

Contents

Dedication	v
Author Biography	vii
Preface.....	xix

CHAPTER 1 Introduction..... 1

1.1 Historical Perspective	1
1.2 Fiber Characteristics	3
1.2.1 Material and Fabrication.....	4
1.2.2 Fiber Losses	5
1.2.3 Chromatic Dispersion	6
1.2.4 Polarization-Mode Dispersion	11
1.3 Fiber Nonlinearities	15
1.3.1 Nonlinear Refraction	15
1.3.2 Stimulated Inelastic Scattering	16
1.3.3 Importance of Nonlinear Effects.....	18
1.4 Overview.....	19
Problems.....	21
References	22

CHAPTER 2 Pulse Propagation in Fibers..... 27

2.1 Maxwell's Equations	27
2.2 Fiber Modes	30
2.2.1 Eigenvalue Equation	30
2.2.2 Single-Mode Condition	31
2.2.3 Characteristics of the Fundamental Mode	32
2.3 Pulse-Propagation Equation.....	34
2.3.1 Nonlinear Pulse Propagation	34
2.3.2 Higher-Order Nonlinear Effects	39
2.3.3 Raman Response Function and its Impact.....	41
2.3.4 Extension to Multimode Fibers	45
2.4 Numerical Methods	47
2.4.1 Split-Step Fourier Method	47
2.4.2 Finite-Difference Methods.....	51
Problems.....	52
References	53

CHAPTER 3 Group-Velocity Dispersion	57
3.1 Different Propagation Regimes.....	57
3.2 Dispersion-Induced Pulse Broadening	59
3.2.1 Gaussian Pulses	60
3.2.2 Chirped Gaussian Pulses.....	62
3.2.3 Hyperbolic-Secant Pulses	64
3.2.4 Super-Gaussian Pulses	65
3.2.5 Experimental Results	67
3.3 Third-Order Dispersion	68
3.3.1 Evolution of Chirped Gaussian Pulses.....	69
3.3.2 Broadening Factor.....	71
3.3.3 Arbitrary-Shape Pulses	74
3.3.4 Ultrashort-Pulse Measurements.....	76
3.4 Dispersion Management	78
3.4.1 GVD-Induced Limitations	78
3.4.2 Dispersion Compensation	80
3.4.3 Compensation of Third-Order Dispersion	81
Problems.....	83
References	84
CHAPTER 4 Self-Phase Modulation.....	87
4.1 SPM-Induced Spectral Changes	87
4.1.1 Nonlinear Phase Shift	88
4.1.2 Changes in Pulse Spectra.....	90
4.1.3 Effect of Pulse Shape and Initial Chirp	93
4.1.4 Effect of Partial Coherence	96
4.2 Effect of Group-Velocity Dispersion	98
4.2.1 Pulse Evolution	98
4.2.2 Broadening Factor.....	100
4.2.3 Optical Wave Breaking	102
4.2.4 Experimental Results	105
4.2.5 Effect of Third-Order Dispersion.....	106
4.2.6 SPM Effects in Fiber Amplifiers.....	108
4.3 Semianalytic Techniques	111
4.3.1 Moment Method	111
4.3.2 Variational Method.....	112
4.3.3 Specific Analytic Solutions.....	114
4.4 Higher-Order Nonlinear Effects	115
4.4.1 Self-Strengthening	116
4.4.2 Effect of GVD on Optical Shocks	119
4.4.3 Intrapulse Raman Scattering.....	121

