

INDEX

A

Absorption, 12, 29
Absorption filters, 71, 86
Acceptance cone, 43–44
Access DWDM networks, 183
Acousto-optic couplers, 95
Acousto-optic filter (AOF), demultiplexers, 87, 95
Acousto-optic switching, 142, 148
Acousto-optic tunable filters (AOTFs), 71, 82–83
Acronyms/abbreviations, 223–231
Active region, lasers, 103
Active demultiplexers, 91
ACTS organization, 210
Add-drop multiplexers (*see* optical add-drop multiplexers), 151
Aggregate bandwidth, DWDM networks, 180, 187, 192
AlGaAs lasers, 102, 103, 105
All-Optical Networking Consortium, 209–210
AllWave Fibre , 55–56
All-optical switching, cross-connects, optical (OCX), 141
Amplifier spontaneous emission (ASE), EDFA, 124
Amplification and amplifiers, 5, 6, 119–130, 187, 191
amplified spontaneous light emission (ASE), 124
antireflective coatings, 121
bandwidth, 119, 121

classification of optical fiber amplifiers, 126–127
cross-gain modulation, 128
cross-talk, 121, 124
dispersion-shifted fiber (DSF), 128
DWDM networks, 187, 191
dynamic range, 121, 124
erbium-doped fiber amplifiers (EDFA), 51, 57, 121, 122–125, 179, 191
Fabry–Perot laser amplifiers, 121
fiber-optic amplifier (FOA), 122
four-wave mixing, 128
frequency shifters, 129
gain, 119, 121
gain bandwidth, 119
gain efficiency, 119
gain over bandwidth, 121
gain saturation, 119, 124
gain time, 124
injection current distributed-feedback (DFB) laser amplifiers, 121
interferometric techniques, 128
lasers, 121
line amplifiers, 126, 127
maximum output power, 121
noise, 119
noise figure, 121, 124
optical add-drop multiplexers (OADM), 125
optical density (OD), 121
optical fiber amplifiers (OFAs), 126
output saturation power, 121
polarization sensitivity, 119, 120, 122, 124

- power amplifiers, 126–127
 praseodymium-doped fiber amplifier (PDFA), 57, 121, 125
 preamplifiers, 126, 127
 probe signals in frequency shifters, 129
 pumps, in laser, 121, 123, 129
 quantum yield (*Q*), 121
 Raman scattering amplifiers, 57, 121
 Raman supercontinuum, 126
 regenerators, 120
 saturation power, 119, 121, 124
 semiconductor optical amplifiers (SOA), 121, 122
 sensitivity, 119, 120, 124
 signal to noise ratio (OSNR), 126
 spontaneous lifetime in EDFAs, 123
 spontaneous noise in EDFAs, 124
 standards for optical amplifiers, 127
 stimulated Brillouin amplifiers, 121, 126
 stimulated Raman amplifiers, 121, 126
 telluride-erbium-doped fiber amplifiers, 57
 traveling wave laser amplifiers, 121
 wavelength converters, 127–129
- Amplitude**
 Fabry–Perot interferometer, 71
 lasers, 101
 light-emitting diodes, 100
- Amplitude modulators**, 167
- Amplitude shift keying (ASK)**, 165, 169–170, 173–174
- Angle of deflection**, 15
- Angle of incidence**, 13–14, 15
- Angstrom as unit of measure**, 7
- Angular dispersion**, 15
- Anisotropy and anisotropic materials**, 12, 24, 25, 28
- Anomalous dispersion regime**, 65
- Answers to chapter questions**, 233–240
- Antireflective coatings**
 amplifiers, 121
 in fibers, 19
- Aperture**, 43–44
- Applicability of DWDM**, 182–185
- Arrayed lasers**, 107–108
- Arrayed waveguide grating (AWG)**,
 demultiplexers, 93–94
- Associative RAM-based CAM (AR-CAM)**, 216
- Asynchronous transfer mode (ATM)**, 5
 DWDM networks, 179, 182, 183, 193, 201
 ultrafast pattern recognition, 217
- Attenuation**
 in DWDM networks, 190–191
 in fiber, 54–57
- Attenuator, optical**, 11
- Avalanche photodetector (APD)**, 105, 115, 117
 lasers, 105
- B**
- Backbone networks using DWDM**, 182–185
- Backplanes, optical**, 213–214
- Backward scattering**, 60
- Bandwidth**, 3
 amplifiers, 119, 121
 bit rate increases to increase bandwidth, 4, 6
 DWDM networks, 177, 180, 187, 192, 196
 fiber, 37
 increasing bandwidth of fiber, 4
 light-emitting diodes, 100
 wavelength increases to increase bandwidth, 4, 6
- Beam-splitter, polarizing**, 81, 95
- Beat length of fiber**, 59
- Bend radius**, 30
- “Big fat pipe” topology, 181
- Bipolar signal coding**, 168–169
- Birefringence**, 12, 26, 59
- Birefringence filters**, 82, 86–87
- Bit error rate (BER)**, DWDM networks, 189, 190, 193
- Bit rate**, 4, 6, 46
- Blaze angle**, in diffraction grating, 17
- Blue band**, 56
- Blue shift**, 65
- Boltzmann’s Constant**, 99
- Bragg condition**, 77
 acousto-optical tunable filters (AOTFs), 82
- Bragg grating**, 53, 76–80
 Bragg condition, 77
 Bragg reflector, 77
 distributed Bragg reflector (DBR), 104, 107
 fiber Bragg grating (FBG), 77–79
 mechanical tuning, 80
 monolithic Bragg lasers, 104
 photonic lattice, 79
 power-reflected coefficient, 76
 power-transmitted coefficient, 76
 thermal tuning, 80
 tunable Bragg gratings, 80
- Bragg laser, monolithic**, 104
- Bragg reflector**, 71, 77
- Brewster’s law**, 24
- Brillouin scattering**, 28, 60, 62, 121, 126
- Broadband rates for DWDM networks**, 183
- Broadcast and select function**, 181
- Bus, wavelength bus**, 218–219

