

An Introduction to
COHERENT OPTICS
and **HOLOGRAPHY**

George W. Stroke

*Department of Electrical Engineering
The University of Michigan
Ann Arbor, Michigan*

ACADEMIC PRESS



New York • London • 1966

COPYRIGHT © 1966 BY ACADEMIC PRESS INC.

ALL RIGHTS RESERVED.

NO PART OF THIS BOOK MAY BE REPRODUCED IN ANY FORM,
BY PHOTOSTAT, MICROFILM, OR ANY OTHER MEANS, WITHOUT
WRITTEN PERMISSION FROM THE PUBLISHERS.

ACADEMIC PRESS INC.
111 Fifth Avenue, New York, New York 10003

United Kingdom Edition published by
ACADEMIC PRESS INC. (LONDON) LTD.
Berkeley Square House, London W.1

First printing January 1966
Second printing September 1966

LIBRARY OF CONGRESS CATALOG CARD NUMBER: 65-28633

PRINTED IN THE UNITED STATES OF AMERICA

CONTENTS

PREFACE	vii
---------------	-----

I. Introduction

1. Emergence of Modern Optics as a Branch of Electrical Engineering	1
2. Mathematical Character of Electro-Optical Engineering.....	1
3. Mathematical Methods of Modern Optics	2
4. Some Limitations of Operational Formulation of Optical Image Formation and the Need for Boundary-Value Solutions in the Study of Diffraction of Electromagnetic Waves in Optics.....	2
5. Grating Equation as an Example of Boundary-Value Solution of a Diffraction Problem	4
6. Gratings as Information Carriers in Optics (Application to Wavefront-Reconstruction Imaging).....	8
7. Optics and Communication Theory. Historical Background,.....	13
References	14

II. Diffraction Theory (Qualitative Introduction)

1. The Two Aspects of the Diffraction of Light.....	16
2. Theoretical Calculation of Energy Distribution in Diffraction and of Spectral Diffraction Patterns.....	16
2.1. Electromagnetic Boundary-Value Solutions.....	16
2.2. Image-Formation Solutions Using Huygens' Principle.....	21
3. Image-Formation Theory and Optical Signal Processing in Fourier-Transform Formulation.....	24
References	25

III. Image Formation in Noncoherent Light (Elements and Definitions)

1. Image of Point Source.....	26
2. Summation of Light from Several Source Points Reaching One Image Point.....	27
3. Spread Function.....	28
4. Image of Extended Source in Noncoherent Light	29
5. Method of Computing Image Intensities and Transfer Functions.....	29
6. Analysis of Image Formation in Terms of Spatial Fourier Space.....	31
7. Physical Significance of Spread Function and of Fourier-Space Analysis of Image Formation.....	33
7.1. Point Source (Dirac Delta Function) \rightarrow Diffraction Pattern— Spread Function	34
7.2. Sinusoidal Intensity Objects \rightarrow Spatial Frequency-Response Function—Fourier Transform of Diffraction Pattern.....	34
8. Application of "Fourier-Space" Representation to "Synthesis" of Object-Functions.....	37
References	37

IV. Coherence Characteristics of Light (Experimental Characterization)

1. Introduction	38
2. Characterization of Coherence	38
2.1. Correlation Method	38
2.2. Alternate Way of Looking at Time Coherence (Interference Theory)	40
a. Monochromatic (single-frequency) light.....	40
b. Polychromatic light (noncoherent source).....	41
2.3. Comparison of the Correlation and Interferometric Method.....	42
2.4. Narrow Spectrum (Flat-Top Line).....	42
2.5. Photoelectric Interferometry with Gaussian Line Shapes, in Interferometers with Moving Mirrors.....	43
2.6. Physical Significance of Power Spectra	45
a. Case of a single-frequency signal.....	45
b. Case of a multiple-frequency signal	47
2.7. Heterodyne Analysis of Signals, Beat Frequencies, etc.	48
a. Beat frequencies between coherent waves and relativistic effect for light reflected from moving mirrors	48
b. Parallelism tolerances for the two interfering waves in photoelectric interferometry and heterodyning experiments.....	51
c. Photoelectric mixing of incoherent light.....	54
d. Photoelectric mixing of coherent laser light with noncoherent thermal light	54
2.8. Spatial Coherence.....	57
2.9. Partial Coherence with Extended Noncoherent Source	60
a. Two-slit (Young) interferometer and Michelson's stellar interferometer	63
2.10. Intensity Correlations in Partially Coherent Fields	66
2.11. Intensity Interferometers	66
a. Method No. 1.....	66
b. Method No. 2.....	68
References	69

