

OPTICS



1400
Ajoy Ghatak

CONTENTS

<i>Preface</i>	xiii
1. History of Optics	1
<i>References</i>	9
2. What Is Light?	11
2.1 Introduction	11
2.2 The Corpuscular Model	11
2.3 The Wave Model	13
2.4 The Particle Nature of Radiation	15
2.5 Wave Nature of Matter	17
2.6 The Uncertainty Principle	18
2.7 The Single-Slit Diffraction Experiment	18
2.8 The Probabilistic Interpretation of Matter Waves	19
2.9 An Understanding of Interference Experiments	21
2.10 The Polarization of a Photon	23
2.11 The Time-Energy Uncertainty Relation	24
<i>Summary</i>	24
<i>Problems</i>	25
<i>Solutions</i>	25
<i>References and Suggested Readings</i>	26
Part 1 Geometrical Optics	29
Fermat's Principle and Its Applications	
3.1 Introduction	29
3.2 Laws of Reflection and Refraction from Fermat's Principle	31
3.3 Ray Paths in an Inhomogeneous Medium	34
3.4 The Ray Equation and its Solutions	39
3.5 Refraction of Rays at the Interface between an Isotropic Medium and an Anisotropic Medium	44
<i>Summary</i>	47
<i>Problems</i>	47
<i>References and Suggested Readings</i>	51
Refraction and Reflection by Spherical Surfaces	53
4.1 Introduction	53
4.2 Refraction at a Single Spherical Surface	54
4.3 Reflection by a Single Spherical Surface	55
4.4 The Thin Lens	56
4.5 The Principal Foci and Focal Lengths of a Lens	57

- 4.6 The Newton Formula 59
- 4.7 Lateral Magnification 59
- 4.8 Aplanatic Points of a Sphere 60
- 4.9 The Cartesian Oval 62
- 4.10 Geometrical Proof for the Existence of Aplanatic Points 62
- 4.11 The Sine Condition 63
- Summary 65
- Problems 65
- References and Suggested Readings 66

5. The Matrix Method in Paraxial Optics

- 5.1 Introduction 67
- 5.2 The Matrix Method 68
- 5.3 Unit Planes 73
- 5.4 Nodal Planes 74
- 5.5 A System of Two Thin Lenses 75
- Summary 77
- Problems 77
- References and Suggested Readings 78

6. Aberrations

- 6.1 Introduction 79
- 6.2 Chromatic Aberration 79
- 6.3 Monochromatic Aberrations 83
- Summary 90
- Problems 90
- References and Suggested Readings 91

Part 2 Vibrations and Waves

7. Simple Harmonic Motion, Forced Vibrations, and Origin of Refractive Index

- 7.1 Introduction 95
- 7.2 Simple Harmonic Motion 95
- 7.3 Damped Simple Harmonic Motion 99
- 7.4 Forced Vibrations 101
- 7.5 Origin of Refractive Index 103
- 7.6 Rayleigh Scattering 107
- Summary 108
- Problems 108
- References and Suggested Readings 110

8. Fourier Series and Applications

- 8.1 Introduction 111
- 8.2 Transverse Vibrations of a Plucked String 113
- 8.3 Application of Fourier Series in Forced Vibrations 115
- 8.4 The Fourier Integral 116
- Summary 117
- Problems 117
- References and Suggested Readings 118