C

- C-band, 56, 58, 113, 211
Call admission control (CAC), DWDM networks, 193
Campus DWDM networks, 183
Candelas/candles as unit of measure, 9
Cascaded amplifiers, DWDM, 180
Cavity loss, Fabry–Perot interferometer, 74
Chalcogenide glass (GeSeTe), 41, 213
Channel bit rate/modulation, DWDM networks, 187, 189
Channel calculations, DWDM networks, 196
Channel capacity, DWDM networks, 187, 189
Channel dispersion, DWDM networks, 187, 190
Channel performance, DWDM networks, 187, 190
Channel spacing/separation, DWDM networks, 187, 189
Channel tuning, 87
Channel width, DWDM networks, 187, 189
Channels, DWDM networks, 180, 181, 187, 189, 196
Chirped-pulse laser sources, 102, 109
Chirped-pulse wavelength division multiplexing (CPWDM) lasers, 109
Chirping, optical, 64
Chromatic dispersion, 48–50, 53
DWDM networks, 191
limits of, 51–52
Chromatic dispersion coefficient (CDC), 49, 51–52
Circulators, 138–139
Cladding of fiber, 37, 40
Coarse wavelength division multiplexing (CWDM), 4, 179, 183, 200
Coating of fiber, 37
Coding techniques, 165–172
 4B/5B coding, 169
 8B/10B coding, 169
 amplitude modulators, 167
 amplitude-shift keying (ASK), 165, 169–170
 bipolar signals, 168–169
 coherent detection techniques, 165–166, 169–170
 dense wavelength division multiplexing (DWDM), 165
 distributed feedback (DFB) lasers, 171
 frequency-shift keying (FSK), 165, 171–172
 heterodyne detection techniques, 165
 homodyne detection techniques, 165
 intensity modulation with direct detection (IM/DD), 165–166, 169
line coding, 212
multilevel signals, 169
multiple quantum well (MQW) structures, 169
narrowband FSK, 171
non-return-to-zero (NRZ) coding, 167–168
on-off keying (OOK), 169
phase-shift keying (PSK), 165, 170–171
return-to-zero (RZ) coding, 167–168, 169
unipolar signals, 168–169
wideband FSK, 171
Coherent detection techniques, 165–166, 169–170
Coherent light, 19, 101, 163
Collimated light and prisms, 16, 91–92
Collision length in fiber, 68
Collision-induced temporal shift, 68
Columbia University lightwave group, 210
Comb generators, 108
Compatibility, interdomain, DWDM networks, 194–195
Compensation for chromatic dispersion, 53
Compton’s experiment in light, 7
Cone, light-emitting diodes, 100
Connectors, fiber, 68–69
Constructive interference, 18–19
Content-addressable memory (CAM), 216
Continuous wave (CW) light, 97
Core of fiber, 37, 37, 40
Couplers, optical directional, 132–134
 star couplers, 144
Cracks, effects of, in fiber, 30
Critical angle, 13–14
Critical cone, 43–44
Cross-connect, optical (OCX), 5, 6, 141–150, 212–213
 acousto-optic couplers, 142
 acousto-optic switching, 148
 all-optical switching, 141
 electro-optic couplers, 142
 electro-optic switching, 148
 electromechanical switches, mirror array, 142, 146–148
 free space optical switching, 142–143
 hybrid approach, 141
LiNbO₃ switching devices, 149
Mach–Zehnder interferometers, 142
microelectromechanical switches (MEMS), reflectors, 145–146
modeling of OCX, 142
nonlinear electro-optic devices, 149
photochromic switching, 149
polymer-based switches, 149

reflectors, 145–146
 SiO_2 -on-Si planar switches, 149
 solid-state cross connects, 142, 143–145
 star couplers, 144
 switching speeds, 148–149
 thermo-optic switching, 148
 ultrafast switching, 212–213
 waveguide grating router (WGR), 142
 wavelength routing, 142
 write once read many (WORM) applications, 149

Cross-gain modulation, amplifiers, 128
 Cross-talk, 4
 amplifiers, 121, 124
 in DWDM networks, 180, 189
 Crystals, 25, 26
 Cut off frequency
 in fiber, 41, 58–59
 in photodetectors, 115, 116

D

Dark current, photodetectors, 115, 116, 117
 Data traffic, 3, 6
 Decibel as unit of measure, 55–56
 Decoding techniques, 173–176
 amplitude-shift keying (ASK), 173–174
 frequency-shift keying (FSK), 173, 174–175
 phase-shift keying (PSK), 173, 174–175
 quantum limit of receiver, 173
 Deflection, angle of, 15
 Delay in fiber, 45–46
 variable delay lines, 213
 Demodulators
 amplitude-shift keying (ASK), 173–174
 frequency-shift keying (FSK), 174–175
 phase-shift keying (PSK), 174–175
 Demultiplexers, 5, 91–96
 acousto-optic filter (AOF), 95
 active, 91
 arrayed waveguide grating (AWG), 93–94
 diffraction gratings, 92–93
 graded index (GRIN) rod, 94
 Mach-Zehnder interferometer, 94
 optical multiplexers, 95–96
 passive, 91
 phased-array gratings (PHASARS), 94
 photonic crystalline optics, 92
 polarizing beam-splitter, 95
 prisms, 91–92
 spectral filters, 94–95
 superprisms, 92
 waveguide grating routers (WGR), 94, 109–110

Dense wavelength division multiplexing (DWDM), 4–5, 6–7, 51, 165, 177–222
 ACTS organization, 210
 aggregate bandwidth, 180, 187, 192
 All-Optical Networking Consortium, 209–210
 amplification, optical, 187, 191
 applicability of DWDM, 182–185
 asynchronous transfer mode (ATM), 179, 182, 183, 193, 201, 214
 backbone networks using DWDM, 182–185
 backplanes, optical, 213–214
 bandwidth, 177, 180, 187, 192, 196
 “big fat pipe” topology, 181
 bit error rate (BER), 189, 190, 193
 broadband rates, 183
 broadcast and select function, 181
 call admission control (CAC), 193
 channel bit rate/modulation, 187, 189
 channel calculations, 196
 channel capacity, 187, 189
 channel dispersion, 187, 190
 channel performance, 187, 190
 channel spacing/separation, 187, 189
 channel width, 187, 189
 channels, 180, 181, 187, 189, 196
 coarse WDM (CWDM), 179, 183, 200
 Columbia University Lightwave Group, 210
 compatibility, interdomain, 194–195
 cross-talk, 180, 189
 digital wrappers, 185
 dispersion, 187, 190
 downtime, 193
 effective area, 191
 engineering of DWDM systems, 187–196
 erbium-doped fiber amplifiers (EDFA), 179, 191
 Ethernet, 201, 214
 faults, 189–190, 193, 202–203
 fiber technology, 58, 187, 191, 200
 fiber-distributed data interface (FDDI), 202
 FiberVista technology, 200
 flexibility, 188, 194
 forward error correction (FEC), 185
 four-wave mixing (FWM), 66
 frame relay, 193
 fully meshed topology, 181
 gain, 192
 heterogeneous traffic, 179
 homogenous traffic, 179
 hubs, 198–200, 201–202
 interdomain compatibility, 188, 194–195
 Internet/Internet Protocol (IP), 179, 182, 183, 193, 201, 214