V. Image Formation in Coherent Light

1. Introduction	70
2. Coherent Illumination.....	70
2.1. Example 1. Illumination of an Extended Field by a Point Source..	70
2.2. Example 2. Equivalence of Coherent Object and Coherently Illuminated Object.....	70
3. Image Formation in Coherent Light, Considered as Double Diffraction..	72
4. Abbe and Rayleigh Resolution Criteria.....	74
5. Transfer Functions in Coherent and Noncoherent Light.....	76
6. Phase-Contrast Filtering.....	77
7. Optical Filtering with Holographically Matched Spatial Filters	79
7.1. Realization of the Complex Filter and of Filtering Operation.....	83
8. Optical Computing, Correlating, and Signal Processing	86
8.1. Spectrum Analyzers.....	86
8.2. Optical Cross Correlators	89
9. Interferometry and Optical Image Synthesis (Complex Amplitude Addition) by Successive Addition of Holographic Intensities in a Single Hologram.....	90
References.....	96

VI. Theoretical and Experimental Foundations of Optical Holography (Wavefront-Reconstruction Imaging)

1. Background and Experimental Foundations.....	98
2. Theoretical Foundations	100
2.1. The Recording Process	106
2.2. The Reconstruction Process.....	108
2.3. Physics of the Method.....	109
2.4. Magnification.....	111
2.5. Resolution	114
3. High-Resolution Fourier-Transform Holography.....	116
3.1. Introduction	116
3.2. Physical Principles of High-Resolution Lensless Fourier-Transform Holography.....	120
3.3. Mathematical Analysis of Lensless Fourier-Transform Holography.....	121
3.4. Comparison of Fourier-Transform and Fresnel-Transform Holography for High-Resolution Imaging	124
4. Resolution-Retrieving Compensation of Source Effects in Holography... ..	127
4.1. Concise Analysis	128
4.2. More Formal Analysis.....	133
4.3. Concluding Remarks	137
5. Coherence Requirements in Holography.....	137
6. Summary and Results	139
7. Electron Microscopy and X-Ray-Hologram Microscopy	143
8. Conclusion.....	144
9. Holography with Noncoherent Light.....	149
9.1. Holographic Fourier-Transform Spectroscopy with Spectrally Noncoherent Light	151
9.2. Image-Forming Holography with Spatially Noncoherent Light.....	158
References.....	161

VII. Fourier Transforms, Convolutions, Correlations, Spectral Analysis, and the Theory of Distributions

1. Fourier Transforms	164
1.1. Some Properties of Fourier Transforms	165
1.2. Linearity.....	165
1.3. Translation Theorem.....	165
1.4. Reciprocal Translation Theorem.....	166
1.5. Table of Fourier-Transform Properties	167
1.6. Two-Dimensional and Multidimensional Fourier Transforms	168
1.7. Scale Change in Fourier Transforms	168
1.8. Fourier Transform of the Complex Conjugate of a Function.....	169
1.9. Fourier Cosine Transforms and Fourier Sine Transforms.....	169
1.10. Symmetry Relations	169
2. Convolution Integrals.....	170
2.1. Definition of Convolution.....	170
2.2. Multidimensional Convolutions and Convolutions of Several Functions.....	170
2.3. Convolution Theorem (Fourier Transform of Convolution Integral).	171

3. Correlation Functions.....	174
3.1. Definition of Correlation Functions.....	174
3.2. Transforms of Correlation Functions.....	174
4. Distributions.....	177
4.1. Definitions.....	177
4.2. Impulse Response of a Linear System.....	178
4.3. Response of a Linear System to an Arbitrary Input Function.....	178
5. Spectral Analysis.....	179
References.....	180

Reprinted Papers

A New Microscopic Principle..... by D. Gabor.....	181
<i>Nature</i> 161, No. 4098, 777-778 (1948)	
Microscopy by Reconstructed Wave-Fronts.... by D. Gabor.....	184
<i>Proc. Roy. Soc. (London)</i> A197, 454-487 (1949)	
Introduction.....	184
The Principle of Wave-Front Reconstruction.....	187
Illumination by a Homocentric Wave.....	189
Reconstruction with Homocentric Illumination.....	193
The Spurious Part of the Reconstruction in Homocentric Illumination.....	195
Improving the Separation by Masking and Other Means.....	201
Illuminating Waves with Astigmatism and Spherical Aberration.....	202
Reconstruction in the Presence of Spherical Aberration and Astigmatism..	206
Coherence Criteria.....	208
The Optical Reconstruction.....	210
Experimental Tests.....	214
Conclusion.....	219
References.....	220
Microscopy by Reconstructed Wave-Fronts: II.. by D. Gabor.....	221
<i>Proc. Phys. Soc. (London)</i> 64 (Pt. 6), No. 378B, 449-469 (1951)	
1. Introduction.....	221
2. The Principle of Wave-Front Reconstruction.....	222
3. Theory of Image Formation in the Transmission Method.....	225
4. The Reconstruction.....	231
5. Coherence Criteria.....	233
Transverse Coherence.....	233
Longitudinal Coherence.....	234
Chromatic Coherence.....	235
The Coherent Current.....	235
6. Conditions for the Taking of Holograms.....	237
7. The Dark-Field Method of Reconstruction.....	238
References.....	241
AUTHOR INDEX.....	243
SUBJECT INDEX.....	246