

Contents

<i>Author biography</i>	xvii
<i>Preface</i>	xix
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	22
References	22
2. Pulse propagation in fibers	27
2.1. Maxwell's equations	27
2.2. Fiber modes	29
2.2.1. Eigenvalue equation	30
2.2.2. Characteristics of the fundamental mode	32
2.3. Pulse-propagation equation	34
2.3.1. Nonlinear wave equation	34
2.3.2. Higher-order nonlinear effects	40
2.3.3. Raman response function and its impact	42
2.4. Numerical methods	46
2.4.1. Split-step Fourier method	46
2.4.2. Finite-difference methods	50
Problems	52
References	53
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	68
3.3. Third-order dispersion	69
3.3.1. Chirped Gaussian pulses	70
3.3.2. Broadening factor	71
3.3.3. Ultrashort-pulse measurements	74
3.4. Dispersion management	76
3.4.1. Dispersion compensation	76
3.4.2. Compensation of third-order dispersion	78
3.4.3. Dispersion-varying fibers	80
Problems	81
References	82
4. Self-phase modulation	85
4.1. SPM-induced spectral changes	85
4.1.1. Nonlinear phase shift	85
4.1.2. Changes in pulse spectra	88
4.1.3. Effect of pulse shape and initial chirp	90
4.1.4. Effect of partial coherence	93
4.2. Effect of group-velocity dispersion	95
4.2.1. Pulse evolution	96
4.2.2. Broadening factor	98
4.2.3. Optical wave breaking	100
4.2.4. Experimental results	103
4.2.5. Effect of third-order dispersion	104
4.2.6. SPM effects in fiber amplifiers	105
4.3. Semianalytic techniques	108
4.3.1. Moment method	108
4.3.2. Variational method	110
4.3.3. Specific analytic solutions	111
4.4. Higher-order nonlinear effects	113
4.4.1. Self-steepening	114
4.4.2. Effect of GVD on optical shocks	117
4.4.3. Intrapulse Raman scattering	119
Problems	121
References	123
5. Optical solitons	127
5.1. Modulation instability	127
5.1.1. Linear stability analysis	127
5.1.2. Gain spectrum	129
5.1.3. Experimental observation	131
5.1.4. Ultrashort pulse generation	132
5.1.5. Impact of loss and third-order dispersion	134
5.1.6. Spatial modulation of fiber parameters	136

5.2. Fiber solitons	138
5.2.1. Inverse scattering method	139
5.2.2. Fundamental soliton	141
5.2.3. Second and higher-order solitons	143
5.2.4. Experimental confirmation	146
5.2.5. Soliton stability	147
5.3. Other types of solitons	150
5.3.1. Dark solitons	150
5.3.2. Bistable solitons	154
5.3.3. Dispersion-managed solitons	155
5.3.4. Optical similaritons	156
5.4. Perturbation of solitons	159
5.4.1. Perturbation methods	159
5.4.2. Fiber loss	160
5.4.3. Soliton amplification	162
5.4.4. Soliton interaction	165
5.5. Higher-order effects	169
5.5.1. Moment equations for pulse parameters	169
5.5.2. Third-order dispersion	171
5.5.3. Self-steepening	173
5.5.4. Intrapulse Raman scattering	175
5.6. Propagation of femtosecond pulses	180
Problems	182
References	183
6. Polarization effects	189
6.1. Nonlinear birefringence	189
6.1.1. Origin of nonlinear birefringence	190
6.1.2. Coupled-mode equations	192
6.1.3. Elliptically birefringent fibers	193
6.2. Nonlinear phase shift	194
6.2.1. Nondispersive XPM	194
6.2.2. Optical Kerr effect	196
6.2.3. Pulse shaping	200
6.3. Evolution of polarization state	202
6.3.1. Analytic solution	202
6.3.2. Poincaré-sphere representation	204
6.3.3. Polarization instability	207
6.3.4. Polarization chaos	210
6.4. Vector modulation instability	210
6.4.1. Low-birefringence fibers	211
6.4.2. High-birefringence fibers	213
6.4.3. Isotropic fibers	215
6.4.4. Experimental results	217