- interoperability of DWDM networks, 185, 188, 194–195
lasers, 105
latency, 185
loss, 192, 195
maximum allowable power per channel, 191
mesh topology, 198–200
Metropolitan Optical Network project (MONET), 197, 210
modulation, 187
monitoring of optical networks, 213
MTONC organization, 210
multichannel frequency stabilization, 187, 190
narrowband rates, 183
network management protocols, 188, 193, 214
nodes, 181–182, 214
nominal center frequencies, 187, 188–189, 196
opaque systems, 215
operations, administration, maintenance, and provisioning (OAM&P), 185
optical add-drop multiplexers (OADM), 181, 197–199, 202
optical amplification, 187, 191
optical power budget, 191–192
point-to-point topology, 181, 197–198
power budget, optical, 191–192
power gain, 192
power launched, 187, 191
power loss, 192, 195
power received, 187
protection of DWDM networks, 188, 193
protocols, 187, 188, 193
quality of service, 185
receive direction, 201–202
reconfigurability, dynamic, 213
reliability, 188, 193, 214
research in DWDM technology, 209–210
ring topology, 181, 198–200
routers, 181–182, 181
scalability, 188, 194
SDH support, 179, 182, 183, 184, 193, 214
security, 214
service protection, 188
services supported, 187, 192, 193, 214
signaling, 193
single-mode power loss calculations, 195
SONET support, 177, 179, 182, 183, 184, 193, 209, 214
standards, 180, 185, 194–195, 206–207, 214
star topology, 181, 198–200
survivability of DWDM networks, 188, 193
synchronous transport module (STM), 198, 201
TCP/IP, 201
telephony, 193
time division multiplexing (TDM), 179, 182, 183
topologies of DWDM networks, 181–182, 197–207
transmit direction, 201
transparency, 214
ultrafast pattern recognition, 215–218
ultrahigh speed at longer spans, 214–215
uninterrupted service, 188
video, 179, 193
voice, 179
wavelength bus, 218–219
wavelength division multiplexing (WDM), 177, 179
wavelengths, 179, 180, 181, 187, 188–190, 194, 214
WaveStar technology, 183–184
wrappers, digital, 185
Destructive interference, 19
Dielectric constants, 25, 41
Dielectric coefficients and dispersion, 26–27
Dielectric thin film (DTF) filter, 80–81
Dielectric thin-film interference, 71
Diffraction, 7, 12, 16, 20, 71
Diffraction at infinity, 16, 20
Diffraction coupler, 134
Diffraction gratings, 17, 20, 88–89, 92–93
Digital transmission
 bipolar, 168–169
 multilevel, 169
 unipolar, 168–169
Digital wrappers, DWDM networks, 185
Directional couplers, optical, 132–134
Dispersion, 12, 15, 28, 48–57, 65
 DWDM networks, 187, 190
Dispersion flattened compensated fiber (DFCF), 51
Dispersion-compensated fiber (DCF), 51, 53
Dispersion-flattened fibers (DFF), 50–51
Dispersion-shift-compensated fiber (DSCF), 51
Dispersion-shifted fibers (DSF), 50–51, 113
 amplifiers, 128
Dispersion-slope-compensated fiber (DSCF), 51
Distributed Bragg reflector (DBR), 104, 107
Distributed feedback (DFB) lasers, 105, 110–111, 171
Dopants in fiber, 38, 37, 40
Downtime, DWDM networks, 193
Dynamic range, amplifiers, 121, 124

Dynamic reconfigurability, 213
 Dynamic wavelength equalizers (DWE), 136
 Dynamically wavelength selectable OADM,
 152

E

8B/10B coding, 169
 Effective area, DWDM networks, 191
 Eigenvalues and modes of fiber, 41
 Einstein's equation, 8
 Electro-optic couplers, 142
 Electro-optic switching, 148
 Electroabsorption (EA) lasers, 107
 Electroabsorption modulated DFB laser (EML),
 111
 Electromagnetic fields, 11, 22
 Electromechanical switches, mirror array, 142,
 146–148
 Engineering of DWDM systems, 187–196
 Equalizers, optical, 136–137
 Erbium-doped fiber amplifier (EDFA), 61, 121,
 122–125, 179, 191
 Etalon, 73
 Ethernet support, DWDM networks, 201
 Exit cone, 44
 Extinction of reflection, 19
 Extinction ratio, 24, 112
 Extraordinary ray, 26

F

4B/5B coding, 169
 Fabry–Perot filters, 75–76, 87
 Fabry–Perot interferometer, 1, 72–76
 amplitude, 73
 cavity loss, 74
 etalon, 73
 Fabry–Perot filter, 75–76, 87
 Fabry–Perot resonator, 72–74
 finesse, 74
 line spacing, 75
 line width (channel width), 75
 modes, 73
 phase, 73
 power-reflected coefficients, 72
 resonant wavelengths or modes, in
 resonator, 73
 spectral width, 75
 Fabry–Perot lasers, 103–104, 105
 Fabry–Perot laser amplifiers, 121
 Fabry–Perot resonator, 72–74
 Fading, 7
 Fall time, photodetectors, 115, 116