9. The Dirac Delta Function and Fourier Transforms

- 9.1 Introduction 119

9.2 Dirac Delta Function 119

9.3	Integral Representation of the Delta Function	120
9.4	Delta Function as a Distribution	120
9.5	Fourier Integral Theorem	121
9.6	The Two- and Three-Dimensional Fourier Transform	123
	Summary	124
	Problems	124
10.	Group Velocity and Pulse Dispersion	127
10.1	Introduction	127
10.2	Group Velocity	127
10.3	Group Velocity of a Wave Packet	131
10.4	Self Phase Modulation	137
	Summary	139
	Problems	140
	References and Suggested Readings	141
11.	Wave Propagation and the Wave Equation	143
11.1	Introduction	143
11.2	Sinusoidal Waves: Concept of Frequency and Wavelength	145
11.3	Types of Waves	146
11.4	Energy Transport in Wave Motion	146
11.5	The One-Dimensional Wave Equation	147
11.6	Transverse Vibrations of a Stretched String	148
11.7	Longitudinal Sound Waves in a Solid	149
11.8	Longitudinal Waves in a Gas	150
11.9	The General Solution of the One-Dimensional Wave Equation	151
	Summary	154
	Problems	154
	References and Suggested Readings	155
12.	Huygens' Principle and Its Applications	157
12.1	Introduction	157
12.2	Huygens' Theory	157
12.3	Rectilinear Propagation	158
12.4	Application of Huygens' Principle to Study Refraction and Reflection	159
	Summary	165
	Problems	165
	References and Suggested Readings	165
 Part 3 Interference		
13.	Superposition of Waves	169
13.1	Introduction	169
13.2	Stationary Waves on a String	169
13.3	Stationary Waves on a String Whose Ends are Fixed	171
13.4	Stationary Light Waves: Ives' and Wiener's Experiments	172
13.5	Superposition of Two Sinusoidal Waves	172
13.6	The Graphical Method for Studying Superposition of Sinusoidal Waves	173
13.7	The Complex Representation	175
	Summary	175
	Problems	175
	References and Suggested Readings	176

14. Two-Beam Interference by Division of Wave Front

- 14.1 Introduction 177
- 14.2 Interference Pattern Produced on the Surface of Water 178
- 14.3 Coherence 181
- 14.4 Interference of Light Waves 182
- 14.5 The Interference Pattern 183
- 14.6 The Intensity Distribution 184
- 14.7 Fresnel's Two-Mirror Arrangement 189
- 14.8 Fresnel Biprism 189
- 14.9 Interference with White Light 190
- 14.10 Displacement of Fringes 191
- 14.11 Lloyd's Mirror Arrangement 192
- 14.12 Phase Change on Reflection 192
- Summary 193
- Problems 193
- References and Suggested Readings 194

15. Interference by Division of Amplitude

- 15.1 Introduction 195
- 15.2 Interference by a Plane Parallel Film When Illuminated by a Plane Wave 196
- 15.3 The Cosine Law 197
- 15.4 Nonreflecting Films 198
- 15.5 High Reflectivity by Thin Film Deposition 201
- 15.6 Reflection by a Periodic Structure 202
- 15.7 Interference by a Plane Parallel Film When Illuminated by a Point Source 206
- 15.8 Interference by a Film with Two Nonparallel Reflecting Surfaces 208
- 15.9 Colors of Thin Films 211
- 15.10 Newton's Rings 212
- 15.11 The Michelson Interferometer 216
- Summary 219
- Problems 219
- References and Suggested Readings 220

16. Multiple-Beam Interferometry

- 16.1 Introduction 221
- 16.2 Multiple Reflections from a Plane Parallel Film 221
- 16.3 The Fabry-Perot Etalon 223
- 16.4 The Fabry-Perot Interferometer 225
- 16.5 Resolving Power 226
- 16.6 The Lummer-Gehrcke Plate 229
- 16.7 Interference Filters 230
- Summary 231
- Problems 231
- References and Suggested Readings 231

17. Coherence

- 17.1 Introduction 233
- 17.2 The Line Width 235
- 17.3 The Spatial Coherence 236
- 17.4 Michelson Stellar Interferometer 238
- 17.5 Optical Beats 239
- 17.6 Coherence Time and Line Width via Fourier Analysis 241
- 17.7 Complex Degree of Coherence and Fringe Visibility in Young's Double-Hole Experiment 243

- 17.8 Fourier Transform Spectroscopy 244
 Summary 249
 Problems 249
 References and Suggested Readings 250