6.5. Birefringence and solitons	220
6.5.1. Low-birefringence fibers	220
6.5.2. High-birefringence fibers	221
6.5.3. Soliton-dragging logic gates	225
6.5.4. Vector solitons	226
6.6. Higher-order effects	228
6.6.1. Extended coupled-mode equations	229
6.6.2. Impact of TOD and Raman nonlinearity	230
6.6.3. Interaction of two vector solitons	233
6.7. Random birefringence	236
6.7.1. Polarization-mode dispersion	236
6.7.2. Vector form of the NLS equation	237
6.7.3. Effects of PMD on solitons	239
Problems	241
References	241
7. Cross-phase modulation	245
7.1. XPM-induced nonlinear coupling	245
7.1.1. Nonlinear refractive index	245
7.1.2. Coupled NLS equations	247
7.2. XPM-induced modulation instability	248
7.2.1. Linear stability analysis	248
7.2.2. Experimental results	250
7.3. XPM-paired solitons	252
7.3.1. Bright-dark soliton pair	252
7.3.2. Bright-gray soliton pair	253
7.3.3. Periodic solutions	254
7.3.4. Multiple coupled NLS equations	256
7.4. Spectral and temporal effects	257
7.4.1. Asymmetric spectral broadening	258
7.4.2. Asymmetric temporal changes	263
7.4.3. Higher-order nonlinear effects	266
7.5. Applications of XPM	267
7.5.1. XPM-induced pulse compression	267
7.5.2. XPM-induced optical switching	270
7.5.3. XPM-induced wavelength conversion	271
7.6. Polarization effects	272
7.6.1. Vector theory of XPM	272
7.6.2. Polarization evolution	273
7.6.3. Polarization-dependent spectral broadening	276
7.6.4. Pulse trapping and compression	278
7.6.5. XPM-induced wave breaking	281
7.7. XPM effects in birefringent fibers	282
7.7.1. Fibers with low birefringence	283
7.7.2. Fibers with high birefringence	287

7.8. Two counterpropagating waves	288
Problems	291
References	292
8. Stimulated Raman scattering	297
8.1. Basic concepts	297
8.1.1. Raman-gain spectrum	298
8.1.2. Raman threshold	299
8.1.3. Coupled amplitude equations	302
8.1.4. Effect of four-wave mixing	305
8.2. Quasi-continuous SRS	307
8.2.1. Single-pass Raman generation	307
8.2.2. Raman fiber lasers	309
8.2.3. Raman fiber amplifiers	312
8.2.4. Raman-induced crosstalk	317
8.3. SRS with short pump pulses	319
8.3.1. Pulse-propagation equations	319
8.3.2. Nondispersive case	320
8.3.3. Effects of GVD	323
8.3.4. Raman-induced index changes	326
8.3.5. Experimental results	327
8.3.6. Synchronously pumped Raman lasers	331
8.3.7. Short-pulse Raman amplification	332
8.4. Soliton effects	334
8.4.1. Raman solitons	334
8.4.2. Raman soliton lasers	338
8.4.3. Soliton-effect pulse compression	341
8.5. Polarization effects	342
8.5.1. Vector theory of Raman amplification	342
8.5.2. PMD effects on Raman amplification	346
Problems	349
References	350
9. Stimulated Brillouin scattering	355
9.1. Basic concepts	355
9.1.1. Physical process	355
9.1.2. Brillouin-gain spectrum	356
9.2. Quasi-CW SBS	360
9.2.1. Brillouin threshold	360
9.2.2. Polarization effects	361
9.2.3. Techniques for controlling the SBS threshold	363
9.2.4. Experimental results	365
9.3. Brillouin fiber amplifiers	368
9.3.1. Gain saturation	368
9.3.2. Amplifier design and applications	370

9.4. SBS dynamics	372
9.4.1. Coupled amplitude equations	372
9.4.2. SBS with Q-switched pulses	374
9.4.3. SBS-induced index changes	378
9.4.4. Relaxation oscillations	383
9.4.5. Modulation instability and chaos	385
9.5. Brillouin fiber lasers	387
9.5.1. CW operation	387
9.5.2. Pulsed operation	391
Problems	394
References	395
10. Four-wave mixing	401
10.1. Origin of four-wave mixing	401
10.2. Theory of four-wave mixing	403
10.2.1. Coupled amplitude equations	404
10.2.2. Approximate solution	405
10.2.3. Effect of phase matching	406
10.2.4. Ultrafast four-wave mixing	408
10.3. Phase-matching techniques	409
10.3.1. Physical mechanisms	410
10.3.2. Nearly phase-matched four-wave mixing	411
10.3.3. Phase matching near the zero-dispersion wavelength	412
10.3.4. Phase matching through self-phase modulation	413
10.3.5. Phase matching in birefringent fibers	416
10.4. Parametric amplification	419
10.4.1. Review of early work	419
10.4.2. Gain spectrum and its bandwidth	421
10.4.3. Single-pump configuration	423
10.4.4. Dual-pump configuration	427
10.4.5. Effects of pump depletion	432
10.5. Polarization effects	434
10.5.1. Vector theory of four-wave mixing	435
10.5.2. Polarization dependence of parametric gain	437
10.5.3. Linearly and circularly polarized pumps	440
10.5.4. Effect of residual fiber birefringence	443
10.6. Applications of four-wave mixing	446
10.6.1. Parametric amplifiers and wavelength converters	446
10.6.2. Tunable fiber-optic parametric oscillators	448
10.6.3. Ultrafast signal processing	451
10.6.4. Quantum correlation and noise squeezing	453
10.6.5. Phase-sensitive amplification	456
Problems	457
References	458

