

Contents

Introduction	1
1. Maxwell's Equations, Power, and Energy	11
1.1 Maxwell's Field Equations	11
1.2 Poynting's Theorem	15
1.3 Energy and Power Relations and Symmetry of the Tensor $\bar{\epsilon}$..	17
1.4 Uniqueness Theorem	22
1.5 The Complex Maxwell's Equations	23
1.6 Operations with Complex Vectors	25
1.7 The Complex Poynting Theorem	28
1.8 The Reciprocity Theorem	33
1.9 Summary	34
Problems	35
Solutions	37
2. Waveguides and Resonators	39
2.1 The Fundamental Equations of Homogeneous Isotropic Waveguides	39
2.2 Transverse Electromagnetic Waves	44
2.3 Transverse Magnetic Waves	47
2.4 Transverse Electric Waves	53
2.4.1 Mode Expansions	56
2.5 Energy, Power, and Energy Velocity	59
2.5.1 The Energy Theorem	59
2.5.2 Energy Velocity and Group Velocity	60
2.5.3 Energy Relations for Waveguide Modes	61
2.5.4 A Perturbation Example	62
2.6 The Modes of a Closed Cavity	64
2.7 Real Character of Eigenvalues and Orthogonality of Modes ..	67
2.8 Electromagnetic Field Inside a Closed Cavity with Sources ..	72
2.9 Analysis of Open Cavity	74
2.10 Open Cavity with Single Input	77
2.10.1 The Resonator and the Energy Theorem	78

2.10.2	Perturbation Theory and the Generic Form of the Impedance Expression	79
2.11	Reciprocal Multiports	83
2.12	Simple Model of Resonator	84
2.13	Coupling Between Two Resonators	88
2.14	Summary	91
	Problems	92
	Solutions	95
3.	Diffraction, Dielectric Waveguides, Optical Fibers, and the Kerr Effect	99
3.1	Free-Space Propagation and Diffraction	100
3.2	Modes in a Cylindrical Piecewise Uniform Dielectric	106
3.3	Approximate Approach	109
3.4	Perturbation Theory	113
3.5	Propagation Along a Dispersive Fiber	113
3.6	Solution of the Dispersion Equation for a Gaussian Pulse	115
3.7	Propagation of a Polarized Wave in an Isotropic Kerr Medium	117
3.7.1	Circular Polarization	119
3.8	Summary	120
	Problems	120
	Solutions	123
4.	Shot Noise and Thermal Noise	127
4.1	The Spectrum of Shot Noise	128
4.2	The Probability Distribution of Shot Noise Events	134
4.3	Thermal Noise in Waveguides and Transmission Lines	136
4.4	The Noise of a Lossless Resonator	140
4.5	The Noise of a Lossy Resonator	143
4.6	Langevin Sources in a Waveguide with Loss	144
4.7	Lossy Linear Multiports at Thermal Equilibrium	146
4.8	The Probability Distribution of Photons at Thermal Equilibrium	150
4.9	Gaussian Amplitude Distribution of Thermal Excitations	152
4.10	Summary	154
	Problems	155
	Solutions	156
5.	Linear Noisy Multiports	157
5.1	Available and Exchangeable Power from a Source	159
5.2	The Stationary Values of the Power Delivered by a Noisy Multiport and the Characteristic Noise Matrix	160