Part 4 Diffraction

18. Fraunhofer Diffraction I

253

- 18.1 Introduction 253
18.2 Single-Slit Diffraction Pattern 254
18.3 Diffraction by a Circular Aperture 258
18.4 Directionality of Laser Beams 260
18.5 Limit of Resolution 264
18.6 Two-Slit Fraunhofer Diffraction Pattern 267
18.7 N -Slit Fraunhofer Diffraction Pattern 269
18.8 The Diffraction Grating 272
18.9 Oblique Incidence 275
18.10 X-ray Diffraction 276
18.11 The Self-Focusing Phenomenon 280
18.12 Optical Media Technology—An Essay 282
 Summary 285
 Problems 285
 References and Suggested Readings 287

19. Fraunhofer Diffraction II and Fourier Optics

289

- 19.1 Introduction 289
19.2 The Fresnel Diffraction Integral 289
19.3 Uniform Amplitude and Phase Distribution 291
19.4 The Fraunhofer Approximation 291
19.5 Fraunhofer Diffraction by a Long Narrow Slit 291
19.6 Fraunhofer Diffraction by a Rectangular Aperture 292
19.7 Fraunhofer Diffraction by a Circular Aperture 293
19.8 Array of Identical Apertures 294
19.9 Spatial Frequency Filtering 296
19.10 The Fourier Transforming Property of a Thin Lens 298
 Summary 300
 Problems 300
 References and Suggested Readings 301

20. Fresnel Diffraction

303

- 20.1 Introduction 303
20.2 Fresnel Half-Period Zones 304
20.3 The Zone Plate 306
20.4 Fresnel Diffraction—A More Rigorous Approach 308
20.5 Gaussian Beam Propagation 310
20.6 Diffraction by a Straight edge 312
20.7 Diffraction of a Plane Wave by a Long Narrow Slit and Transition to the Fraunhofer Region 318
 Summary 320
 Problems 321
 References and Suggested Readings 323

325

21. Holography

- 21.1 Introduction 325
21.2 Theory 327

21.3	Requirements	330
21.4	Some Applications	330
	Summary	332
	Problems	332
	References and Suggested Readings	333

Part 5 Electromagnetic Character of Light

22. Polarization and Double Refraction

22.1	Introduction	337
22.2	Production of Polarized Light	340
22.3	Malus' Law	343
22.4	Superposition of Two Disturbances	344
22.5	The Phenomenon of Double Refraction	347
22.6	Interference of Polarized Light: Quarter Wave Plates and Half Wave Plates	351
22.7	Analysis of Polarized Light	354
22.8	Optical Activity	354
22.9	Change in the SOP (State of Polarization) of a Light Beam Propagating Through an Elliptic Core Single-Mode Optical Fiber	356
22.10	Wollaston Prism	358
22.11	Rochon Prism	359
22.12	Plane Wave Propagation in Anisotropic Media	359
22.13	Ray Velocity and Ray Refractive Index	363
22.14	Jones' Calculus	365
22.15	Faraday Rotation	367
22.16	Theory of Optical Activity	369
	Summary	371
	Problems	372
	References and Suggested Readings	374

23. Electromagnetic Waves

23.1	Maxwell's Equations	375
23.2	Plane Waves in a Dielectric	375
23.3	The Three-Dimensional Wave Equation in a Dielectric	378
23.4	The Poynting Vector	379
23.5	Energy Density and Intensity of an Electromagnetic Wave	382
23.6	Radiation Pressure	382
23.7	The Wave Equation in a Conducting Medium	384
23.8	The Continuity Conditions	385
23.9	Physical Significance of Maxwell's Equations	386
	Summary	388
	Problems	388
	References and Suggested Readings	389

4. Reflection and Refraction of Electromagnetic Waves

24.1	Introduction	391
24.2	Reflection and Refraction at an Interface of Two Dielectrics	391
24.3	Reflection by a Conducting Medium	404
24.4	Reflectivity of a Dielectric Film	406
	Summary	407
	Problems	408
	References and Suggested Readings	408

Part 6 Photons

25. The Particle Nature of Radiation

411

- 25.1 Introduction 412
- 25.2 The Photoelectric Effect 412
- 25.3 The Compton Effect 414
- 25.4 The Photon Mass 418
- 25.5 Angular Momentum of a Photon 418
- Summary 420
- Problems 421
- References and Suggested Readings 421

