation, 108, 350–351
- noise and jitter, 139–144
- self-referencing interferometry:
 - mode-locked frequency combs, 351–354
 - spectral (SPIDER), 137–139
 - time-domain, of chirped pulses, 135–137
- spectrogram, 115–118, 280
- in frequency-resolved optical gating (FROG), 119, 121–122, 124
- terminology and definitions, 85–88
- Ultrafast time-resolved spectroscopy:
 - characteristics of, 2–3, 422–426
 - dephasing:
 - linear spectroscopies, 469–475
 - measurement using transient gratings, 481–494
 - models of, 475–481
 - two-dimensional spectroscopy, 494–499
 - fluorescence, 241, 423, 425–426, 448–450, 468
 - impulsive stimulated Raman scattering (ISRS), 499–505
 - pump-probe, 422–425
 - degenerate:
 - coherent coupling, 429–431, 433–434, 438–439, 441–442
 - co-polarized fields, 426–431
 - vector fields and orientational effects, 431–439

- nondegenerate and spectrally resolved:
 - dye molecules, 440–444
 - GaAs and related semiconductors, 444–451
 - significance of, 439–440
- quantum mechanics:
 - basics of, 451–455
 - density matrix, 456–460
- wave packets:
 - characteristics of, 460–461
 - molecules, 462–469
 - semiconductors, 461–462, 494
- Ultrashort pulse manipulation:
 - acousto-optic dispersive filters, 390–394, 414, 421
 - amplification, 405–416
 - chirp processing, 397–400
 - pulse shaping:
 - applications of, 130–135, 280, 356, 367–368, 374–375, 397, 502
 - direct space-to-time (DST), 386–390
 - Fourier transform, 362–364
 - using fixed masks, examples of, 364–369
 - programmable, 369–376
 - theory, 376–386
 - second-order nonlinear optics:
 - quasi-phase matching, 232–233
 - sum frequency generation, 242
 - space-time duality, 394–397, 400–401
 - time lens processing, 399–405
- Ultrashort-pulse SHG, *see* Second harmonic generation (SHG)
- Ultraviolet, 2–4, 152–153, 175, 237, 296, 405, 504
- Uncertainty relation, 88, 117–118
- Uniaxial media, 211. *See also* Birefringence
- Units of measurement, 1–2, 5
- Up-chirp, 59, 76, 78–79, 113, 122, 271, 274–276, 284
- Upconversion:
 - fluorescence spectroscopy, via upconversion gating, 450–451
 - spectrally and temporally resolved upconversion technique (STRUT), 132–134
 - sum frequency generation, 241–243
- Velocity:
 - group, *see* Group velocity; Group velocity dispersion (GVD)
 - matching, noncollinear optical parametric amplification, 250–256
 - mismatch, electro-optic sampling, 515–516, 526–527
 - phase, *see* Phase velocity
- Vibration(s) *or* vibrational:
 - motion, *see* Motion
 - Raman scattering, 296–298
 - impulsive stimulated Raman scattering (ISRS), 499–505
 - relaxation, 440–444
 - ultrafast spectroscopy, 424, 440–447, 456, 463–469, 493–494
- Vision process, 3
- Wave equation, *see also* Propagation
 - forced, 201–204, 223, 524
 - paraxial, 17–18, 215–216
 - plane waves, 6–8
 - scalar, 259
- Wave function, 57, 434, 441, 443, 445, 451–454. *See also* Wave packet.
- Waveguides, *see also* Optical fibers
 - nonlinear envelope equation, 295–296, 313
 - nonlinear optics in, 261–264
- Wave impedance, *see* Impedance
- Wavelength-division-multiplexed (WDM) communications, 4, 340
- Wave packet(s):
 - characteristics of, 460–461
 - molecules, 462–469
 - semiconductors, 461–462, 494
- White light:
 - generation, *see* Continuum generation
 - interferometry, 171, 187
- X-ray, 2, 4, 152, 405, 424–425