

Contents

I	Introduction	1
1	A Quick Survey	3
II	Physical Foundations	13
2	Treatment with Ray Optics	15
2.1	Waveguiding by Total Internal Reflection	15
2.2	Step Index Fiber	17
2.3	Modal Dispersion	20
2.4	Gradient Index Fibers	22
2.5	Mode Coupling	23
2.6	Shortcomings of the Ray-Optical Treatment	24
3	Treatment with Wave Optics	25
3.1	Maxwell's Equations	25
3.2	Wave Equation	27
3.3	Linear and Nonlinear Refractive Index	28
3.3.1	Linear Case	28
3.3.2	Nonlinear Case	29
3.4	Separation of Coordinates	30
3.5	Modes	32
3.6	Solutions for $m = 0$	35
3.7	Solutions for $m = 1$	37
3.8	Solutions for $m > 1$	38
3.9	Field Amplitude Distribution of the Modes	38
3.10	Numerical Example	41
3.11	Number of Modes	42
3.12	A Remark on Microwave Waveguides	43
3.13	Energy Transport	43
4	Chromatic Dispersion	47
4.1	Material Dispersion	48
4.1.1	Treatment with Derivatives to Wavelength	50
4.1.2	Treatment with Derivatives to Frequency	51
4.2	Waveguide and Profile Dispersion	53
4.3	Normal, Anomalous, and Zero Dispersion	54
4.4	Impact of Dispersion	55

4.5	Optimized Dispersion: Alternative Refractive Index Profiles	58
4.5.1	Gradient Index Fibers	58
4.5.2	W Fibers	59
4.5.3	T Fibers	61
4.5.4	Quadruple-Clad Fibers	61
4.5.5	Dispersion-Shifted or Dispersion-Flattened?	62
4.6	Polarization Mode Dispersion	64
4.6.1	Quantifying Polarization Mode Dispersion	64
4.6.2	Avoiding Polarization Mode Dispersion	65
4.7	Microstructured Fibers	67
4.7.1	Holey Fibers	69
4.7.2	Photonic Crystal Fibers	73
4.7.3	New Possibilities	74
5	Losses	75
5.1	Loss Mechanisms in Glass	75
5.2	Bend Loss	77
5.3	Other Losses	79
5.4	Ultimate Reach and Possible Alternative Constructions	80
5.4.1	Heavy Molecules	81
5.4.2	Hollow Core Fibers	82
5.4.3	Sapphire Fibers	83
5.4.4	Plastic Fibers	83
III	Technical Conditions for Fiber Technology	85
6	Manufacturing and Mechanical Properties	87
6.1	Glass as a Material	87
6.1.1	Historical Issues	87
6.1.2	Structure	88
6.1.3	How Glass Breaks	91
6.2	Manufacturing of Fibers	93
6.2.1	Making a Preform	93
6.2.2	Pulling Fibers from the Preform	96
6.3	Mechanical Properties of Fibers	98
6.3.1	Pristine Glass	98
6.3.2	Reduction of Structural Stability	99
7	How to Measure Important Fiber Characteristics	101
7.1	Loss	101
7.2	Dispersion	102
7.3	Geometry of Fiber Structure	106
7.4	Geometry of Amplitude Distribution	108
7.4.1	Near-Field Methods	108
7.4.2	Far-Field Methods	110
7.5	Cutoff Wavelength	112
7.6	Optical Time Domain Reflectometry (OTDR)	114

8	Components for Fiber Technology	117
8.1	Cable Structure	117
8.2	Preparation of Fiber Ends	119
8.3	Connections	120
8.3.1	Nonpermanent Connections	120
8.3.2	Permanent Connections	123
8.4	Elements for Spectral Manipulation	124
8.4.1	Fabry-Perot Filters	124
8.4.2	Fiber-Bragg Structures	124
8.5	Elements for Polarization Manipulation	125
8.5.1	Polarization Adjusters	125
8.5.2	Polarizers	127
8.6	Direction-Dependent Devices	128
8.6.1	Isolators	128
8.6.2	Circulators	130
8.7	Couplers	131
8.7.1	Power Splitting/Combining Couplers	131
8.7.2	Wavelength-Dependent Couplers	133
8.8	Optical Amplifiers	134
8.8.1	Amplifiers Involving Active Fibers	135
8.8.2	Amplifiers Involving Semiconductor Devices	138
8.9	Light Sources	139
8.9.1	Light from Semiconductors	139
8.9.2	Luminescent Diodes	140
8.9.3	Laser Diodes	140
8.9.4	Fiber Lasers	145
8.10	Optical Receivers	145
8.10.1	Principle of pn and pin Photodiodes	146
8.10.2	Materials	148
8.10.3	Speed	148
8.10.4	Noise	148
8.10.5	Avalanche Diodes	149
IV	Nonlinear Phenomena in Fibers	151
9	Basics of Nonlinear Processes	153
9.1	Nonlinearity in Fibers vs. in Bulk	153
9.2	Kerr Nonlinearity	155
9.3	Nonlinear Wave Equation	156
9.3.1	Envelope Equation Without Dispersion	156
9.3.2	Introducing Dispersion by a Fourier Technique	158
9.3.3	The Canonical Wave Equation: NLSE	160
9.3.4	Discussion of Contributions to the Wave Equation	161
9.3.5	Dimensionless NLSE	162
9.4	Solutions of the NLSE	165
9.4.1	Modulational Instability	165
9.4.2	The Fundamental Soliton	165
9.4.3	How to Excite the Fundamental Soliton	170
9.4.4	Collisions of Solitons	174

