
Optical Electronics in Modern Communications

Fifth Edition

Amnon Yariv
California Institute of Technology

Physikalische Bibliothek
Fachbereich 5
Technische Universität Darmstadt
Hochschulstraße 4
D-64289 Darmstadt

pb 2809

New York Oxford
Oxford University Press
1997

Contents

Chapter 1	ELECTROMAGNETIC THEORY	1
1.0	Introduction	1
1.1	Complex-Function Formalism	1
	Time-Averaging of Sinusoidal Products	3
1.2	Considerations of Energy and Power in Electromagnetic Fields	3
	Dipolar Dissipation in Harmonic Fields	5
1.3	Wave Propagation in Isotropic Media	7
	Power Flow in Harmonic Fields	10
1.4	Wave Propagation in Crystals—The Index Ellipsoid	12
	Birefringence	13
	Index Ellipsoid	14
	Normal (index) Surfaces	17
1.5	Jones Calculus and Its Application to Propagation in Optical Systems with Birefringent Crystals	17
	Intensity Transmission	24
	Circular Polarization Representation	26
	Faraday Rotation	27
1.6	Diffraction of Electromagnetic Waves	30
	PROBLEMS	34
	REFERENCES	38

Chapter 2	THE PROPAGATION OF RAYS AND BEAMS	39
2.0	Introduction	39
2.1	Lens Waveguide	39
	Identical-Lens Waveguide	44
2.2	Propagation of Rays Between Mirrors	45
	Reentrant Rays	45
2.3	Rays in Lenslike Media	46
2.4	Wave Equation in Quadratic Index Media	48
2.5	Gaussian Beams in a Homogeneous Medium	50
2.6	Fundamental Gaussian Beam in a Lenslike Medium—The ABCD Law	53
	Transformation of the Gaussian Beam—The ABCD Law	54
2.7	A Gaussian Beam in Lens Waveguide	57
2.8	High-Order Gaussian Beam Modes in a Homogeneous Medium	57
2.9	High-Order Gaussian Beam Modes in Quadratic Index Media	58
	Pulse Spreading in Quadratic Index Glass Fibers	63
2.10	Propagation in Media with a Quadratic Gain Profile	65
2.11	Elliptic Gaussian Beams	66
	Elliptic Gaussian Beams in a Quadratic Lenslike Medium	69
2.12	Diffraction Integral for a Generalized Paraxial A,B,C,D System	70
	PROBLEMS	72
	REFERENCES	74
Chapter 3	PROPAGATION OF OPTICAL BEAMS IN FIBERS	76
3.0	Introduction	76
3.1	Wave Equations in Cylindrical Coordinates	77
3.2	The Step-Index Circular Waveguide	80
	Mode Characteristics and Cutoff Conditions	83
3.3	Linearly Polarized Modes	89
	Power Flow and Power Density	96
3.4	Optical Pulse Propagation and Pulse Spreading in Fibers	98
	Frequency Chirp	105
3.5	Compensation for Group Velocity Dispersion	106
	Compensation for Pulse Broadening by Fibers with Opposite Dispersion	108
	Compensation for Pulse Broadening by Phase Conjugation	108
3.6	Analogy of Spatial Diffraction and Temporal Dispersion	113
3.7	Attenuation in Silica Fibers	115
	PROBLEMS	116
	REFERENCES	119
Chapter 4	OPTICAL RESONATORS	121
4.0	Introduction	121
	Mode Density in Optical Resonators	122