Part 7 Lasers and Fiber Optics

26. Lasers: An Introduction

425

- 26.1 Introduction 426
- 26.2 The Fiber Laser 431
- 26.3 The Ruby Laser 432
- 26.4 The He-Ne Laser 434
- 26.5 Optical Resonators 436
- 26.6 Einstein Coefficients and Optical Amplification 440
- 26.7 The Line Shape Function 446
- 26.8 Typical Parameters for a Ruby Laser 447
- 26.9 Monochromaticity of the Laser Beam 448
- 26.10 Raman Amplification and Raman Laser 449
- Summary 452
- Problems 453
- References and Suggested Readings 454

27. Optical Waveguides I: Optical Fiber Basics Using Ray Optics

455

- 27.1 Introduction 456
- 27.2 Some Historical Remarks 456
- 27.3 Total Internal Reflection 459
- 27.4 The Optical Fiber 460
- 27.5 Why Glass Fibers? 461
- 27.6 The Coherent Bundle 462
- 27.7 The Numerical Aperture 462
- 27.8 Attenuation in Optical Fibers 463
- 27.9 Multimode Fibers 465
- 27.10 Pulse Dispersion in Multimode Optical Fibers 466
- 27.11 Dispersion and Maximum Bit Rates 469
- 27.12 General Expression for Ray Dispersion Corresponding to a Power Law Profile 470
- 27.13 Plastic Optical Fibers 471
- 27.14 Fiber-Optic Sensors 471
- Problems 472
- References and Suggested Readings 473

28. Optical Waveguides II: Basic Waveguide Theory and Concept of Modes

475

- 28.1 Introduction 475
- 28.2 TE Modes of a Symmetric Step Index Planar Waveguide 476
- 28.3 Physical Understanding of Modes 480
- 28.4 TM Modes of a Symmetric Step Index Planar Waveguide 481

28.5	TE Modes of a Parabolic Index Planar Waveguide	482
28.6	Waveguide Theory and Quantum Mechanics	483
	Problems	485
	References and Suggested Readings	485

29. Optical Waveguides III: Single-Mode Fibers

29.1	Introduction	487
29.2	Basic Equations	487
29.3	Guided Modes of a Step Index Fiber	489
29.4	Single-Mode Fiber	491
29.5	Pulse Dispersion in Single-Mode Fibers	493
29.6	Dispersion Compensating Fibers	495
	Problems	497
	References and Suggested Readings	498

Part 8 Special Theory of Relativity

30. Special Theory of Relativity I: Time Dilation and Length Contraction

30.1	Introduction	501
30.2	Speed of Light for a Moving Source	502
30.3	Time Dilation	503
30.4	The Mu Meson Experiment	504
30.5	The Length Contraction	505
30.6	Understanding the Mu Meson Experiment via Length Contraction	506
30.7	Length Contraction of a Moving Train	506
30.8	Simultaneity of Two Events	407
30.9	The Twin Paradox	508
30.10	The Michelson-Morley Experiment	509
30.11	Brief Historical Remarks	511
	Problems	512
	References and Suggested Readings	512

31. Special Theory of Relativity II: Mass-Energy Relationship and Lorentz Transformations

31.1	Introduction	513
31.2	The Mass-Energy Relationship	513
31.3	The Doppler Shift	515
31.4	The Lorentz Transformation	516
31.5	Addition of Velocities	518
	References and Suggested Readings	518

Appendix A: Gamma Functions and Integrals Involving Gaussian Functions

Appendix B: Evaluation of the Integral

Appendix C: The Reflectivity of a Fiber Bragg Grating

Appendix D: Diffraction of a Gaussian Beam

Appendix E: TE and TM Modes in Planar Waveguides

Appendix F: Solution for the Parabolic Index Waveguide

Appendix G: Invariance of the Wave Equation Under Lorentz Transformation

Name Index

Subject Index