

Preface	iv
1 Introduction	1
1.1 Optics, Information, and Communication	1
1.2 The Book	2
2 Analysis of Two-Dimensional Signals and Systems	5
2.1 Fourier Analysis in Two Dimensions	6
2.1.1 Definition and Existence Conditions	6
2.1.2 The Fourier Transform as a Decomposition	8
2.1.3 Fourier Transform Theorems	9
2.1.4 Separable Functions	11
2.1.5 Functions with Circular Symmetry: Fourier-Bessel Transforms	12
2.1.6 Some Frequently Used Functions and Some Useful Fourier Transform Pairs	14
2.2 Spatial Frequency and Space-Frequency Localization	17
2.2.1 Local Spatial Frequencies	18
2.2.2 The Wigner Distribution Function	21
2.3 Linear Systems	25
2.3.1 Linearity and the Superposition Integral	25
2.3.2 Invariant Linear Systems: Transfer Functions	26

2.4	Two-Dimensional Sampling Theory	28
2.4.1	The Whittaker-Shannon Sampling Theorem	29
2.4.2	Oversampling, Undersampling and Aliasing	32
2.4.3	Space-Bandwidth Product	33
2.5	The Discrete Fourier Transform	35
2.6	The Projection-Slice Theorem	37
2.7	Phase Retrieval from Fourier Magnitude	38
3	Foundations of Scalar Diffraction Theory	43
3.1	Historical Introduction	43
3.2	From a Vector to a Scalar Theory	47
3.3	Some Mathematical Preliminaries	50
3.3.1	The Helmholtz Equation	50
3.3.2	Green's Theorem	51
3.3.3	The Integral Theorem of Helmholtz and Kirchhoff	51
3.4	The Kirchhoff Formulation of Diffraction by a Planar Screen	54
3.4.1	Application of the Integral Theorem	55
3.4.2	The Kirchhoff Boundary Conditions	56
3.4.3	The Fresnel-Kirchhoff Diffraction Formula	57
3.5	The Rayleigh-Sommerfeld Formulation of Diffraction	58
3.5.1	Choice of Alternative Green's Functions	59
3.5.2	The Rayleigh-Sommerfeld Diffraction Formula	61
3.5.3	Reproduction of Boundary Conditions	62
3.6	Kirchhoff and Rayleigh-Sommerfeld Theories Compared	63
3.7	Further Discussion of the Huygens-Fresnel Principle	64
3.8	Generalization to Nonmonochromatic Waves	66
3.9	Diffraction at Boundaries	67
3.10	The Angular Spectrum of Plane Waves	68
3.10.1	The Angular Spectrum and Its Physical Interpretation	68
3.10.2	Propagation of the Angular Spectrum	69
3.10.3	Effects of a Diffracting Aperture on the Angular Spectrum	71
3.10.4	The Propagation Phenomenon as a Linear Spatial Filter	72
4	Fresnel and Fraunhofer Diffraction	75
4.1	Background	75
4.1.1	The Intensity of a Wave Field	75
4.1.2	The Huygens-Fresnel Principle in Rectangular Coordinates	77
4.2	The Fresnel Approximation	78
4.2.1	Positive vs. Negative Phases	80
4.2.2	Accuracy of the Fresnel Approximation	80
4.2.3	Finite Integral of the Quadratic-Phase Exponential Function	81