4.1	Fabry-Perot Etalon	125	
4.2	Fabry-Perot Etalons as Optical Spectrum Analyzers	129	
4.3	Optical Resonators with Spherical Mirrors	132	
	Optical Resonator Algebra	133	
	The Symmetrical Mirror Resonator	134	
4.4	Mode Stability Criteria	135	
4.5	Modes in a Generalized Resonator—The Self-Consistent Method	138	
	Stability of the Resonator Modes	139	
4.6	Resonance Frequencies of Optical Resonators	140	
4.7	Losses in Optical Resonators	143	
4.8	Optical Resonators—Diffraction Theory Approach	145	
	Equivalent Resonator Systems	149	
4.9	Mode Coupling	154	
	Equivalent Resonator Systems	149	
	Mode Solution by Numerical Iteration	151	
	PROBLEMS	156	
	REFERENCES	158	
Chapter 5	INTERACTION OF RADIATION AND ATOMIC SYSTEMS	159	
5.0	Introduction	159	
5.1	Spontaneous Transitions Between Atomic Levels—Homogeneous and Inhomogeneous Broadening	159	
	The Concept of Spontaneous Emission	160	
	Lineshape Function—Homogeneous and Inhomogeneous Broadening	161	
	Homogeneous and Inhomogeneous Broadening	162	
5.2	Induced Transitions	165	
5.3	Absorption and Amplification	168	
5.4	Derivation of $\chi'(v)$	171	
5.5	The Significance of $\chi(v)$	174	
5.6	Gain Saturation in Homogeneous Laser Media	176	
5.7	Gain Saturation in Inhomogeneous Laser Media	179	
	PROBLEMS	182	
	REFERENCES	183	
Chapter 6	THEORY OF LASER OSCILLATION AND ITS CONTROL IN THE CONTINUOUS AND PULSED REGIMES	185	
6.0	Introduction	185	
6.1	Fabry-Perot Laser	185	
6.2	Oscillation Frequency	189	
6.3	Three- and Four-Level Lasers	192	
6.4	Power in Laser Oscillators	194	
	Rate Equations	194	
6.5	Optimum Output Coupling in Laser Oscillators	197	
6.6	Multimode Laser Oscillation and Mode Locking	201	
	Mode Locking	203	

	Methods of Mode Locking	206	
	Theory of Mode Locking	210	
6.7	Mode Locking in Homogeneously Broadened Laser Systems		212
	Transfer Function of the Gain Medium	213	
	Transfer Function of the Loss Cell	213	
	Mode Locking by Phase Modulation	217	
6.8	Pulse Length Measurement and Narrowing of Chirped Pulses		218
	Pulse Narrowing by Chirping and Compression	222	
	The Grating Pair Compressor	226	
6.9	Giant Pulse (<i>Q</i> -switched) Lasers	227	
	Methods of <i>Q</i> -Switching	233	
6.10	Hole-Burning and the Lamb Dip in Doppler-Broadened Gas Lasers		235
	PROBLEMS	238	
	REFERENCES	239	
Chapter 7	SOME SPECIFIC LASER SYSTEMS	242	
7.0	Introduction	242	
7.1	Pumping and Laser Efficiency		242
7.2	Ruby Laser	243	
7.3	Nd ³⁺ :YAG Laser	248	
7.4	Neodymium-Glass Laser		251
7.5	He-Ne Laser	255	
7.6	Carbon Dioxide Laser		257
7.7	Ar ⁺ Laser	259	
7.8	Excimer Lasers	260	
7.9	Organic-Dye Lasers	262	
7.10	High-Pressure Operation of Gas Lasers		267
7.11	The <i>Er</i> -Silica Laser	270	
	PROBLEMS	270	
	REFERENCES	270	
Chapter 8	SECOND-HARMONIC GENERATION AND PARAMETRIC OSCILLATION	273	
8.0	Introduction	273	
8.1	On the Physical Origin of Nonlinear Polarization	273	
8.2	Formalism of Wave Propagation in Nonlinear Media		282
8.3	Optical Second-Harmonic Generation	285	
	Phase-Matching in Second-Harmonic Generation		286
	Experimental Verification of Phase-Matching		290
	Second-Harmonic Generation with Focused Gaussian Beams		291
	Second-Harmonic Generation with a Depleted Input		293
8.4	Second-Harmonic Generation Inside the Laser Resonator		295

8.5	Photon Model of Second-Harmonic Generation	299
8.6	Parametric Amplification	300
8.7	Phase-Matching in Parametric Amplification	306
8.8	Parametric Oscillation	308
8.9	Frequency Tuning in Parametric Oscillation	311
8.10	Power Output and Pump Saturation in Optical Parametric Oscillators	314
8.11	Frequency Up-Conversion	316
8.12	Quasi Phase-Matching	319
	Quasi Phase-Matching in Crystal Dielectric Waveguides	320
	PROBLEMS	322
	REFERENCES	323

Chapter 9 ELECTROOPTIC MODULATION OF LASER BEAMS 326

9.0	Introduction	326
9.1	Electrooptic Effect	326
	The General Solution	333
9.2	Electrooptic Retardation	341
9.3	Electrooptic Amplitude Modulation	344
9.4	Phase Modulation of Light	347
9.5	Transverse Electrooptic Modulators	348
9.6	High-Frequency Modulation Considerations	349
	Transit-Time Limitations to High-Frequency Electrooptic Modulation	350
	Traveling-Wave Modulators	351
9.7	Electrooptic Beam Deflection	353
9.8	Electrooptic Modulation—Coupled Wave Analysis	356
	The Wave Equation	358
9.9	Phase Modulation	360
	Amplitude Modulation (advanced topic)	364
	PROBLEMS	367
	REFERENCES	370