5.3	The Characteristic Noise Matrix in the Admittance Representation Applied to a Field Effect Transistor	166
5.4	Transformations of the Characteristic Noise Matrix	168
5.5	Simplified Generic Forms of the Characteristic Noise Matrix.	172
5.6	Noise Measure of an Amplifier	175
5.6.1	Exchangeable Power	175
5.6.2	Noise Figure	176
5.6.3	Exchangeable Power Gain	177
5.6.4	The Noise Measure and Its Optimum Value	179
5.7	The Noise Measure in Terms of Incident and Reflected Waves	181
5.7.1	The Exchangeable Power Gain	183
5.7.2	Excess Noise Figure.	184
5.8	Realization of Optimum Noise Performance	185
5.9	Cascading of Amplifiers	189
5.10	Summary	190
	Problems	192
	Solutions	193
6.	Quantum Theory of Waveguides and Resonators.	197
6.1	Quantum Theory of the Harmonic Oscillator	198
6.2	Annihilation and Creation Operators.	203
6.3	Coherent States of the Electric Field	205
6.4	Commutator Brackets, Heisenberg's Uncertainty Principle and Noise.	209
6.5	Quantum Theory of an Open Resonator	211
6.6	Quantization of Excitations on a Single-Mode Waveguide	215
6.7	Quantum Theory of Waveguides with Loss	217
6.8	The Quantum Noise of an Amplifier with a Perfectly Inverted Medium	220
6.9	The Quantum Noise of an Imperfectly Inverted Amplifier Medium.	223
6.10	Noise in a Fiber with Loss Compensated by Gain	226
6.11	The Lossy Resonator and the Laser Below Threshold.	229
6.12	Summary	237
	Problems	238
	Solutions	239
7.	Classical and Quantum Analysis of Phase-Insensitive Systems.	241
7.1	Renormalization of the Creation and Annihilation Operators	242
7.2	Linear Lossless Multiports in the Classical and Quantum Domains	243

7.3	Comparison of the Schrödinger and Heisenberg Formulations of Lossless Linear Multiports	248
7.4	The Schrödinger Formulation and Entangled States	251
7.5	Transformation of Coherent States	254
7.6	Characteristic Functions and Probability Distributions	256
7.6.1	Coherent State	256
7.6.2	Bose–Einstein Distribution	258
7.7	Two-Dimensional Characteristic Functions and the Wigner Distribution	259
7.8	The Schrödinger Cat State and Its Wigner Distribution	263
7.9	Passive and Active Multiports	267
7.10	Optimum Noise Measure of a Quantum Network	272
7.11	Summary	276
	Problems	277
	Solutions	278
8.	Detection	281
8.1	Classical Description of Shot Noise and Heterodyne Detection	282
8.2	Balanced Detection	285
8.3	Quantum Description of Direct Detection	288
8.4	Quantum Theory of Balanced Heterodyne Detection	290
8.5	Linearized Analysis of Heterodyne Detection	292
8.6	Heterodyne Detection of a Multimodal Signal	295
8.7	Heterodyne Detection with Finite Response Time of Detector	296
8.8	The Noise Penalty of a Simultaneous Measurement of Two Noncommuting Observables	298
8.9	Summary	300
	Problems	301
	Solutions	302
9.	Photon Probability Distributions and Bit-Error Rate of a Channel with Optical Preamplication	305
9.1	Moment Generating Functions	305
9.1.1	Poisson Distribution	308
9.1.2	Bose–Einstein Distribution	308
9.1.3	Composite Processes	309
9.2	Statistics of Attenuation	311
9.3	Statistics of Optical Preamplication with Perfect Inversion	314
9.4	Statistics of Optical Preamplication with Incomplete Inversion	320
9.5	Bit-Error Rate with Optical Preamplication	324
9.5.1	Narrow-Band Filter, Polarized Signal, and Noise	324
9.5.2	Broadband Filter, Unpolarized Signal	327

9.6	Negentropy and Information	330
9.7	The Noise Figure of Optical Amplifiers	333
9.8	Summary	339
	Problems	340
	Solutions	342
10.	Solitons and Long-Distance Fiber Communications	345
10.1	The Nonlinear Schrödinger Equation	346
10.2	The First-Order Soliton	348
10.3	Properties of Solitons	352
10.4	Perturbation Theory of Solitons	354
10.5	Amplifier Noise and the Gordon–Haus Effect	357
10.6	Control Filters	361
10.7	Erbium-Doped Fiber Amplifiers and the Effect of Lumped Gain	365
10.8	Polarization	367
10.9	Continuum Generation by Soliton Perturbation	370
10.10	Summary	374
	Problems	376
	Solutions	377
11.	Phase-Sensitive Amplification and Squeezing	379
11.1	Classical Analysis of Parametric Amplification	380
11.2	Quantum Analysis of Parametric Amplification	383
11.3	The Nondegenerate Parametric Amplifier as a Model of a Linear Phase-Insensitive Amplifier	386
11.4	Classical Analysis of Degenerate Parametric Amplifier	387
11.5	Quantum Analysis of Degenerate Parametric Amplifier	390
11.6	Squeezed Vacuum and Its Homodyne Detection	393
11.7	Phase Measurement with Squeezed Vacuum	395
11.8	The Laser Resonator Above Threshold	398
11.9	The Fluctuations of the Photon Number	403
11.10	The Schawlow–Townes Linewidth	406
11.11	Squeezed Radiation from an Ideal Laser	408
11.12	Summary	412
	Problems	413
	Solutions	414
12.	Squeezing in Fibers	417
12.1	Quantization of Nonlinear Waveguide	418
12.2	The x Representation of Operators	420
12.3	The Quantized Equation of Motion of the Kerr Effect in the x Representation	422