4.2.4	The Fresnel Approximation and the Angular Spectrum	83
4.2.5	Fresnel Diffraction Between Confocal Spherical Surfaces	84
4.2.6	Fresnel Diffraction in Terms of Ray Transfer Matrices	85
4.3	The Fraunhofer Approximation	88
4.4	Examples of Fraunhofer Diffraction Patterns	90
4.4.1	Rectangular Aperture	90
4.4.2	Circular Aperture	91
4.4.3	Thin Sinusoidal Amplitude Grating	93
4.4.4	Thin Sinusoidal Phase Grating	96
4.4.5	General Method for Calculating Diffraction Efficiency of Gratings	98
4.5	Examples of Fresnel Diffraction Calculations	99
4.5.1	Fresnel Diffraction by a Square Aperture	99
4.5.2	Fresnel Diffraction by a Circular Aperture	102
4.5.3	Fresnel Diffraction by a Sinusoidal Amplitude Grating-Talbot Images	104
4.6	Beam Optics	108
4.6.1	Gaussian Beams	108
4.6.2	Hermite-Gaussian Beams	111
4.6.3	Laguerre-Gaussian Beams	112
4.6.4	Bessel Beams	113
5	Computational Diffraction and Propagation	121
5.1	Approaches to Computational Diffraction	121
5.2	Sampling a Space-Limited Quadratic-Phase Exponential	122
5.3	The Convolution Approach	125
5.3.1	Bandwidth and Sampling Considerations	125
5.3.2	Discrete Convolution Equations	127
5.3.3	Simulation Results	128
5.3.4	Convolution by Fourier Transforms	129
5.4	The Fresnel Transform Approach	130
5.4.1	Sampling Increments	130
5.4.2	Sampling Ratio Q	131
5.4.3	Finding the Required M , Q , and N	132
5.4.4	The Discrete Diffraction Formulas	132
5.4.5	Examples of the Dependence of M and N on N_F	133
5.4.6	Summary of Steps Using the Fresnel Transform Approach	133
5.4.7	Computational Complexity of the Fresnel Transform Approach	135
5.5	The Fresnel Transfer Function Approach	135
5.5.1	Sampling Considerations	136
5.5.2	Finding N , M and Q for each N_F	136
5.5.3	The Discrete Diffraction Formulas	137

5.5.4	Examples of the Dependence of M , N and Q on N_F	138
5.5.5	Summary of Steps Using the Fresnel Transfer Function Approach	138
5.5.6	Computational Complexity of the Fresnel Transfer Function Approach	140
5.6	The Exact Transfer Function Approach	140
5.6.1	Sampling in the Frequency Domain	140
5.6.2	Sampling in the Space Domain	141
5.6.3	Simulation Results	143
5.6.4	Computational Complexity of the Exact Transfer Function Approach	144
5.7	Comparison of Computational Complexities	145
5.8	Extension to More Complex Apertures	148
5.8.1	One-Dimensional Case	148
5.8.2	Two-Dimensional Apertures Separable in (x,y) Coordinates	149
5.8.3	Circularly-Symmetric Apertures	150
5.8.4	More General Cases	151
5.9	Concluding Comments	152
6	Wave-Optics Analysis of Coherent Optical Systems	155
6.1	A Thin Lens as a Phase Transformation	155
6.1.1	The Thickness Function	156
6.1.2	The Paraxial Approximation	158
6.1.3	The Phase Transformation and Its Physical Meaning	158
6.2	Fourier Transforming Properties of Lenses	161
6.2.1	Input Placed against the Lens	162
6.2.2	Input Placed in Front of the Lens	164
6.2.3	Input Placed behind the Lens	166
6.2.4	Example of an Optical Fourier Transform	167
6.3	Image Formation: Monochromatic Illumination	168
6.3.1	The Impulse Response of a Positive Lens	168
6.3.2	Eliminating Quadratic-Phase Factors: The Lens Law	169
6.3.3	The Relation between Object and Image	172
6.4	Analysis of Complex Coherent Optical Systems	174
6.4.1	The Ray Matrix Approach	174
6.4.2	Analysis of Two Optical Systems Using Ray Matrices	175
7	Frequency Analysis of Optical Imaging Systems	185
7.1	Generalized Treatment of Imaging Systems	186
7.1.1	A Generalized Model	186
7.1.2	Effects of Diffraction on the Image	187
7.1.3	Polychromatic Illumination: The Coherent and Incoherent Cases	189