Far end, fiber technology, 63–64
 Faraday effect, 24–25
 Fast tuning filters, 87
 Faults in DWDM networks, 189–190, 193,
 202–203
 Feedback, lasers, 103
 Fiber Bragg grating (FBG), 77–79
 Fiber technology, 4, 5., 37–70
 acceptance cone, 43–44
 anomalous dispersion regime, 65
 attenuation, 54–57
 backward scattering, 60
 bandwidth of, 4, 37
 birefringence, 59
 bit rate, 46
 blue band, 56
 blue shift, 65
 Bragg gratings, 53
 Brillouin scattering, 60, 62
 C-band, 58, 113
 chirping, 64
 chromatic dispersion coefficient (CDC), 49,
 51–52
 chromatic dispersion compensation, 53
 chromatic dispersion limits, ITU-T, 51–52
 chromatic dispersion, 48–50
 cladding, 37, 40
 collision length, 68
 collision-induced temporal shift, 68
 connectors, 37, 68–69
 copper cabling vs., 37
 core, 37, 40
 cost of installation, 37
 critical cone, 43–44
 cut off frequency, 41, 58–59
 decibel, 55–56
 in dense WDM (DWDM), 51, 58, 66, 187,
 191, 200
 dielectric constants, 41
 dispersion flattened compensated fiber
 (DFCF), 51
 dispersion, 65
 dispersion-compensated fiber (DCF),
 51, 53
 dispersion-flattened fibers (DFF), 50–51
 dispersion-shift-compensated fiber
 (DSCF), 51
 dispersion-shifted fiber (DSF), 50–51, 113,
 128
 dispersion-slope-compensated fiber
 (DSCF), 51
 dopants, 37, 38, 40
 eigenvalues, 41

- electromagnetic interference, 37
erbium-doped fiber amplifiers (EDFA), 51, 57
exit cone, 44
far end, 63–64
fiber attenuation or loss, 54–57
fifth window, 55, 56
forward scattering, 60
four-photon mixing (FPM), 60, 62–63
four-wave mixing (FWM), 60, 62–63, 66
fourth window, 56
Gaussian index, 40
Gaussian pulses, 64
graded index, 42, 43
group velocity dispersion (GVD), 49
group velocity, 44–45
hyperbolic secant function, in solitons, 67
index of refraction, 38, 40–41
installation, 37
interference, 37
intermodal delay difference, 45–46
isotropic medium, 61
jitter, 68
Kevlar, 37
L-band, 50, 56, 58
loss, 54–57
manufacture of, 38
material dispersion, 48
maximum bit rate, 46
modal dispersion, 45–47
mode mixing, 47
modes, 41–42, 45
modified chemical vapor deposition (MCVD), 38, 39
modulation instability, 65
multimode graded index, 42
multimode, 41, 42
near end, 63–64
negative dispersion-flattened fibers, 51
nonlinear phenomena, 60–64
nonzero dispersion fiber (NZDF), 51
normal dispersion regime, 65
numerical aperture, 43–44
optical power, 55–56
outer vapor deposition (OVD), 38
permittivity in vacuum, 61
phase change, 64
phase velocity, 44
photon–atom interaction, 60
polarization, 59
polarization-maintaining fiber (PMF), 113
polarization mode dispersion (PMD), 54
positive dispersion-flattened fibers, 51
preform fiber processes, 38–39
propagation of light, 43
pulse spread, chromatic dispersion, 49
Raman scattering, 60, 61
Rayleigh scattering, 54
red band, 56
red shift, 65
reduction of modal dispersion, 47
refractive index, 38, 40–41
S-band, 56, 58
scaling factor, 47
scattering, 60, 62
Schrödinger equation, 67
self phase modulation (SPM), 65
self-modulation, 65
silica, 38, 39
single mode, 41, 42
single-mode chromatic dispersion calculations, 52–53
single-mode fiber cutoff wavelength, 58–59
sol gel method, 39
solitons, 67–68
spectral broadening, 64–65
spectrum utilization, 56–57
step index, 40, 43
stimulated Brillouin scattering, 62
stimulated Raman scattering (SRS), 61–62
susceptibility, 60
temporal FWM (tFWM), 63–64
timing jitter, 68
transverse electric field, 41
transverse magnetic field, 41
travel time variation, chromatic dispersion, 49
triangular index, 40
TrueWave fibers, 51
vapor phase axial deposition (VAD), 38
wavelength dispersion, 48–49, 65
wavelength division multiplexing (WDM), 58
zero-dispersion wavelength, 50
Fiber to the desktop PC (FTTPC), 5, 213
Fiber to the home (FTTH), 5
Fiber-distributed data interface (FDDI), 202
Fiber-optic amplifier (FOA), 122
FiberVista technology, DWDM networks, 200
Fifth window, 55, 56
Filters, 5, 6, 11, 71–89
absorption, 71, 86
acousto-optic filter (AOF), 87, 95
acousto-optic tunable filters (AOTFs), 71, 82–83
birefringence, 27, 82, 86–87