Chapter 10 NOISE IN OPTICAL DETECTION AND GENERATION 372

10.0	Introduction	372
10.1	Limitations Due to Noise Power	373
	Measurement of Optical Power	373
10.2	Noise—Basic Definitions and Theorems	376
	Wiener-Khinchine Theorem	378
10.3	The Spectral Density Function of a Train of Randomly Occurring Events	379
10.4	Shot Noise	381
10.5	Johnson Noise	383
	Statistical Derivation of Johnson Noise	386

10.6	Spontaneous Emission Noise in Laser Oscillators	388
10.7	Phasor Derivation of the Laser Linewidth	393
	The Phase Noise	393
	The Laser Field Spectrum	396
10.8	Coherence and Interference	401
	Delayed Self-Heterodyning of Laser Fields	404
	Special Case $t_d \gg \tau_c$	406
10.9	Error Probability in a Binary Pulse Code Modulation System	407
	PROBLEMS	410
	REFERENCES	411

Chapter 11 DETECTION OF OPTICAL RADIATION 413

11.0	Introduction	413
11.1	Optically Induced Transition Rates	414
11.2	Photomultiplier	415
11.3	Noise Mechanisms in Photomultipliers	417
	Minimum Detectable Power in Photomultipliers—Video Detection	418
	Signal-Limited Shot Noise	420
11.4	Heterodyne Detection with Photomultipliers	421
	Limiting Sensitivity as a Result of the Particle Nature of Light	423
11.5	Photoconductive Detectors	425
	Generation Recombination Noise in Photoconductive Detectors	428
	Heterodyne Detection in Photoconductors	430
11.6	The p - n Junction	432
11.7	Semiconductor Photodiodes	436
	Frequency Response of Photodiodes	438
	Detection Sensitivity of Photodiodes	443
11.8	The Avalanche Photodiode	446
11.9	Power Fluctuation Noise in Lasers	449
11.10	Infrared Imaging and Background-Limited Detection	454
11.11	Optical Amplification in Fiber Links	461
	PROBLEMS	470
	REFERENCES	471

Chapter 12 INTERACTION OF LIGHT AND SOUND 474

12.0	Introduction	474
12.1	Scattering of Light by Sound	474
12.2	Particle Picture of Bragg Diffraction of Light by Sound	477
	Doppler Derivation of the Frequency Shift	478

- 12.3 Bragg Diffraction of Light by Acoustic Waves—Analysis 479
- 12.4 Deflection of Light by Sound 486
- PROBLEMS 489
- REFERENCES 490

Chapter 13 PROPAGATION AND COUPLING OF MODES IN OPTICAL DIELECTRIC WAVEGUIDES—PERIODIC WAVEGUIDES 491

- 13.0 Introduction 491
- 13.1 Waveguide Modes—A General Discussion 492
 - Confined Modes in a Symmetric Slab Waveguide 494
- 13.2 TE and TM Modes in an Asymmetric Slab Waveguide 499
 - TE Modes 499
 - TM Modes 501
- 13.3 A Perturbation Theory of Coupled Modes in Dielectric Optical Waveguides 502
- 13.4 Periodic Waveguide 504
 - Some General Properties of the Coupled Mode Equations 506
- 13.5 Coupled-Mode Solutions 509
 - Numerical Example 512
- 13.6 Periodic Waveguides as Optical Filters and Reflectors—Periodic Fibers 512
- 13.7 Electrooptic Modulation and Mode Coupling in Dielectric Waveguides 515
- 13.8 Directional Coupling 521
- 13.9 The Eigenmodes of a Coupled Waveguide System (supermodes) 526
- 13.10 Laser Arrays 531
- PROBLEMS 538
- REFERENCES 539

Chapter 14 HOLOGRAPHY AND OPTICAL DATA STORAGE 541

- 14.0 Introduction 541
- 14.1 The Mathematical Basis of Holography 542
 - The Holographic Process Viewed as Bragg Diffraction 542
 - Basic Holography Formalism 545
- 14.2 The Coupled Wave Analysis of Volume Holograms 546
 - Multihologram Recording and Readout—Crosstalk 549
 - Wavelength Multiplexing 552
 - Crosstalk in Data-Bearing Holograms 552
- PROBLEMS 556
- REFERENCES 557