7.2	Frequency Response for Diffraction-Limited Coherent Imaging	194
7.2.1	The Amplitude Transfer Function	194
7.2.2	Examples of Amplitude Transfer Functions	195
7.3	Frequency Response for Diffraction-Limited Incoherent Imaging	197
7.3.1	The Optical Transfer Function	197
7.3.2	General Properties of the OTF	199
7.3.3	The OTF of an Aberration-Free System	200
7.3.4	Examples of Diffraction-Limited OTFs	201
7.4	Aberrations and Their Effects on Frequency Response	204
7.4.1	The Generalized Pupil Function	205
7.4.2	Effects of Aberrations on the Amplitude Transfer Function	206
7.4.3	Effects of Aberrations on the OTF	206
7.4.4	Example of a Simple Aberration: A Focusing Error	207
7.4.5	Apodization and Its Effects on Frequency Response	211
7.5	Comparison of Coherent and Incoherent Imaging	214
7.5.1	Frequency Spectrum of the Image Intensity	215
7.5.2	Two-Point Resolution	216
7.5.3	Other Effects	219
7.6	Confocal Microscopy	221
7.6.1	Coherent Case	222
7.6.2	Incoherent Case	223
7.6.3	Optical Sectioning	224
8	Point-Spread Function and Transfer Function Engineering	231
8.1	Cubic Phase Mask for Increased Depth of Field	231
8.1.1	Depth of Focus	231
8.1.2	Depth of Field	233
8.1.3	The Cubic Phase Mask	233
8.2	Rotating Point-Spread Functions for Depth Resolution	237
8.3	Point-Spread Function Engineering for Exoplanet Discovery	241
8.3.1	The Lyot Coronagraph	241
8.3.2	Apodization for Starlight Suppression	242
8.4	Resolution beyond the Classical Diffraction Limit	248
8.4.1	Analytic Continuation	248
8.4.2	Synthetic Aperture Fourier Holography	251
8.4.3	Fourier Ptychography	252
8.4.4	Coherent Spectral Multiplexing	253
8.4.5	Incoherent Structured Illumination Imaging	258
8.4.6	Super-Resolved Fluorescence Microscopy	260
8.5	Light Field Photography	263

9	Wavefront Modulation	269
9.1	Wavefront Modulation with Photographic Film	270
9.1.1	The Physical Processes of Exposure, Development, and Fixing	270
9.1.2	Definition of Terms	272
9.1.3	Photographic Film or Plate in Coherent Optical Systems	274
9.1.4	The Modulation Transfer Function	276
9.1.5	Bleaching of Photographic Emulsions	279
9.2	Wavefront Modulation with Diffractive Optical Elements	280
9.2.1	Single Step Lithography	281
9.2.2	Multistep Lithography	283
9.2.3	Other Types of Diffractive Optics	287
9.2.4	A Word of Caution	287
9.3	Liquid Crystal Spatial Light Modulators	287
9.3.1	Properties of Liquid Crystals	288
9.3.2	Spatial Light Modulators Based on Liquid Crystals	297
9.4	Deformable Mirror Spatial Light Modulators	301
9.5	Acousto-Optic Spatial Light Modulators	304
9.6	Other Methods of Wavefront Modulation	308
10	Analog Optical Information Processing	309
10.1	Historical Background	310
10.1.1	The Abbe-Porter Experiments	310
10.1.2	The Zernike Phase-Contrast Microscope	312
10.1.3	Improvement of Photographs: Maréchal	314
10.1.4	Application of Coherent Optics to More General Data Processing	316
10.2	Coherent Optical Information Processing Systems	316
10.2.1	Coherent System Architectures	316
10.2.2	Constraints on Filter Realization	319
10.3	The VanderLugt Filter	321
10.3.1	Synthesis of the Frequency-Plane Mask	321
10.3.2	Processing the Input Data	324
10.3.3	Advantages of the VanderLugt Filter	326
10.4	The Joint Transform Correlator	326
10.5	Application to Character Recognition	329
10.5.1	The Matched Filter	329
10.5.2	A Character-Recognition Problem	330
10.5.3	Optical Synthesis of a Character-Recognition Machine	332
10.5.4	Sensitivity to Scale Size and Rotation	334
10.6	Image Restoration	335
10.6.1	The Inverse Filter	335

10.6.2	The Wiener Filter, or the Least-Mean-Square-Error Filter	336
10.6.3	Filter Realization	337
10.7	Acousto-Optic Signal Processing Systems	341
10.7.1	Bragg Cell Spectrum Analyzer	342
10.7.2	Space-Integrating Correlator	343
10.7.3	Time-Integrating Correlator	345
10.7.4	Other Acousto-Optic Signal Processing Architectures	347
10.8	Discrete Analog Optical Processors	347
10.8.1	Discrete Representation of Signals and Systems	347
10.8.2	A Parallel Incoherent Matrix-Vector Multiplier	348
10.8.3	Methods for Handling Bipolar and Complex Data	350
II	Holography	357
11.1	Historical Introduction	357
11.2	The Wavefront Reconstruction Problem	358
11.2.1	Recording Amplitude and Phase	358
11.2.2	The Recording Medium	359
11.2.3	Reconstruction of the Original Wavefront	360
11.2.4	Linearity of the Holographic Process	361
11.2.5	Image Formation by Holography	361
11.3	The Gabor Hologram	363
11.3.1	Origin of the Reference Wave	364
11.3.2	The Twin Images	364
11.3.3	Limitations of the Gabor Hologram	365
11.4	The Leith-Upatnieks Hologram	366
11.4.1	Recording the Hologram	366
11.4.2	Obtaining the Reconstructed Images	368
11.4.3	The Minimum Reference Angle	369
11.4.4	Holography of Three-Dimensional Scenes	371
11.4.5	Practical Problems in Holography	374
11.5	Image Locations and Magnification	375
11.5.1	Image Locations	376
11.5.2	Axial and Transverse Magnifications	378
11.5.3	An Example	379
11.6	Some Different Types of Holograms	380
11.6.1	Fresnel, Fraunhofer, Image, and Fourier Holograms	381
11.6.2	Transmission and Reflection Holograms	382
11.6.3	Holographic Stereograms	384
11.6.4	Rainbow Holograms	385
11.6.5	Multiplex Holograms	387
11.6.6	Embossed Holograms	389