- Bragg condition, 77
 Bragg grating, 76–80
 Bragg reflector, 71, 77
 channels, 87
 collinear AOTF, 83
 dielectric thin film (DTF), 80–81
 dielectric thin-film interference, 71
 diffraction, 71
 diffraction gratings, 88–89
 Doppler effect, 83
 Fabry–Perot filter, 75–76, 87
 Fabry–Perot interferometer, 71–76
 Fabry–Perot resonator, 72–74
 fast tuning, 87
 fiber Bragg grating (FBG), 77–79
 finesse, Fabry–Perot interferometer, 74
 fixed, 71
 hybrid, 71, 87
 interference, 71
 line spacing, 75
 line width (channel width), 75
 loss, 87
 Mach–Zehnder, 19, 83–86
 mechanical tuning, 80, 87
 noncollinear AOTF, 83
 optical frequency discriminator (OFD), 86
 photonic lattice, 79
 polarization independent, 83
 polarizing beam-splitters, 81, 95
 power-reflected coefficients, 72, 76
 power-transmitted coefficient, 76
 spectral filters, 94–95
 spectral width, 75
 surface acoustic wave (SAW) device, 82
 thermal tuning, 80
 tunable Bragg gratings, 80
 tunable optical filters (TOFs), 71, 81, 87–88
 Finesse, Fabry–Perot interferometer, 74
 Fixed filters, 71
 Fixed frequency lasers, 103
 Fixed-wavelength OADM, 152
 Flexibility of DWDM networks, 188, 194
 Flux density, 9
 Forward error correction (FEC), DWDM
 networks, 185
 Forward scattering, 60
 Forward-biased noise, photodetectors, 115, 116
 Four-photon mixing (FPM), 60, 62–63
 Four-wave mixing (FWM), 28, 60, 62–63, 66,
 128
 Fourth window, 56
 Frame relay, in DWDM networks, 193
 Free space optical switching,, 142–143
 Frequency, light, 7, 8, 13
 Frequency bandwidth, photodetectors, 115, 116
 Frequency division multiplexing (FDM), 5–6
 Frequency modulators, lasers, 112
 Frequency-shift keying (FSK), 165, 171–175
 Fresnel’s phenomenon (*see also* diffraction), 16
 Fully meshed topology, 181
- G**
- GaAs lasers, 105
 Gain
 amplifiers, 119, 121
 DWDM networks, 192
 lasers, 101
 Gain bandwidth, amplifiers, 119
 Gain efficiency, amplifiers, 119
 Gain over bandwidth, amplifiers, 121
 Gain saturation, amplifiers, 119, 124
 Gain time, amplifiers, 124
 Gaussian beams, 17
 Gaussian index, 40
 Gaussian pulses, 64
 Generators, optical comb generators, 108
 Graded index fiber, 42, 43
 Graded index (GRIN) rod, 94
 Grating constant, 17
 Gratings, 1, 71–89
 arrayed waveguide grating (AWG), 93–94
 Bragg grating, 76–80
 diffraction gratings, 17, 20, 88–89, 92–93
 fiber Bragg grating (FBG), 77–79
 hybrid filters, 87
 lasers, 101
 mechanical tuning, 80
 phased-array gratings (PHASARS), 94
 thermal tuning, 80
 tunable Bragg gratings, 80
 waveguide grating router (WGR) , 94,
 109–110
- Group velocity , fiber technology, 44–45
 Group velocity dispersion (GVD), 49
- H**
- Half-wavelength plate, 28
 Hertz as unit of measure, 7
 Heterodyne detection techniques, 165
 Heterogeneity, optical, 29
 Heterogeneous traffic, 179
 High-speed data communications, 3
 Holograms, 20
 Holography, 12, 20–22
 Homodyne detection techniques, 165

Homogeneity, optical, 29
Homogenous traffic, 179
Hubs, DWDM networks, 198–200, 201–202
Huygens–Fresnel principle, 18
Hybrid filters, 71
Hybrid approach to cross-connects, 141
Hydroxyl radical (OH), 30
Hyperbolic secant function, in solitons, 67

I

Illuminance, 9
Image recognition systems (*see also* holography), 20–22
Impurities in matter, effect of, 29–30
Incidence, angle of, 13–14, 15
Index of refraction, 12–14, 15, 25, 26, 38, 40–41
DWDM networks, 191
fiber technology, 38, 40–41
heterogeneity of materials and light, 29
homogeneity of materials vs., 29
impurities in material vs., 29–30
mechanical pressure vs., 30
microcracks vs., 30
silica, 28
temperature variations vs., 31
Infinity, diffraction at, 16, 20
InGaAsP lasers, 102, 105
Injection current distributed-feedback (DFB) laser amplifiers, 121
Input-output response, light-emitting diodes, 99
Insertion loss, optical isolators, 137
Integrated cavity lasers, 107
Integration of optical technology, 212
Intensity modulation with direct detection (IM/DD), 165–166, 169
Intensity modulator lasers, 112
Interdomain compatibility, DWDM networks, 188, 194–195
Interference, 7, 12, 18–19, 71
filters, 71
intersymbol interference (ISI), 212
Interferometers, 73
Fabry–Perot interferometer, 71–76
Mach–Zehnder interferometer, 94, 109
Interferometric techniques, amplifiers, 128
Intermodal delay difference, 45–46
Internet, 3, 5, 6
DWDM networks, 179, 182, 183, 193, 201
ultrafast pattern recognition, 217–218
Interoperability of DWDM networks, 188, 194–195

Intersymbol interference (ISI), 212
Ionization, 12
Isolators, optical, 137–138, 137
Isotropy and isotropic materials, 12, 25, 28, 61

J

Jitter, 68, 190

K

Kevlar as coating, 37

L

L-band, 50, 56, 58, 211
LRC filters, 71
Laser sources, 5, 97, 100–111, 212
active regions, 103
AlGaAs lasers, 102, 103, 105
amplifiers, 121
amplitude, 101
arrayed, 107–108
avalanche photodetector (APD), 105
chirped-pulse, 109
chirped-pulse wavelength division multiplexing (CPWDM), 109
chirping, 102, 109
coherent light, 101
dense wavelength division multiplexing (DWDM), 105
dispersion-shifted fiber (DSF), 113
distributed Bragg reflector (DBR), 104, 107
distributed-feedback (DFB), 105, 110–111, 171
electroabsorption (EA), 107
electroabsorption modulated DFB laser (EML), 111
extinction ratio, 112
Fabry–Perot, 105
feedback, 103
fixed frequency, 103
frequency modulators, 112
GaAs lasers, 105
gain, 101
grating, 101
InGaAsP lasers, 102, 105
integrated cavity, 107
intensity modulators, 112
light-emitting diodes, 102
Mach–Zehnder interferometer, 109
Mach–Zehnder laser, 105
Mach–Zehnder modulation (M–Z), 111
metal organic chemical vapor deposition (MOCVD), 105