12.4	Squeezing	424
12.5	Generation of Squeezed Vacuum with a Nonlinear Interferometer	427
12.6	Squeezing Experiment	432
12.7	Guided-Acoustic-Wave Brillouin Scattering	434
12.8	Phase Measurement Below the Shot Noise Level	436
12.9	Generation of Schrödinger Cat State via Kerr Effect	440
12.10	Summary	442
	Problems	442
	Solutions	443
13.	Quantum Theory of Solitons and Squeezing	445
13.1	The Hamiltonian and Equations of Motion of a Dispersive Waveguide	446
13.2	The Quantized Nonlinear Schrödinger Equation and Its Linearization	449
13.3	Soliton Perturbations Projected by the Adjoint	453
13.4	Renormalization of the Soliton Operators	457
13.5	Measurement of Operators	461
13.6	Phase Measurement with Soliton-like Pulses	462
13.7	Soliton Squeezing in a Fiber	465
13.8	Summary	469
	Problems	471
	Solutions	472
14.	Quantum Nondemolition Measurements and the “Collapse” of the Wave Function	473
14.1	General Properties of a QND Measurement	475
14.2	A QND Measurement of Photon Number	475
14.3	“Which Path” Experiment	481
14.4	The “Collapse” of the Density Matrix	484
14.5	Two Quantum Nondemolition Measurements in Cascade	490
14.6	The Schrödinger Cat Thought Experiment	493
14.7	Summary	497
	Problems	498
	Solutions	499
	Epilogue	503
	Appendices	505
A.1	Phase Velocity and Group Velocity of a Gaussian Beam	505
A.2	The Hermite Gaussians and Their Defining Equation	506
A.2.1	The Defining Equation of Hermite Gaussians	506
A.2.2	Orthogonality Property of Hermite Gaussian Modes	507

A.2.3 The Generating Function and Convolutions
of Hermite Gaussians 508

A.3 Recursion Relations of Bessel Functions 512

A.4 Brief Review of Statistical Function Theory 513

A.5 The Different Normalizations of Field Amplitudes
and of Annihilation Operators 515

 A.5.1 Normalization of Classical Field Amplitudes 515

 A.5.2 Normalization of Quantum Operators 516

A.6 Two Alternative Expressions for the Nyquist Source 517

A.7 Wave Functions and Operators in the n Representation 518

A.8 Heisenberg's Uncertainty Principle 523

A.9 The Quantized Open-Resonator Equations 524

A.10 Density Matrix and Characteristic Functions 527

 A.10.1 Example 1. Density Matrix of Bose-Einstein State 528

 A.10.2 Example 2. Density Matrix of Coherent State 528

A.11 Photon States and Beam Splitters 529

A.12 The Baker-Hausdorff Theorem 530

 A.12.1 Theorem 1 530

 A.12.2 Theorem 2 531

 A.12.3 Matrix Form of Theorem 1 531

 A.12.4 Matrix Form of Theorem 2 532

A.13 The Wigner Function of Position and Momentum 533

A.14 The Spectrum of Non-Return-to-Zero Messages 535

A.15 Various Transforms of Hyperbolic Secants 538

A.16 The Noise Sources Derived from a Lossless Multiport
with Suppressed Terminals 541

A.17 The Noise Sources of an Active System
Derived from Suppression of Ports 542

A.18 The Translation Operator and the Transformation
of Coherent States from the β Representation
to the x Representation 543

A.19 The Heisenberg Equation in the Presence of Dispersion 544

A.20 Gaussian Distributions and Their $e^{-1/2}$ Loci 544

References 549

Index 555