Problems	124
References	125
CHAPTER 5 Optical Solitons	129
5.1 Modulation Instability	129
5.1.1 Linear Stability Analysis.....	130
5.1.2 Gain Spectrum	131
5.1.3 Experimental Results	133
5.1.4 Ultrashort Pulse Generation.....	135
5.1.5 Impact on Lightwave Systems	137
5.2 Fiber Solitons.....	139
5.2.1 Inverse Scattering Method	140
5.2.2 Fundamental Soliton	142
5.2.3 Second and Higher-Order Solitons	144
5.2.4 Experimental Confirmation	147
5.2.5 Soliton Stability	148
5.3 Other Types of Solitons	151
5.3.1 Dark Solitons	151
5.3.2 Bistable Solitons	154
5.3.3 Dispersion-Managed Solitons.....	156
5.3.4 Optical Similaritons	156
5.4 Perturbation of Solitons	159
5.4.1 Perturbation Methods.....	159
5.4.2 Fiber Losses	161
5.4.3 Soliton Amplification.....	163
5.4.4 Soliton Interaction	166
5.5 Higher-Order Effects	170
5.5.1 Moment Equations for Pulse Parameters.....	170
5.5.2 Third-Order Dispersion.....	172
5.5.3 Self-Strengthening	174
5.5.4 Intrapulse Raman Scattering.....	176
5.5.5 Propagation of Femtosecond Pulses	181
Problems	183
References	184
CHAPTER 6 Polarization Effects	193
6.1 Nonlinear Birefringence	193
6.1.1 Origin of Nonlinear Birefringence.....	194
6.1.2 Coupled-Mode Equations	196
6.1.3 Elliptically Birefringent Fibers	197

6.2	Nonlinear Phase Shift	199
6.2.1	Nondispersive XPM.....	199
6.2.2	Optical Kerr Effect.....	200
6.2.3	Pulse Shaping.....	204
6.3	Evolution of Polarization State	206
6.3.1	Analytic Solution	207
6.3.2	Poincaré-Sphere Representation.....	209
6.3.3	Polarization Instability.....	212
6.3.4	Polarization Chaos	214
6.4	Vector Modulation Instability	215
6.4.1	Low-Birefringence Fibers.....	215
6.4.2	High-Birefringence Fibers	218
6.4.3	Isotropic Fibers	220
6.4.4	Experimental Results	221
6.5	Birefringence and Solitons	224
6.5.1	Low-Birefringence Fibers.....	225
6.5.2	High-Birefringence Fibers	226
6.5.3	Soliton-Dragging Logic Gates.....	229
6.5.4	Vector Solitons	230
6.6	Random Birefringence	233
6.6.1	Polarization-Mode Dispersion	233
6.6.2	Vector Form of the NLS Equation	234
6.6.3	Effects of PMD on Solitons	236
	Problems	239
	References	240
CHAPTER 7 Cross-Phase Modulation		245
7.1	XPM-Induced Nonlinear Coupling.....	246
7.1.1	Nonlinear Refractive Index.....	246
7.1.2	Coupled NLS Equations	247
7.2	XPM-Induced Modulation Instability.....	248
7.2.1	Linear Stability Analysis.....	249
7.2.2	Experimental Results	251
7.3	XPM-Paired Solitons	252
7.3.1	Bright–Dark Soliton Pair	252
7.3.2	Bright–Gray Soliton Pair	254
7.3.3	Periodic Solutions.....	255
7.3.4	Multiple Coupled NLS Equations	256
7.4	Spectral and Temporal Effects	258
7.4.1	Asymmetric Spectral Broadening	259
7.4.2	Asymmetric Temporal Changes.....	264

7.4.3 Higher-Order Nonlinear Effects	267
7.5 Applications of XPM	268
7.5.1 XPM-Induced Pulse Compression.....	268
7.5.2 XPM-Induced Optical Switching	270
7.5.3 XPM-Induced Nonreciprocity	272
7.6 Polarization Effects.....	274
7.6.1 Vector Theory of XPM.....	274
7.6.2 Polarization Evolution	275
7.6.3 Polarization-Dependent Spectral Broadening.....	278
7.6.4 Pulse Trapping and Compression	280
7.6.5 XPM-Induced Wave Breaking	282
7.7 XPM Effects in Birefringent Fibers.....	284
7.7.1 Fibers with Low Birefringence	284
7.7.2 Fibers with High Birefringence	287
Problems.....	289
References	290