Chapter 15	SEMICONDUCTOR LASERS—THEORY AND APPLICATIONS	558
15.0	Introduction	558
15.1	Some Semiconductor Physics Background	559
	The Fermi-Dirac Distribution Law	562
15.2	Gain and Absorption in Semiconductor (laser) Media	565
15.3	GaAs/Ga _{1-x} Al _x As Lasers	570
15.4	Some Real Laser Structures	577
	Quaternary GaInAsP Semiconductor Lasers	578
	Power Output of Injection Lasers	581
15.5	Direct-Current Modulation of Semiconductor Lasers	582
15.6	Gain Suppression and Frequency Chirp in Current-Modulated Semiconductor Lasers	587
	Amplitude-phase coupling	592
	The Field Spectrum of a Chirping Laser	594
15.7	Integrated Optoelectronics	596
	PROBLEMS	599
	REFERENCES	601
Chapter 16	ADVANCED SEMICONDUCTOR LASERS: QUANTUM WELL LASERS, DISTRIBUTED FEEDBACK LASERS, VERTICAL CAVITY SURFACE EMITTING LASERS	604
16.0	Introduction	604
16.1	Carriers in Quantum Wells (Advanced Topic)	605
	The Density of States	608
16.2	Gain in Quantum Well Lasers	610
	Multiquantum Well Laser	614
16.3	Distributed Feedback Lasers	616
	Oscillation Condition	619
	Gain-Coupled Distributed Feedback Lasers	626
16.4	Vertical Cavity Surface Emitting Semiconductor Lasers	628
	The Oscillation Condition of a Vertical Cavity Laser	630
	The Bragg Mirror	631
	The Oscillation Frequencies	633
	PROBLEMS	636
	REFERENCES	637
Chapter 17	PHASE CONJUGATE OPTICS—THEORY AND APPLICATIONS	639
17.0	Introduction and Background	639
17.1	The Distortion Correction Theorem	640
17.2	The Generation of Phase Conjugate Waves	641
17.3	The Coupled-Mode Formulation of Phase Conjugate Optics	643
	Some Consideration of Units	648

17.4	Some Experiments Involving Phase Conjugation	649
17.5	Optical Resonators with Phase Conjugate Reflectors	651
17.6	The <i>ABCD</i> Formalism of Phase Conjugate Optical Resonators	653
	The <i>ABCD</i> Matrix of a Phase Conjugate Mirror	653
17.7	Dynamic Distortion Correction Within a Laser Resonator	655
17.8	Holographic Analogs of Phase Conjugate Optics	657
17.9	Imaging Through a Distorted Medium	659
17.10	Image Processing by Four-Wave Mixing	661
17.11	Compensation of Fiber Dispersion	665
	PROBLEMS	665
	REFERENCES	665

Chapter 18 **TWO-BEAM COUPLING AND PHASE CONJUGATION IN PHOTOREFRACTIVE MEDIA 668**

18.0	Introduction	668
18.1	Two-Wave Coupling in a Fixed Grating	669
18.2	The Photorefractive Effect—Two Beam Coupling	671
	The Grating Formation	680
	Refractive Two-Beam Coupling	681
	Two-Beam Coupling—Symmetric Geometry	683
18.3	Photorefractive Self-Pumped Phase Conjugation	684
18.4	Applications of Photorefractive Oscillators	686
	Rotation Sensing	686
	Mathematical and Logic Operations of Images	688
	PROBLEMS	691
	REFERENCES	691

Chapter 19 **OPTICAL SOLITONS 693**

19.0	Introduction	693
19.1	The Mathematical Description of Solitons	693
	The Wave Equation	695
	Numerical Example—Optical Solitons in Silica Fibers	699
	PROBLEMS	700
	REFERENCES	701

Chapter 20 **A CLASSICAL TREATMENT OF QUANTUM OPTICS, QUANTUM NOISE, AND SQUEEZING 703**

20.0	Introduction	703
20.1	The Quantum Uncertainty Goes Classical	703
	The Uncertainty Principle	704
	The Energy of an Electromagnetic Mode	709
	Uncertainty in Energy	709

	Phase Uncertainty	710
	Fluctuation of Photoelectron Number	710
	Minimum Detectable Optical Power Increment	711
20.2	Squeezing of Optical Fields	712
	Experimental Demonstrations of Squeezing	716
	REFERENCES	721
Appendix A	THE KRAMERS-KRONIG RELATIONS	723
Appendix B	THE ELECTROOPTIC EFFECT IN CUBIC $\bar{4}3m$ CRYSTALS	726
Appendix C	NOISE IN TRAVELING WAVE LASER AMPLIFIERS	730
Appendix D	TRANSFORMATION OF A COHERENT ELECTROMAGNETIC FIELD BY A THIN LENS	734
Index		737