11. Highly nonlinear fibers	463
11.1. Nonlinear parameter	463
11.1.1. Units and values of n_2	463
11.1.2. SPM-based techniques	465
11.1.3. XPM-based technique	468
11.1.4. FWM-based technique	469
11.1.5. Variations in n_2 values	471
11.2. Fibers with silica cladding	474
11.3. Tapered fibers with air cladding	476
11.4. Microstructured fibers	480
11.4.1. Design and fabrication	480
11.4.2. Modal and dispersive properties	482
11.4.3. Hollow-core photonic crystal fibers	485
11.4.4. Bragg fibers	486
11.5. Non-silica fibers	487
11.5.1. Lead-silicate fibers	488
11.5.2. Chalcogenide fibers	491
11.5.3. Bismuth-oxide fibers	492
11.6. Theory of narrow-core fibers	493
Problems	498
References	499
12. Novel nonlinear phenomena	503
12.1. Soliton fission and dispersive waves	503
12.1.1. Fission of second- and higher-order solitons	503
12.1.2. Generation of dispersive waves	507
12.2. Intrapulse Raman scattering	512
12.2.1. Enhanced RIFS through soliton fission	512
12.2.2. Cross-correlation technique	516
12.2.3. Wavelength tuning through RIFS	518
12.2.4. Effects of birefringence	521
12.2.5. Suppression of Raman-induced frequency shifts	523
12.2.6. Soliton dynamics near a zero-dispersion wavelength	527
12.2.7. Multipeak Raman solitons	530
12.3. Frequency combs and cavity solitons	532
12.3.1. CW-pumped ring cavities	533
12.3.2. Nonlinear dynamics of ring cavities	534
12.3.3. Frequency combs without a cavity	537
12.4. Second-harmonic generation	538
12.4.1. Physical mechanisms	539
12.4.2. Thermal poling and quasi-phase matching	541
12.4.3. SHG theory	544
12.5. Third-harmonic generation	546
12.5.1. THG in highly nonlinear fibers	546
12.5.2. Effects of group-velocity mismatch	547

12.5.3. Effects of fiber birefringence	549
Problems	551
References	552
13. Supercontinuum generation	557
13.1. Pumping with picosecond pulses	557
13.1.1. Nonlinear mechanisms	558
13.1.2. Experimental progress after 2000	560
13.2. Pumping with femtosecond pulses	563
13.3. Temporal and spectral evolution of pulses	568
13.3.1. Numerical modeling of supercontinuum	569
13.3.2. Role of cross-phase modulation	572
13.3.3. XPM-induced trapping	575
13.3.4. Role of four-wave mixing	580
13.4. CW or quasi-CW pumping	581
13.4.1. Nonlinear mechanisms	582
13.4.2. Experimental results	585
13.5. Polarization effects	588
13.6. Coherence properties	593
13.6.1. Effect of pump coherence	593
13.6.2. Spectral incoherent solitons	596
13.6.3. Techniques for improving spectral coherence	599
13.7. Ultraviolet and mid-infrared supercontinua	601
13.7.1. Extension into ultraviolet region	602
13.7.2. Extension into mid-infrared region	604
13.8. Optical rogue waves	607
13.8.1. L-shaped statistics of pulse-to-pulse fluctuations	607
13.8.2. Techniques for controlling rogue-wave statistics	608
13.8.3. Modulation instability revisited	611
Problems	614
References	615
14. Multimode fibers	621
14.1. Modes of optical fibers	621
14.1.1. Step-index fibers	621
14.1.2. Graded-index fibers	625
14.1.3. Multicore fibers	627
14.1.4. Excitation of fiber modes	630
14.2. Nonlinear pulse propagation	631
14.2.1. Multimode propagation equations	631
14.2.2. Few-mode fibers	633
14.2.3. Random linear mode coupling	635
14.2.4. Graded-index fibers	638
14.3. Modulation instability and solitons	640
14.3.1. Modulation instability	641

14.3.2. Multimode solitons	644
14.3.3. Solitons in specific fiber modes	649
14.4. Intermodal nonlinear phenomena	651
14.4.1. Intermodal FWM	651
14.4.2. Intermodal SRS	657
14.4.3. Intermodal SBS	662
14.5. Spatio-temporal dynamics	665
14.5.1. Spatial beam cleanup	666
14.5.2. Supercontinuum generation	668
14.6. Multicore fibers	674
Problems	678
References	679
A. System of units	685
B. Nonlinear response of fibers	687
References	688
C. Derivation of the generalized NLS equation	689
D. Numerical code for the NLS equation	693
E. List of acronyms	695
<i>Index</i>	697