11.7	Thick Holograms	390
11.7.1	Recording a Volume Holographic Grating	391
11.7.2	Reconstructing Wavefronts from a Volume Grating	392
11.7.3	Fringe Orientations for More Complex Recording Geometries	394
11.7.4	Gratings of Finite Size	396
11.7.5	Diffraction Efficiency—Coupled Mode Theory	398
11.8	Recording Materials	408
11.8.1	Silver Halide Emulsions	408
11.8.2	Photopolymer Films	408
11.8.3	Dichromated Gelatin	409
11.8.4	Photorefractive Materials	409
11.9	Computer-Generated Holograms	412
11.9.1	The Sampling and Computation Problems	413
11.9.2	The Representational Problem	413
11.10	Degradations of Holographic Images	421
11.10.1	Effects of Film MTF	422
11.10.2	Effects of Film Nonlinearities	424
11.10.3	Effects of Film-Grain Noise	425
11.10.4	Speckle Noise	426
11.11	Digital Holography	426
11.11.1	Offset Reference-Wave Digital Holography	427
11.11.2	Phase-Shifting Digital Holography	427
11.12	Holography with Spatially Incoherent Light	428
11.13	Applications of Holography	431
11.13.1	Microscopy and High-Resolution Volume Imagery	431
11.13.2	Interferometry	432
11.13.3	Imaging through Distorting Media	438
11.13.4	Holographic Data Storage	442
11.13.5	Holographic Weights for Artificial Neural Networks	443
11.13.6	Other Applications	447

12 Fourier Optics in Optical Communications 453

12.1	Introduction	453
12.2	Fiber Bragg Gratings	454
12.2.1	Introduction to Optical Fibers	454
12.2.2	Recording Gratings in Optical Fibers	457
12.2.3	Effects of an FBG on Light Propagating in the Fiber	458
12.2.4	Applications of FBGs	461
12.2.5	Gratings Operated in Transmission	463
12.3	Ultrashort Pulse Shaping and Processing	463
12.3.1	Mapping of Temporal Frequencies to Spatial Frequencies	464
12.3.2	Pulse Shaping System	466

12.3.3	Applications of Spectral Pulse Shaping	467
12.4	Spectral Holography	469
12.4.1	Recording the Hologram.....	469
12.4.2	Reconstructing the Signals	472
12.4.3	Effects of Delay between the Reference Pulse and the Signal Waveform	474
12.5	Arrayed Waveguide Gratings	474
12.5.1	Component Parts of an Arrayed Waveguide Grating	475
12.5.2	Applications of AWGs	481
A	Delta Functions and Fourier Transform Theorems	487
A.1	Delta Functions	487
A.2	Derivation of Fourier Transform Theorems.....	489
B	Introduction to Paraxial Geometrical Optics	495
B.1	The Domain of Geometrical Optics	495
B.2	Refraction, Snell's Law, and the Paraxial Approximation	497
B.3	The Ray-Transfer Matrix	498
B.4	Conjugate Planes, Focal Planes, and Principal Planes	501
B.5	Entrance and Exit Pupils	506
C	Polarization and Jones Matrices	509
C.1	Definition of the Jones Matrix	509
C.2	Examples of Simple Polarization Transformations	511
C.3	Reflective Polarization Devices.....	513
D	The Grating Equation	515
	Bibliography.....	517
	Index	534