- modulation depth, 112
- modulators, 111–113
- molecular beam epitaxy (MBE), 105
- monolithic, 103
- monolithic Bragg lasers, 104
- monolithic DFB arrays, 110–111, 110
- monolithic Fabry–Perot lasers, 103–104, 103
- monolithic tunable, 107
- multifrequency cavity lasers (MFL), 109–110
- multifrequency lasers, 101, 107–108
- multiple quantum well (MQW), 105, 112
- multiple quantum well lasers (MQWL), 106
- optical comb generators, 108
- oscillation, 101
- phase condition, 101
- phase modulators, 112
- photodiode (PIN), 105
- photon activity, 101
- polarization-maintaining fiber (PMF), 113
- pump lasers, 123
- ruby, 101–102
- semiconductor lasers, 97, 102–103
- semiconductor materials, 101
- semiconductor quantum well, 105–106
- single longitudinal mode, 101
- single transverse mode, 101
- single-frequency, 101, 107
- single-mode, 101
- spectrum slicing, 113
- stimulated emission, 101
- supercontinuum sources, 113
- thermoelectric cooler (TEC), 105
- tunable, 103, 107
- vertical cavity surface-emitting lasers (VCSEL), 106–107
- waveguide grating router (WGR), 109–110
- waveguides, 113
- wavelength division multiplexing (WDM), 107
- write once read many (WORM) devices, 21
- Latency, 185
- Lattice, photonic lattice, 79
- Law of inverse squares, 9
- Light-emitting diodes (LEDs), 97, 98–100
 - amplitude, 100
 - bandwidth, 100
 - Boltzmann's constant, 99
 - cone, 100
 - diodelike behavior, 99
 - input–output response, 99
 - lasers, 102
 - modulation response, 100
 - n-doped semiconductors, 98
 - output power, 98
 - p-doped semiconductors, 98
 - Planck's constant, 98, 99
 - quantum efficiency, 98
 - spectral range, 98, 100
 - switching speed, 98
 - temperature vs. output spectrum, 99
- Light sources, 97–114
 - continuous wave (CW), 97
 - dispersion-shifted fiber (DSF), 113
 - lasers, 97, 100–111
 - light-emitting diodes (LED), 97, 98–100
 - modulated light, 97
 - polarization-maintaining fiber (PMF), 113
 - semiconductor lasers, 97
 - spectrum slicing, 113
 - supercontinuum sources, 113
 - waveguides, 113
- Light, properties of, 3–33
- Lightguides, 133
- LiNbO_3 switching devices, cross-connects, 149
- Line amplifiers, 126, 127
- Line coding techniques, 212
- Line spacing
 - diffraction, line spacing d, 17
 - Fabry–Perot interferometer, 75
- Line width (channel width), 75
- Local area networks (LAN), 56
- Local oscillators, 165–166
- Loss, 5, 7
 - DWDM networks, 192, 195
 - fiber technology, 54–57, 54
 - filters, 87
 - insertion loss, 137
- Lumens, 9
- Luminance, 9
- Luminous flux, 9
- Luminous intensity, 9
- M**
- Mach–Zehnder couplers, 134
- Mach–Zehnder filter, 19, 83–86
- Mach–Zehnder interferometers, 1, 94, 109, 142
- Mach–Zehnder lasers, 105
- Mach–Zehnder modulation (M–Z), 111
- Management of DWDM networks, 188, 193, 214
- Manufacturing process of fiber, 38–40
- Material dispersion, 28, 48
- Materials, optical, 211
- Matter, nonlinear properties of, 1
- Matter and light interactions, 11–33
- Maximum allowable power per channel, DWDM networks, 191

Maximum bit rate, 46
Maxwell's wave equations, 7, 42
Mechanical pressure, effect of, 30
Mechanical tuning, filters, 80, 87
Memory, 216
 associative RAM-based CAM (AR-CAM), 216
 content-addressable memory (CAM), 216
 optical, 213
Mesh topology, DWDM networks, 198–200
Metal organic chemical vapor deposition (MOCVD), 105
Metropolitan area networks (MAN), 3, 56
Metropolitan Optical Network project (MONET), DWDM networks, 197, 210
Microcracks, effects of, 30
Microelectromechanical switches (MEM),
 reflectors, 145–146
Micromirrors, 22
Modal dispersion, 45–47
Mode mixing, 47
Mode shift, 24–25
Modes
 Fabry–Perot interferometer, 71
 fiber technology, 41–42, 45
 lasers, 101
Modified chemical vapor deposition (MCVD), 38, 39
Modulated light, 97
Modulation and modulators, 6
 amplitude modulators, 167
 DWDM networks, 187
 frequency modulators, 112
 intensity modulators, 112
 lasers, 111–113
 Mach–Zehnder modulation (M–Z), 111
 phase modulators, 112
Modulation depth, 112
Modulation instability, 65
Modulation response, light-emitting diodes, 100
Molecular beam epitaxy (MBE) lasers, 105
Monitoring of optical networks/DWDM, 213
Monochromatic light, 7, 20
Monolithic Bragg lasers, 104
Monolithic lasers, 103
Monolithic DFB array lasers, 110–111
Monolithic Fabry–Perot lasers, 103–104
Monolithic tunable lasers, 107
MTONC organization, 210
Multichannel frequency stabilization, DWDM networks, 187, 190
Multifrequency cavity lasers (MFL), 109–110
Multifrequency lasers, 101, 107–108
Multilevel signal coding, 169

Multimode fiber, 41, 42
Multimode graded index fiber, 42
Multiple quantum well (MQW) lasers, 105, 106, 112, 169
Multiplexers/multiplexing (*see also* optical add-drop multiplexers), 5
 gratings, 93
 optical add-drop multiplexers (OADM) (*see* optical add-drop multiplexers)
 prisms, 91–92

N

N-doped semiconductors, light-emitting diodes, 98
Nano technology, 22
Narrowband FSK, 171
Narrowband rates, DWDM networks, 183
Near end fiber, 63–64
Negative dispersion-flattened fibers, 51
Network management protocols, DWDM networks, 188, 193
Nit, 10
Nodes, 181–182
Noise
 amplifiers, 119
 DWDM networks, 189
Noise equivalent power, photodetectors, 115, 116
Noise figure, amplifiers, 121, 124
Nominal center frequencies, DWDM networks, 187, 188–189, 196
Nonhomogeneity, optical, 12
Nonlinear effects, 4
Nonlinear electro-optic devices, cross-connects, 149
Nonlinear phenomena, 12, 28, 60–64
Nonoptical transparency, 12
Non-return-to-zero (NRZ) coding, 167–168
Nonzero dispersion fiber (NZDF), 51
Normal dispersion regime, fiber 65
Numerical aperture, fiber, 43–44

O

On–off keying (OOK), 169
Opaque DWDM systems, 215
Opaque matter, 11
Opaque WDM systems, 6
Operations, administration, maintenance, and provisioning (OAM&P), 185
Optical add-drop multiplexers (OADM), 5, 6, 125, 151–163, 213
 DWDM networks, 181, 197–199, 202

