

Contents

Preface	xv
Acknowledgments	xvii
Acronyms	xix
Industrial Property	xxiii
Introduction: From Diffraction to Diffractive Optics	1
1 Introduction	1
2 Huygens–Fresnel Diffraction	4
3 Fraunhofer and Fresnel Diffraction	5
4 Examples of Far-Field Diffraction Patterns	8
4.1 Long, Narrow Slit Example	8
4.2 Double Slit Example	10
4.3 Diffraction Grating	11
4.4 Fraunhofer Diffraction for a Rectangular Aperture	13
4.5 Fraunhofer Diffraction for a Circular Aperture	14
5 Conclusion	15
Chapter 1 Design and Simulation of Diffractive Optical Elements	17
1 Introduction	17
2 Diffraction Modelling of DOEs: Theoretical Background	17
2.1 Diffraction of Monochromatic Waves	17
2.1.1 Review of Scalar Diffraction Theory for DOE Modelling	18
Limitations of the Kirchhoff Model	22
2.1.2 Review of Rigorous Diffraction Models	24
Grating Description	26
Lord Rayleigh’s Early Propositions	27
Integral Method	27
Differential Method	28

	Modal Approach	30
	Rigorous Coupled Wave Analysis Approach	30
	Two-Wave Theory	31
	Raman-Nath's Method	31
	Kogelnik's Method	31
	Analytical Methods	31
	Rytov's Method	32
	Effective Medium Theory (EMT)	32
	Farn's Method	32
2.1.3	Review of Intermediate Diffraction Models	34
	Optimum Etch Depth	35
	Geometrical Shadow Duty Cycle	36
2.2	Theoretical Aspects of DOE Performance in the Paraxial Domain	37
2.2.1	Energetic Considerations of Scalar Diffraction	37
	Diffraction Efficiency for Amplitude DOEs	38
	Diffraction Efficiency for Multilevel Surface Relief DOEs	39
	Diffraction Efficiency for Analog Surface Relief DOEs	42
2.2.2	Geometric Considerations of Scalar Diffraction	46
2.2.3	Physical DOE Layout Considerations for Diffraction Efficiency	49
3	Numerical Implementation Techniques	50
3.1	Numerical Implementation of Scalar Theory	50
3.1.1	Object Sampling Considerations	51
3.1.2	Finite Pixel Size Considerations	52
3.1.3	From the DFT to the FFT Algorithm	56
3.1.4	CPU Time Considerations	56
3.2	Numerical Implementation of Rigorous Diffraction Theories	57
3.2.1	Numerical RCWA Resolution Method	58
	Modelling of a Periodic Profile of Infinite Extent	58
	Global Wavefront Coupling	58
	Field Description Outside the Diffractive Structure Region	59
	Resolution of the Wave Equation	59
	Matrix Representation of the Wave Equation	60
	Approximations of the RCWA Method	60
3.2.2	Discussion on the Coupled Wave Approximations	61
3.2.3	CPU Time Considerations	62
4	DOE Design and Optimization Techniques	62
4.1	Analytical-Type Diffractive Elements	63
4.1.1	Straightforward Design	63

4.1.2	Use of Classical Optical Design (COD) Tools	66
	Radially Symmetrical Phase Profiles for Aspherical Phase Profile Description (the Well-Known Sag Equation)	68
	General Non-symmetrical Aspherical Phase Profile Described as a Polynomial Expansion (i.e. CodeV TM Output Format)	68
4.1.3	Interferogram-Type DOEs	69
4.1.4	Harmonic or Multiorder DOEs	72
4.1.5	Holographic Optical Elements (HOEs)	74
4.2	Numerical-Type Diffractive Elements	75
4.2.1	Characteristics of Numerical-Type DOEs	76
	Degrees of Freedom of Design Process	76
	DOE-Related Degrees of Freedom	76
	Reconstruction Plane-Related Degrees of Freedom	76
4.2.2	Quality Criteria of Reconstruction	77
	Diffraction Efficiency η_d	77
	Root Mean Square Error (RMS-E)	78
	Signal-to-Noise Ratio (SNR)	79
	Strehl Ratio γ	80
	Cost Function Considerations	80
	Space–Bandwidth Product (SBWP)	81
	Implicit Design Constraint Considerations	83
4.2.3	Direct Design Techniques	83
	Talbot Array Illuminators	84
4.2.4	Iterative Optimization Algorithms	86
4.2.5	Input–Output Optimization Algorithms	87
	Direct Binary Search Algorithm	87
	Simulated Annealing (SA) Algorithms	87
	Iterative Discrete On-Axis (IDO) Algorithm	90
4.2.6	IFTA Optimization Algorithms	90
	Gerchberg–Saxton Algorithm	90
	Ping-Pong Algorithm	92
	Yang–Gu Algorithm	93
4.2.7	Algorithms Based on Evolutionary Programming	95
	Genetic Algorithms	97
4.2.8	Global Optimization Algorithms	97
4.3	Multifunctional DOEs: Description and Classification	98
4.3.1	Non-Linear Quantization	100
4.4	Encoding Techniques	101
4.4.1	DOE Data Quantization Process	101
4.4.2	Fringe-Oriented Encoding	104
4.4.3	Cell-Oriented Encoding	104

