

Content

Preface	V
1 Introduction	1
2 Light	6
2.1 What is light?	6
2.2 Duality of waves and particles	8
2.2.1 Wave viewpoint	9
2.2.2 Ray viewpoint	11
2.3 Power and energy of electromagnetic waves	11
3 Fibers	14
3.1 Light propagation in waveguide structures	14
3.1.1 Guided waves in layers	14
3.1.2 Guided waves in glass fibers	15
3.2 Light transmission in glass fibers, multi-mode and single-mode fibers	17
3.2.1 Glass fibers	17
3.2.2 Light propagation in glass fibers, angle of acceptance, numerical aperture	18
3.2.3 Transversal modes in glass fibers, mixing of modes	20
3.2.4 Single-Mode-Condition, Cut-Off-Wavelength in glass fibers	27
3.2.5 Mode-Field Diameter	27
3.3 Attenuation in glass fibers	28
3.3.1 UV absorption	29
3.3.2 Rayleigh scattering	29
3.3.3 Absorption in water	30
3.3.4 IR absorption	31
3.3.5 Attenuation coefficient versus wavelength in glass fibers	31
3.4 Dispersion and dispersion compensation in glass fibers	32
3.4.1 Concept and consequences of dispersion	32
3.4.2 Mechanisms of dispersion	36
3.4.2.1 Modal dispersion	36
3.4.2.2 Material dispersion	37
3.4.2.3 Waveguide dispersion	38
3.4.2.4 Chromatic dispersion	41
3.4.2.5 Bandwidth-Length-Product	43
3.4.2.6 Polarization-Mode-Dispersion (PMD)	44
3.4.2.7 Dispersions compensation	45
3.4.3 Types of glass fibers	47

4	Fiber connections, couplers and switches	50
4.1	Plugs and splices	50
4.1.1	Splices	50
4.1.2	Plugs	51
4.2	Basic function of couplers and switches	54
4.2.1	Couplers	54
4.2.2	Coupler types	56
4.2.2.1	Front face couplers	56
4.2.2.2	Surface area couplers	58
4.2.3	Switches	59
4.2.3.1	Mechanical switching	60
4.2.3.2	Electro-optical switching	60
4.2.3.3	Mechano-optical switching	65
4.2.3.4	Micro-electromechanical systems (MEMS)	66
4.2.3.5	Thermal switch	68
5	Optical transmitters	69
5.1	Basic elements of semiconductor transmitters	69
5.2	Active Element	71
5.2.1	Band structure of semiconductors, direct and indirect transitions	71
5.2.2	Material choice	72
5.2.3	Light emission in semiconductors, LED	75
5.2.3.1	Recombination in semiconductors	75
5.2.3.2	Line width	77
5.2.3.3	p-n-junction as basic structure, LED	78
5.2.4	Semiconductor transmitters – basic structure	79
5.2.4.1	Double-hetero-structure laser (DH-Diode)	79
5.2.4.2	Multi-Quantum-Well Structure (MQW)	80
5.3	Resonators	81
5.3.1	Fabry-Perot Laser	81
5.3.2	Dynamical Single-Mode Laser (DSM)	84
5.4	Laser properties	86
5.4.1	P-I characteristic, temperature behaviour, degradation	86
5.4.2	Spectrum of semiconductor lasers	87
5.4.3	Radiation characteristics	88
5.5	Selected laser types for optical networks	89
5.5.1	MQW-Laser with DFB resonator as edge-emitting diode	89
5.5.2	Vertical Cavity Surface Emitting Laser (VCSEL) as surface-emitting diode	92
6	Modulation of laser light	94
6.1	Tasks and problems of laser modulation	94
6.2	Methods of modulation in optical communication technology	95
6.2.1	Amplitude modulation, power modulation (AM, PM)	95
6.2.2	Pulse-Amplitude modulation (PAM)	95

6.2.3	Pulse-Position modulation (PPM)	96
6.2.4	Pulse-Code modulation (PCM)	96
6.3	Direct modulation of semiconductor lasers	97
6.4	External modulation of semiconductor lasers	103
6.4.1	Phase and frequency modulation	103
6.4.2	Intensity or power modulation	104
7	Optical receivers	106
7.1	Basics of receivers	106
7.2	pin-Diode	108
7.3	Avalanche photo diode (APD)	109
7.4	Noise in receivers, Bit-Error Rate (BER)	111
7.4.1	Shot noise	112
7.4.2	Intensity noise	112
7.4.3	Thermal noise (Nyquist noise)	113
7.4.4	Multiplication noise	114
7.4.5	Bit-Error Rate	115
7.4.6	Optical heterodyne	116
8	Elements of optical networks	119
8.1	Optical amplifiers	119
8.1.1	Erbium doped fiber amplifier (EDFA)	119
8.1.1.1	Amplification in erbium doped glass fibers	119
8.1.1.2	Noise in EDFA's, Amplified Spontaneous Emission (ASE)	122
8.1.1.3	Dense Wavelength Division Multiplexing (DWDM) and EDFA	124
8.1.1.4	Experimental realization of EDFA	125
8.1.1.5	Other rare earth doped amplifiers	126
8.1.2	Raman optical amplifier	127
8.1.2.1	The Raman Effect	127
8.1.2.2	Stokes shift, amplification spectrum	128
8.1.2.3	Experimental realization	130
8.1.2.4	Problems in Raman amplifiers	130
8.1.2.5	Noise in Raman amplifiers	131
8.1.3	Semiconductor optical amplifier (SOA)	131
8.2	Optical elements for multiplexers and demultiplexers	134
8.2.1	Optical filters for multiplexers and demultiplexers	135
8.2.1.1	Filter based on interference	135
8.2.1.2	Fabry-Perot filter	136
8.2.1.3	Fiber-Bragg-Grating	137
8.2.1.4	Waveguide Grating Routers (WGR)	137
8.2.1.5	Optical isolator	138
8.2.1.6	Optical circulator	139
8.2.2	Optical Add-Drop-Multiplexers (OADM)	141
8.2.3	Optical Cross-Connectors	142

9	Measurements in glass fibers and optical transmission systems	145
9.1	Measurements in glass fibers	145
9.1.1	Measurement of refractive index profiles	145
9.1.1.1	Near field scanning	145
9.1.1.2	Refracted near field technique	146
9.1.2	Measurement of fiber attenuation	146
9.1.2.1	Cut-back and substitution methods	146
9.1.2.2	Backscattering, OTDR method	147
9.1.3	Dispersion measurement	150
9.1.3.1	Measurements in time range	151
9.1.3.2	Measurements in frequency range	152
9.2	Measurement of quality of data transfer	152
9.2.1	Measurements of the bit-error ratio, receiver sensitivity	152
9.2.2	Eye diagram	153
10	Nonlinearities in glass fibers	156
10.1	Nonlinearities in optics	157
10.2	Nonlinear effects in glass fibers	158
10.2.1	Nonlinear scattering effects in glass fibers	159
10.2.2	Third order nonlinear effects in glass fibers, Four-Wave-Mixing	159
10.3	Chirp in glass fibers	161
10.4	Polarization-Dispersion-Management with nonlinearities	163
10.4.1	Reduction of chirp	163
10.4.2	Use of chirp	164
10.5	Active compensation of dispersion	166
10.6	Solitons	168
11	Passive and active networks	170
11.1	Topologies of communication	173
11.2	Methods of multiplexing	174
11.2.1	Space multiplex	175
11.2.2	Time multiplex	175
11.2.3	Wavelength multiplex	177
11.3	WDM systems	183
11.4	Signal regeneration	185
	Solutions of exercises	186
	References	189
	Index	191