CHAPTER 8 Stimulated Raman Scattering 295

8.1 Basic Concepts.....	295
8.1.1 Raman-Gain Spectrum.....	296
8.1.2 Raman Threshold.....	297
8.1.3 Coupled Amplitude Equations.....	300
8.1.4 Effect of Four-Wave Mixing	303
8.2 Quasi-Continuous SRS	305
8.2.1 Single-Pass Raman Generation.....	305
8.2.2 Raman Fiber Lasers	307
8.2.3 Raman Fiber Amplifiers.....	310
8.2.4 Raman-Induced Crosstalk.....	315
8.3 SRS with Short Pump Pulses.....	316
8.3.1 Pulse-Propagation Equations	317
8.3.2 Nondispersive Case.....	318
8.3.3 Effects of GVD	320
8.3.4 Raman-Induced Index Changes	323
8.3.5 Experimental Results	325
8.3.6 Synchronously Pumped Raman Lasers	328
8.3.7 Short-Pulse Raman Amplification	330
8.4 Soliton Effects.....	331
8.4.1 Raman Solitons	331
8.4.2 Raman Soliton Lasers	335
8.4.3 Soliton-Effect Pulse Compression	338

8.5 Polarization Effects.....	339
8.5.1 Vector Theory of Raman Amplification.....	339
8.5.2 PMD Effects on Raman Amplification	343
Problems.....	346
References	347
CHAPTER 9 Stimulated Brillouin Scattering.....	353
9.1 Basic Concepts.....	353
9.1.1 Physical Process.....	354
9.1.2 Brillouin-Gain Spectrum	354
9.2 Quasi-CW SBS	358
9.2.1 Brillouin Threshold.....	358
9.2.2 Polarization Effects.....	359
9.2.3 Techniques for Controlling the SBS Threshold	360
9.2.4 Experimental Results.....	363
9.3 Brillouin-Fiber Amplifiers	366
9.3.1 Gain Saturation	366
9.3.2 Amplifier Design and Applications.....	367
9.4 SBS Dynamics	370
9.4.1 Coupled Amplitude Equations	370
9.4.2 SBS with Q-Switched Pulses.....	372
9.4.3 SBS-Induced Index Changes	376
9.4.4 Relaxation Oscillations	380
9.4.5 Modulation Instability and Chaos.....	382
9.5 Brillouin-Fiber Lasers.....	384
9.5.1 CW Operation	384
9.5.2 Pulsed Operation.....	388
Problems.....	391
References	392
CHAPTER 10 Four-Wave Mixing.....	397
10.1 Origin of Four-Wave Mixing	397
10.2 Theory of Four-Wave Mixing	399
10.2.1 Coupled Amplitude Equations	400
10.2.2 Approximate Solution	401
10.2.3 Effect of Phase Matching.....	402
10.2.4 Ultrafast Four-Wave Mixing	404
10.3 Phase-Matching Techniques	405
10.3.1 Physical Mechanisms.....	405

10.3.2 Phase Matching in Multimode Fibers	406
10.3.3 Phase Matching in Single-Mode Fibers.....	409
10.3.4 Phase Matching in Birefringent Fibers	414
10.4 Parametric Amplification	417
10.4.1 Review of Early Work.....	417
10.4.2 Gain Spectrum and Its Bandwidth.....	418
10.4.3 Single-Pump Configuration	421
10.4.4 Dual-Pump Configuration.....	425
10.4.5 Effects of Pump Depletion.....	430
10.5 Polarization Effects.....	431
10.5.1 Vector Theory of Four-Wave Mixing.....	432
10.5.2 Polarization Dependence of Parametric Gain.....	434
10.5.3 Linearly and Circularly Polarized Pumps.....	437
10.5.4 Effect of Residual Fiber Birefringence	439
10.6 Applications of Four-Wave Mixing	443
10.6.1 Parametric Oscillators.....	443
10.6.2 Ultrafast Signal Processing.....	445
10.6.3 Quantum Correlation and Noise Squeezing	447
10.6.4 Phase-Sensitive Amplification	449
Problems.....	451
References	452