4.4.4	Pixel-Oriented Encoding	106
	Complex Kinoform Encoding Method	106
	Real Error Diffusion Encoding Method	107
	Complex Error Diffusion Encoding Method	109
	Lohman Encoding Method	111
	Lee Encoding Method	111
	Burch Encoding Method	113
4.4.5	Spatial Carrier Encoding	113
	High Spatial Frequency Carrier	113
	Grating Dislocation Encoding	114
4.4.6	Encoding Advantages and Limitations	115
5	DOE Modelling and Simulation Techniques	118
5.1	Analytical-Type DOE Modelling and Simulation Techniques	118
5.1.1	Local Grating Approximation	119
5.1.2	Equivalent Lens Model	120
5.1.3	Sweatt Model	121
5.1.4	User-Defined Surfaces (UDS)	121
5.1.5	HOE Simulation Method	122
5.2	Numerical-Type DOE Modelling and Simulation Techniques	122
5.3	BPM Modelling Techniques	123
5.3.1	TE Polarization Mode	124
5.3.2	TM Polarization Mode	124
6	References	125
	Chapter 2 DOE Fabrication and Replication Techniques	130
1	Introduction	130
2	Desktop DOE Production Techniques	131
2.1	Photoreduction Technique	131
2.2	Direct High-Resolution Printing	132
3	Diamond Machine Tools	132
4	Dynamical Devices	133
4.1	Reconfigurable DOEs	134
4.1.1	Acousto-Optical Modulators	134
4.1.2	Electro-Optical Modulators	134
4.1.3	Photorefractive Materials	135
4.1.4	Liquid Crystal Spatial Light Modulators	135
4.1.5	MEMs-Based Reconfigurable DOEs	136
4.2	Switchable DOEs	137
5	Microlithographic Fabrication Technology	138
5.1	Mask Pattern Generators	139
5.1.1	Laser-Beam Writing Machines	139

5.1.2	Electron-Beam Pattern Generators	139
5.2	Photolithographic Transfer	141
5.2.1	Mask Aligners	141
5.2.2	Phase Shift Masks	142
5.2.3	Step and Scan: Steppers	143
5.3	Pattern Etching	144
5.4	Deep Exposure Lithography	144
5.4.1	Deep X-Ray Exposure and Patterning	145
5.4.2	Deep Proton Irradiation	146
5.5	Direct Material Ablation Tools	147
5.5.1	FIB Technology	148
5.5.2	Direct Laser Ablation	148
5.5.3	Fast Atom-Beam Masking	149
6	Microlithographic Fabrication Techniques	150
6.1	Optical Interference	150
6.1.1	Fiber Bragg Grating Fabrication	150
6.2	Conventional Mask Alignments	152
6.3	Grey-Tone Masking	152
6.4	Direct Write Methods	157
6.4.1	Direct Binary Write	158
6.4.2	Direct Analog Write	158
6.5	Ion Exchange Techniques	160
6.5.1	Ion Exchange Fabrication Methods	160
6.6	LIGA Process	161
7	Replication Techniques	161
7.1	Use of Step and Repeat (Stepper)	162
7.2	Plastic Embossing Process	162
7.3	Moulding Processes	162
7.3.1	Injection Moulding DOE Replication Techniques	162
7.4	Sol-Gel Process	165
7.5	Holographic Recording Process	165
8	Summary of DOE Design and Fabrication	169
9	References	169
Chapter 3 CAD/CAM Tools for DOEs		171
1	Introduction	171
2	CAD Design Techniques	171
2.1	General Design Algorithm for CGHs	171
2.1.1	Choice of the Core Propagator	172
2.1.2	Improvements to the Core Algorithm	176
	Improvements of the Quantization Process	176
	Improvements in Uniformity	180
2.2	Optimum Encoding Methods	182

2.3	CAD Simulation Techniques	185
2.3.1	Numerical Propagator Constraints	186
	Far-Field Reconstructions	186
	Near-Field Reconstructions	186
	Straightforward Fresnel Transform (SFFT) Propagator	187
	Convolution-Based Fresnel Transform (CBFT) Propagator	188
	The Kirchhoff-Based 3D Propagators	189
	3DK-Based DOE Design and Optimization	192
2.4	Increasing the Dynamic Range of the FFT-Based Reconstructions	194
2.4.1	Imbedding Process	195
2.4.2	Oversampling Process	195
2.4.3	Effects of Combined Processes	195
2.4.4	Example of Numerical Reconstruction Improvements	197
2.4.5	Spatial Multiplexing Process	198
3	High-Level DOE Operations in CAD/CAM Tools	201
3.1	Spatial Multiplexing	201
3.2	DOE Data Modulation	202
3.3	Complex DOE Data Multiplexing	205
3.4	Iterative DOE Data Multiplexing	208
3.4.1	Solutions to Scaling Problem	209
3.4.2	Adapted Constraint Sets for Convergence of Algorithm	211
4	Associated Tolerancing: Design Rule Checks	212
5	References	214
	Chapter 4 DOE Fabrication Tolerancing Analysis	215
1	Introduction	215
2	Optimum Microlithographic Fabrication Techniques	215
2.1	Basic Requirements	216
2.2	Experimental Investigations	216
2.2.1	Direct Binary Electron-Beam Write	218
	Experimental Validations	218
	Fabrication Error Analysis	220
2.2.2	Direct Analog Electron-Beam Write	221
	Experimental Validations	221
	Fabrication Error Analysis	224
3	Fabrication Constraint Analysis and Modelling	227
3.1	Electron-Beam Proximity Effects	228
3.1.1	2D-EPE Effects	230