9.4.5	Higher-Order Solitons	174
9.4.6	Dark Solitons	176
9.5	Digression: Solitons in Other Fields of Physics	178
9.6	More $\chi^{(3)}$ Processes	180
9.7	Inelastic Scattering Processes	182
9.7.1	Stimulated Brillouin Scattering	183
9.7.2	Stimulated Raman Scattering	188
10	A Survey of Nonlinear Processes	193
10.1	Normal Dispersion	193
10.1.1	Spectral Broadening	193
10.1.2	Pulse Compression	195
10.1.3	Chirped Amplification	195
10.1.4	Optical Wave Breaking	197
10.2	Anomalous Dispersion	199
10.2.1	Modulational Instability	199
10.2.2	Fundamental Solitons	200
10.2.3	Soliton Compression	201
10.2.4	The Soliton Laser and Additive Pulse Mode Locking	202
10.2.5	Pulse Interaction	203
10.2.6	Self-Frequency Shift	205
10.2.7	Long-Haul Data Transmission with Solitons	207
V	Technological Applications of Optical Fibers	209
11	Applications in Telecommunications	211
11.1	Fundamentals of Radio Systems Engineering	211
11.1.1	Signals	211
11.1.2	Modulation	212
11.1.3	Sampling	216
11.1.4	Coding	218
11.1.5	Multiplexing in Time and Frequency: TDM and WDM	218
11.1.6	On and Off: RZ and NRZ	220
11.1.7	Noise	221
11.1.8	Transmission and Channel Capacity	224
11.2	Nonlinear Transmission	225
11.2.1	A Single Wavelength Channel	226
11.2.2	Several Wavelength Channels	229
11.2.3	Alternating Dispersion (“Dispersion Management”)	231
11.3	Technical Issues	234
11.3.1	Monitoring of Operations	234
11.3.2	Eye Diagrams	236
11.3.3	Filtering to Reduce Crosstalk	236
11.4	Telecommunication: A Growth Industry	238
11.4.1	Historical Development	238
11.4.2	The Limits to Growth	243
12	Fiber-Optic Sensors	247
12.1	Why Sensors? Why Fiber-Optic?	247

12.2	Local Measurements	249
12.2.1	Pressure Gauge	249
12.2.2	Hydrophone	249
12.2.3	Temperature Measurement	251
12.2.4	Dosimetry	252
12.3	Distributed Measurements	253
12.4	The Status Today	256
VI	Appendices	257
A	Decibel Units	259
A.1	Definition	259
A.2	Absolute Values	260
A.3	Possible Irritations	260
A.4	Beer's Attenuation and dB Units	261
B	Skin Effect	263
C	Bessel Functions	265
C.1	Terminology for the Various Functions	265
C.2	Relations Between These Functions	266
C.3	Recursion Formulae	266
C.4	Properties of J_m and K_m	266
C.5	Zeroes of J_0 , J_1 , and J_2	267
C.6	Graphs of the Most Frequently Used Functions	267
D	Optics with Gaussian Beams	269
D.1	Why Gaussian Beams?	269
D.2	Formulae for Gaussian Beams	270
D.3	Gaussian Beams and Optical Fibers	271
E	Relations for Secans Hyperbolicus	273
F	Autocorrelation Measurement	275
F.1	Measurement of Ultrashort Processes	275
F.1.1	Correlation	275
F.1.2	Autocorrelation	276
F.1.3	Autocorrelation Measurements	277
F.1.4	A Catalogue of Autocorrelation Shapes	278
	Bibliography	281
	Glossary	293
	Index	299