CHAPTER 11 Highly Nonlinear Fibers	457
11.1 Nonlinear Parameter	457
11.1.1 Units and Values of n_2	458
11.1.2 SPM-Based Techniques	459
11.1.3 XPM-Based Technique	462
11.1.4 FWM-Based Technique	463
11.1.5 Variations in n_2 Values	464
11.2 Fibers with Silica Cladding	467
11.3 Tapered Fibers with Air Cladding.....	469
11.4 Microstructured Fibers.....	474
11.4.1 Design and Fabrication	474
11.4.2 Modal and Dispersive Properties	476
11.4.3 Hollow-Core Photonic Crystal Fibers.....	478
11.4.4 Bragg Fibers.....	480
11.5 Non-Silica Fibers	481
11.5.1 Lead-Silicate Fibers	482
11.5.2 Chalcogenide Fibers	485
11.5.3 Bismuth-Oxide Fibers.....	486

Contents

11.6	Pulse Propagation in Narrow-Core Fibers	487
11.6.1	Vectorial Theory.....	487
11.6.2	Frequency-Dependent Mode Profiles	489
Problems.....		491
References		492
CHAPTER 12 Novel Nonlinear Phenomena		497
12.1	Soliton Fission and Dispersive Waves	497
12.1.1	Fission of Second- and Higher-Order Solitons.....	498
12.1.2	Generation of Dispersive Waves.....	501
12.2	Intrapulse Raman Scattering.....	506
12.2.1	Enhanced RIFS Through Soliton Fission	506
12.2.2	Cross-correlation Technique	510
12.2.3	Wavelength Tuning through RIFS	512
12.2.4	Effects of Birefringence.....	514
12.2.5	Suppression of Raman-Induced Frequency Shifts.....	516
12.2.6	Soliton Dynamics Near a Zero-Dispersion Wavelength ..	520
12.2.7	Multipulse Raman Solitons	523
12.3	Four-Wave Mixing	526
12.3.1	Role of Fourth-Order Dispersion	526
12.3.2	Role of Fiber Birefringence	527
12.3.3	Parametric Amplifiers and Wavelength Converters	531
12.3.4	Tunable Fiber-Optic Parametric Oscillators	532
12.4	Second-Harmonic Generation	534
12.4.1	Physical Mechanisms.....	534
12.4.2	Thermal Poling and Quasi-Phase Matching	536
12.4.3	SHG Theory	539
12.5	Third-Harmonic Generation	541
12.5.1	THG in Highly Nonlinear Fibers	541
12.5.2	Effects of Group-Velocity Mismatch	543
12.5.3	Effects of Fiber Birefringence	545
Problems.....		546
References		547
CHAPTER 13 Supercontinuum Generation.....		553
13.1	Pumping with Picosecond Pulses	553
13.1.1	Nonlinear Mechanisms	554
13.1.2	Experimental Progress After 2000.....	556
13.2	Pumping with Femtosecond Pulses	559
13.2.1	Microstructured Silica Fibers	559
13.2.2	Microstructured Nonsilica Fibers	563

13.3	Temporal and Spectral Evolutions	566
13.3.1	Numerical Modeling of Supercontinuum	566
13.3.2	Role of Cross-Phase Modulation	570
13.3.3	XPM-Induced Trapping	573
13.3.4	Role of Four-Wave Mixing	577
13.4	CW or Quasi-CW Pumping	579
13.4.1	Nonlinear Mechanisms	579
13.4.2	Experimental Progress	582
13.5	Polarization Effects	585
13.5.1	Birefringent Microstructured Fibers	586
13.5.2	Nearly Isotropic Fibers	587
13.5.3	Nonlinear Polarization Rotation in Isotropic Fibers	589
13.6	Coherence Properties	590
13.6.1	Spectral-Domain Degree of Coherence	591
13.6.2	Techniques for Improving Coherence	594
13.6.3	Spectral Incoherent Solitons	596
13.7	Optical Rogue Waves	598
13.7.1	L-Shaped Statistics of Pulse-to-Pulse Fluctuations	599
13.7.2	Techniques for Controlling Rogue-Wave Statistics	600
13.7.3	Modulation Instability Revisited	602
	Problems	606
	References	607
Appendix A	System of Units	613
Appendix B	Numerical Code for the NLS Equation	615
Appendix C	List of Acronyms	619
Index	621