3.1.2	3D EPE Effects	232
3.2	Optical Proximity Effects	236
3.2.1	Quantification of the Effects of 2D OPEs on DOE Performance	237
3.3	Anisotropic Etching	240
3.3.1	Quantification of the Effects of Anisotropic Ribe Etching on the DOE Performances	241
3.3.2	Additional Ribe Etching Constraints and Errors	244
3.4	Other Systematic Fabrication Errors	244
4	Fabrication Tolerancing Methods	247
5	Systematic Fabrication Error Compensation Methods	250
5.1	Systematic Fabrication Error Compensation Techniques	251
5.1.1	Electron-Beam Proximity Compensation Algorithms	252
	Analytical-Type DOE EPE Compensation	253
	Numerical-Type DOE EPE Compensation	256
	Application to 2D EPE Effects	258
	Analytical-Type DOE Compensation	258
	Numerical-Type DOE Compensation	258
	Application to 3D EPE Effects	260
	Analytical-Type DOE Compensation	260
	Numerical-Type DOE Compensation	261
5.1.2	Optical Proximity Compensation Algorithms	265
5.1.3	Compensation of Other Fabrication Errors	266
5.1.4	Direct Linear Compensation Methods	267
	Electron-Beam Dosage	267
	Anisotropic Ion Milling Errors	268
5.2	Decreasing DOE Sensitivity to Fabrication Errors	268
5.2.1	Numerical Propagator Core Alteration	268
5.2.2	Multiple IFTA-Based Iterative Compensation	269
5.2.3	Multiple PI Quantization Techniques	270
6	References	273
Chapter 5 DOE Mask Layout Generation		275
1	Introduction	275
2	Standard Fabrication File Formats	275
2.1	High Level Formats	276
2.2	Intermediate-Level Formats	276
2.3	Source Languages	276
2.4	Low-Level Formats	277
3	DOE Data Fracture Techniques	280
3.1	Analytical-Type DOE Fracture	280
3.1.1	Core Algorithm of the General-Purpose Fracture Process	282

3.1.2	Fracture Error Quantification	289
3.1.3	Fringe Search Algorithm	290
3.1.4	Polygonization of Skeletonized Fringes	291
3.2	Numerical-Type DOE Fracture	293
3.2.1	Finding the Optimum Kinoform Cell Shape	293
3.2.2	Data Compression Applied to the Final Fabrication File	296
	Data Compression Method No. 1	296
	Data Compression Method No. 2	297
3.3	Simulation of Effects of DOE Data Fracture	298
3.4	Final Formatting of the Fractured Patterns	300
3.5	Reticule Layout Placement and Wafer Stepping	302
Chapter 6	System-Oriented DOE Designs: Examples	307
1	Introduction	307
2	Hybrid Optical Systems	309
2.1	Diffraction/Refractive Partitioning Issues	310
2.2	Simulation Techniques for Hybrid Systems	312
2.2.1	DOE Phase Unwrapping Process	313
2.2.2	Hybrid Ray Tracing/Fresnel Propagation Method	313
	Example	318
3	Additional Properties of Hybrid Lenses	320
3.1	Shallow Blazed Diffraction Grooves	321
3.2	Deep Blazed Diffraction Grooves	323
3.3	Binary Diffraction Grooves	324
3.4	Multiplexed Diffraction Grooves	326
4	Optoelectronic Systems	326
4.1	OE Partitioning Issues	328
4.2	Example 1: Optical Clock Distribution for MCM	330
4.2.1	Physical Parameter Optimization	332
4.2.2	Related Constraints	334
4.2.3	OE System Architecture Optimization Procedure	336
4.2.4	Multifunctional DOE Optimization Procedure	338
4.3	Example 2: Free-Space Optical Interconnections	342
4.3.1	Computer Interconnection Architecture	342
4.3.2	Physical Detector Placements	343
4.3.3	DOE Array Design Considerations	344
4.4	Example 3: OE Packaging Issues — Design Compensations	347
4.4.1	OE Packaging Tolerancing	347
4.4.2	DOE Compensation Techniques	349
	Core Propagator Alteration	350
	Use of the MP-GPA Algorithm	352

<i>Contents</i>		xiii
5	Optomechanical Systems	353
5.1	Optomechanical Partitioning Issues	353
5.2	Example 1: Diffractive Synthetic Aperture Zoom	354
5.3	Example 2: Microfluidic System	358
5.4	Example 3: High-Resolution Lidar Signal Analysis Microsystem	361
6	Summary	363
7	References	363
Conclusion		367
Index		369