- dynamically wavelength selectable, 152
 fixed-wavelength, 152
 standards, 163
 wave division multiplexing (WDM) systems, 151
- Optical anisotropy, 25
- Optical amplifiers (*see* amplification and amplifiers)
- Optical attenuators, 11
- Optical comb generators, 108
- Optical cross-connect (OXC), 5, 6
- Optical density (OD), amplifiers, 121
- Optical fiber amplifiers (OFAs), 126
- Optical filters, 6, 11
- Optical frequency discriminator (OFD), 86
- Optical frequency division multiplexing (OFDM), 5–6, 5
- Optical frequency shifter, , 129
- Optical iostropy, 12, 25
- Optical isolators, 137–138
- Optical materials, 211
- Optical modulators, 6
- Optical multiplexers, 95–96
- Optical phase-locked loops (OPLL), 131–132
- Optical power, 28
- Optical power, 28, 55–56, 191–192
- Optical receivers (*see* receivers)
- Optical spectrum, 8
- Optical storage, 21
- Optical transmitters (*see* transmitters)
- Optical transparency, 11, 12
- Ordinary ray, 26
- Organic compounds, 211
- Organic photodetectors of eye (rods, cones), 115
- Oscillators, 101, 165–166
- Outer vapor deposition (OVD), 38
- Output power
- amplifiers, 121
 - light-emitting diodes, 98
- Output saturation, amplifiers, 121
- P**
- P-doped semiconductors, light-emitting diodes, 98
- Particle nature of light, 7–9
- Passive demultiplexers, 91
- Pattern recognition, ultrafast, 215–218
- Permittivity in a vacuum, 28, 61
- Phase change, fiber, 64
- Phase condition, lasers, 101
- Phase modulators, lasers, 112
- Phase shift, 25
- Phase velocity, fiber, 44
- Phase-locked loops, optical (OPLL), 131–132
- Phase-shift keying (PSK), 165, 170–171
- decoding techniques, 173, 174–175
- Phased-array gratings (PHASARS), 94
- Photochromic switching, cross-connects, 149
- Photodetectors, 5, 115–117
- avalanche photodiodes (APD), 115, 117
 - cutoff frequency, 115, 116
 - dark current, 115, 116, 117
 - fall time, 115, 116
 - forward-biased noise, 115, 116
 - frequency bandwidth, 115, 116
 - noise equivalent power, 115, 116
 - organic photodetectors of eye (rods, cones), 115
 - photoresistors, 115
 - photosensitivity, 115
 - Planck's constant, 116
 - positive intrinsic negative (PIN), 115, 116–117
 - quantum efficiency, 115, 116
 - responsivity (R), 116
 - rise time, 115, 116
 - shot noise, 117
 - shunt resistance noise, 116
 - spectral response, 115
 - terminal capacitance, 115, 116
 - timing response, 115, 116
 - wavelength, 116
- Photodiode (PIN), 105
- Photometric units, 10
- Photon activity, lasers, 8, 101
- Photon–atom interaction, 60
- Photonic, 3, 4
- Photonic crystalline optics, 92
- Photonic lattice, 79
- Photons, 7, 8
- Photopolymers, 21
- Photoresistors, 115
- Photosensitivity, photodetectors, 115
- Planck's constant, 7
- light-emitting diodes, 98, 99
 - photodetectors, 116
- Point-to-point DWDM network topology, 181, 197–198
- Polarization, 7, 12, 22–25, 26, 28
- acousto-optic tunable filters (AOTF), 71
 - birefringence, 26
 - Brewster's law, 24
 - extinction ratio, 24
 - Faraday Effect, 24–25
 - fiber technology, 59

mode shift, 24–25
principal transmittance, 24
by reflection, 22–24
by refraction, 22–24
Polarization mode dispersion (PMD), 54
Polarization sensitivity, 119, 120, 122, 124
Polarization-maintaining fiber (PMF), 113
Polarizers, 138–139
Polarizing beam-splitters, 81, 95
Polymer-based switching, cross-connects, 149
Positive dispersion-flattened fibers, 51
Positive intrinsic negative (PIN) diodes, 115, 116–117
Power amplifiers, optical, 126–127
Power budget, optical, DWDM networks, , 191–192
Power gain, DWDM networks, 192
Power launched, DWDM networks, 187, 191
Power loss, DWDM networks, 192, 195
Power received, DWDM networks, 187
Power, optical, 28, 55–56
Power-reflected coefficients, 72, 76
Power-transmitted coefficient, 76
Praseodymium-doped fiber amplifier (PDFA), 57, 121, 125
Preamplifiers, 126, 127
Principal transmittance, 24
Prisms, 15
demultiplexers, 91–92
holography, 19–22
multiplexers, 95
photonic crystalline optics, 92
superprisms, 92
Probe signals in frequency shifters, 129
Propagation of light, 22, 43
Propagation speed, 7
Protection of DWDM networks, 188, 193
Protocols, DWDM networks, 187, 188, 193
Pulse spread, chromatic dispersion, 49
Pumps, in frequency shifters, 121
Pumps, lasers, 123, 129

Q

Quality of service, DWDM networks, 185
Quantum efficiency
light-emitting diodes, 98
photodetectors, 115, 116
Quantum limit of receiver, 173
Quantum well lasers (QWL), 105, 106
Quantum yield (Q), amplifiers, 121
Quarter-wavelength plate, 27–28

R

Raman scattering, 28, 57, 60, 61–62, 121, 126
Raman supercontinuum, 126
Random access memory (RAM), 216
Rayleigh reflection, 126
Rayleigh scattering, 54
Receive direction, DWDM networks, 201–202
Receivers, 6, 35, 212
birefringence, 26
quantum limit of, 173
Reconfigurability, dynamic, DWDM networks, 213
Red band, 56
Red shift, 65
Reflection, 7, 12–13
antireflection coatings, 19
extinction of, 19
polarization by, 22–24
Reflectors
Bragg reflector, 71, 77
cross-connects, optical (OCX), 145–146
distributed Bragg reflector (DBR), 104, 107
Refraction, 7, 12–13
dispersion, 26–27
polarization by, 22–24
Refractive index, 12–14, 15, 25, 26, 38, 40–41
Regenerators, amplifiers, 120
Relationship of frequency, speed, and wavelength, 8
Reliability of DWDM networks, 188, 193
Research in DWDM technology, 209–210
Resonators
Fabry–Perot resonator, 72–74
ring, 135–136
Responsivity (R), photodetectors, 116
Return-to-zero (RZ) coding, 167–168, 169
Ring resonators, 135–136
Ring topology, DWDM networks, 181, 198–200
Rise time, photodetectors, 115, 116
Rotators, 24, 138–139
Routers, 181–182
Ruby lasers, 101–102

