

Contents

1. Introduction	1
------------------------------	---

Part I. Fundamentals of Linear and Nonlinear Optics

2. Overview of Linear Optical Effects	9
2.1 The Wave Equation for Linear Media	10
2.2 Solution of the Linear Wave Equation	13
2.3 The Harmonic Oscillator Model	15
2.4 Attenuation	19
2.5 Amplification	22
2.6 The Refractive Index	26
2.6.1 The Sellmeier Equation	26
2.6.2 Phase Velocity, Group Velocity, and Dispersion	29
2.7 Birefringence	36
Summary	37
Exercises	39
3. Optical Telecommunications	41
3.1 Fiber Types	42
3.1.1 Step-Index and Graded-Index Fibers	43
3.2 Single Mode Fibers	44
3.2.1 Single Mode Fiber Types	46
3.3 Highly Nonlinear and Photonic Fibers	49
3.4 Modulation	56
3.5 Optical Transport Technologies	59
Summary	62
Exercises	62
4. Nonlinear Effects	65
4.1 The Nonlinear Oscillator	66
4.2 Nonlinear Polarization	71
4.3 The Nonlinear Susceptibility	73

4.3.1	Estimation of the Order of Magnitude of the Susceptibilities	78
4.4	The Nonlinear Wave Equation	81
4.5	Second Order Nonlinear Phenomena	82
4.6	Third Order Nonlinear Phenomena	87
4.7	The Nonlinear Refractive Index	91
4.8	Effective Area and Nonlinear Coefficient	96
4.9	Effective Length	98
4.10	Phase Matching	100
4.11	Capacity Limit of Optical Fibers	107
	Summary	113
	Exercises	114

Part II. Nonlinear Effects in Optical Waveguides

5.	The Nonlinear Schrödinger Equation	119
5.1	Derivation of the Nonlinear Schrödinger Equation	119
5.2	Dispersion and Nonlinear Length	125
5.3	The Linear Term	127
5.4	Dispersion Management	134
5.5	The Nonlinear Term	138
5.6	Numerical Solution of the NSE	139
	Summary	140
	Exercises	141
6.	Self- and Cross-Phase Modulation	143
6.1	Self-Phase Modulation (SPM)	144
6.1.1	SPM's Impact on Communication Systems	147
6.1.2	Experimental Results	151
6.2	Cross-Phase Modulation (XPM)	154
6.2.1	Polarization Dependence of XPM	157
6.2.2	XPM's Impact on Communication Systems	159
	Summary	164
	Exercises	165
7.	Four-Wave-Mixing (FWM)	167
7.1	Mixing between WDM Channels	168
7.2	Mathematical Description of FWM	171
7.3	Phase Matching	174
7.4	FWM's Impact on Communication Systems	180
7.5	FWM Suppression	186
7.6	Experimental Results	189
7.7	Polarization Dependence of FWM	194
7.7.1	Numerical Simulation	195

7.7.2 Results.....	196
Summary	200
Exercises	200
8. Intrachannel Nonlinear Effects	201
8.1 Mathematical Description	203
8.2 SPM and IXPM	204
8.3 IFWM and Ghost Pulses	207
8.4 IFWM Suppression	210
Summary	212
Exercises	213
9. Solitons	215
9.1 Mathematical Description	216
9.2 Higher Order Solitons	220
9.3 Limits of Solitons	225
9.3.1 The Gordon-Haus Effect	226
9.3.2 The Acoustic Effect	228
9.4 Increasing the Bit Rate in Soliton Systems	229
9.5 Mutual Interaction Between Solitons	232
9.6 Dispersion-Managed Solitons	234
Summary	236
Exercises	237
10. Raman Scattering	239
10.1 The Scattering of Light	240
10.2 Origin of Raman Scattering	242
10.2.1 Raman Scattering in the Harmonic Oscillator Model ..	244
10.3 Raman Scattering in Optical Fibers	248
10.3.1 Spontaneous and Stimulated Scattering	251
10.3.2 Threshold of Raman Scattering in Optical Waveguides	253
10.4 Impact of Raman Scattering on Communication Systems ...	258
Summary	266
Exercises	267
11. Brillouin Scattering	269
11.1 Scattering of Optical Waves at Sound Waves	270
11.2 Spontaneous and Stimulated Brillouin Scattering	274
11.3 The Brillouin Gain	277
11.3.1 Spectral Distribution	277
11.3.2 Frequency Shift	280
11.3.3 Gain Maximum	281
11.4 Threshold of Brillouin Scattering	283
11.5 SBS's impact on Communication Systems	286

11.6 Brillouin Scattering for Distributed Temperature and Strain Sensors	292
Summary	295
Exercises	296

Part III. Applications of Nonlinear Effects in Telecommunications

12. Optical Signal Processing	299
12.1 Spectrum Slicing and Nonlinear WDM Sources	300
12.2 Wavelength Conversion	305
12.2.1 Wavelength Conversion with FWM	306
12.2.2 Wavelength Conversion with XPM	309
12.2.3 Wavelength Conversion with SOA	311
12.3 Optical Switching	315
12.3.1 Photorefractive Optical Switches	317
12.3.2 Optical Switching with the XPM Effect	323
12.3.3 FWM for Optical Switching	332
12.3.4 Ultrafast Optical Switching	333
12.4 Retiming, Reshaping, and All-Optical Clock Recovery	337
12.5 Optical Filters with SBS	339
Summary	341
Exercises	342
13. Nonlinear Lasers and Amplifiers	343
13.1 Raman Amplifier	344
13.2 Raman Laser	350
13.3 Brillouin Amplifiers and Lasers	352
13.3.1 Radio-over-Fiber	355
13.4 Parametric Amplifiers	358
Summary	365
Exercises	366
14. Nonlinear Optical Phase Conjugation	367
14.1 Phase-Conjugating Mirrors	367
14.2 Distortion Compensation due to Phase Conjugation	370
14.3 Theoretical Description of NPC	373
14.4 Phase Conjugation as Holographic Model	376
14.5 Mid-span Spectral Inversion	378
Summary	383
Exercises	384

A. Appendices	387
A.1 div, grad, curl, rot	394
A.2 The Gaussian Pulse	396
A.3 Logarithmical Units	397
References	399
Index	409