S

S-band, 56, 58
Saturation power, amplifiers, 119, 121, 124
Scalability of DWDM networks, 188, 194
Scaling factor, fiber technology, 47
Scattering, 12, 28, 29, 54, 60, 62, 121, 126
Schrödinger equation, 67
Self phase modulation (SPM), 65
Self-modulation, fiber, 65

Semiconductor lasers, 97, 101
 Semiconductor optical amplifiers (SOA), 122, 121
 Semiconductor quantum well (QWL) lasers, 105–106
 Semitransparent matter, 11
 Sensitivity, amplifiers, 119, 120, 124
 Services supported in DWDM networks, 187, 188, 192, 193
 Shot noise, photodetectors, 117
 Shunt resistance noise, photodetectors, 116
 Signal to noise ratio (OSNR), amplifiers, 126
 Single longitudinal mode lasers, 101
 Single transverse mode lasers, 101
 Single-frequency lasers, 101, 107
 Single-mode fiber cutoff wavelength, 58–59
 Single-mode fiber, 41, 42, 52
 Single-mode lasers, 101
 Single-mode power loss calculations, DWDM networks, 195
 SiO₂-on-Si planar switches, 149
 Snell's Law, 13, 15, 46
 Sol gel method, 39
 Solid-state cross connects, 142, 143–145
 Solid-state materials, 211
 Solid-state technology, 3, 5
 Solitons, 67–68
 SONET, 4, 5, 179, 182, 183, 184, 193, 209, 216–217
 Spectral broadening, fiber, 64–65
 Spectral filters, 94–95
 Spectral range, light-emitting diodes, 98, 100
 Spectral response, photodetectors, 115
 Spectral width, 75
 Spectrum of light, 8
 Spectrum slicing, 113
 Spectrum utilization, fiber technology, 56–57
 Speed of light, 8–9, 13
 Speed, ultrahigh speed at longer spans, 214–215
 Spontaneous lifetime in EDFAs, 123
 Spontaneous noise in EDFAs, 124
 Standards,
 amplifiers, 127
 DWDM networks, 180, 185, 194–195, 206–207, 214
 Star couplers, 144
 Star topology, DWDM networks, 181, 198–200
 Step index fiber, 40, 43
 Stimulated Brillouin scattering (SBS), 28, 62, 121, 126
 Stimulated emission lasers, 101
 Stimulated Raman scattering (SRS), 28, 61–62, 121, 126

Storage, optical, 21
 Supercontinuum light sources, 113
 Superprisms, 92
 Surface acoustic wave (SAW) device, 82
 Survivability of DWDM networks, 188, 193
 Susceptibility, fiber, 60
 Switching, 6, 35
 acousto-optic switching, 148
 all-optical switching, 141
 cross-connects, optical (OCX), 148–149
 electro-optic switching, 148
 electromechanical switches, mirror array, 142, 146–148
 free space optical switching, 142–143
 LiNbO₃ switching devices, 149
 microelectromechanical switches (MEM), reflectors, 145–146
 photochromic switching, 149
 polymer-based switching, 149
 SiO₂-on-Si planar switches, 149
 switching speed, 148–149
 thermo-optic switching, 148
 ultrafast switching, 212–213
 Synchronous digital hierarchy (SDH), 3, 4, 179, 182, 183, 184, 193, 216–217
 Synchronous transport module (STM), 198, 201
 Synchronous optical network (*see* SONET)

T

TCP/IP in DWDM networks, 201
 Telephony over DWDM networks, 193
 Telluride-erbium-doped fiber amplifiers, 57
 Temperature effects, 31
 light-emitting diodes, 99
 Temporal FWM (tFWM), 63–64
 Temporal shift, 63
 Terminal capacitance, photodetectors, 115, 116
 Thermal tuning, 80
 Thermo-optic switching, 148
 Thermoelectric cooler (TEC), 105
 Time division multiplexing (TDM), 3
 DWDM networks, 179, 182, 183
 Timing jitter, 68
 Timing response, photodetectors, 115, 116
 Topologies of DWDM networks, 181–182, 197–207
 Transmit direction, DWDM networks, 201
 Transmittance, principal, 24
 Transmitters, 6, 26
 Transparent matter, 11, 12–31
 Transparent WDM systems, 6
 Transverse electric field in fiber, 41

Transverse magnetic field in fiber, 41
Travel time variation, chromatic dispersion, 49
Traveling wave laser amplifiers, 121
Triangular index, fiber technology, 40
TrueWave fibers, 51
Tunable Bragg gratings, 80
Tunable filters, 71, 87–88
Tunable lasers, 103, 107
Tunable optical filters (TOFs), 81

U

Ultrafast pattern recognition, 215–218
 associative RAM-based CAM (AR-CAM), 216
asynchronous transfer mode (ATM), 217
content-addressable memory (CAM), 216
Internet Protocol (IP), 217–218
memory, 216
random access memory (RAM), 216
SDH support, 216–217
SONET support, 216–217
Ultrafast switching, 212–213
Ultrahigh speed transmission with DWDM, 214–215
Unipolar signal coding, 168–169
Units of measure associated with optics, 9, 10

V

Vapor phase axial deposition (VAD), 38
Variable delay lines, 213
Verdet constant, 24, 138–139
Vertical cavity surface-emitting lasers (VCSEL), 106–107
Video traffic, 3, 6, 179, 193
Voice traffic, 3, 6, 179

W

Watts as unit of measure, 9
Wave division multiplexing (WDM), 4, 6, 177, 179
 amplifiers, 125
 fiber technology, 58
 lasers, 107
 optical add-drop multiplexers (OADM)s, 151
Wave nature of light, 7
Waveguide grating router (WGR), 94, 109–110, 142
Waveguides, laser, 113
Wavelength bus, 218–219
Wavelength converters, 127–129
Wavelength dispersion, 48–49, 65
Wavelength routing, cross-connects, 142
Wavelength-selectable (tunable) filters, 5
Wavelengths, 4, 181

 DWDM networks, 179, 180, 187, 188, 189–190, 194

 light, 7, 8, 11, 13
 photodetectors, 116

WaveStar products in DWDM networks, 183–184

Wideband FSK, 171

Wireless communications, 3

Wrappers, digital, DWDM networks, 185

Write once read many (WORM) devices, 21, 149

Z

Zero-dispersion wavelength, 50