

Martin Maldoan and

Edwin L. Thomas

Periodic Materials and Interference Lithography

for Photonics, Phononics and Mechanics



**WILEY-
VCH**

WILEY-VCH Verlag GmbH & Co. KGaA

Contents

Preface XI

Introduction XIII

Theory 1

1	Structural Periodicity	3
1.1	Nonperiodic versus Periodic Structures	4
1.2	Two-dimensional Point Lattices	6
1.3	Three-dimensional Point Lattices	10
1.3.1	Primitive and Nonprimitive Unit Cells	14
1.4	Mathematical Description of Periodic Structures	16
1.5	Fourier Series	20
1.5.1	Fourier Series for Two-dimensional Periodic Functions	20
1.5.2	Fourier Series for Three-dimensional Periodic Functions	23
1.5.3	Arbitrary Unit Cells	25
	Further Reading	26
	Problems	26
2	Periodic Functions and Structures	29
2.1	Introduction	30
2.2	Creating Simple Periodic Functions in Two Dimensions	31
2.2.1	The Square Lattice	31
2.2.2	The Triangular Lattice	38
2.3	Creating Simple Periodic Functions in Three Dimensions	41
2.3.1	The Simple Cubic Lattice	44
2.3.2	The Face-centered-cubic Lattice	47
2.3.3	The Body-centered-cubic Lattice	51
2.4	Combination of Simple Periodic Functions	59
	Problems	61
3	Interference of Waves and Interference Lithography	63
3.1	Electromagnetic Waves	64

3.2	The Wave Equation	65
3.3	Electromagnetic Plane Waves	68
3.4	The Transverse Character of Electromagnetic Plane Waves	69
3.5	Polarization	72
3.5.1	Linearly Polarized Electromagnetic Plane Waves	73
3.5.2	Circularly Polarized Electromagnetic Plane Waves	74
3.5.3	Elliptically Polarized Electromagnetic Plane Waves	75
3.6	Electromagnetic Energy	75
3.6.1	Energy Density and Energy Flux for Electromagnetic Plane Waves	77
3.6.2	Time-averaged Values	77
3.6.3	Intensity	80
3.7	Interference of Electromagnetic Plane Waves	81
3.7.1	Three-dimensional Interference Patterns	86
3.8	Interference Lithography	89
3.8.1	Photoresist Materials	89
3.8.2	The Interference Lithography Technique	92
3.8.3	Designing Periodic Structures	93
	Further Reading	94
	Problems	94
4	Periodic Structures and Interference Lithography	97
4.1	The Connection between the Interference of Plane Waves and Fourier Series	98
4.2	Simple Periodic Structures in Two Dimensions Via Interference Lithography	100
4.3	Simple Periodic Structures in Three Dimensions Via Interference Lithography	104
	Further Reading	110
	Problems	111
Experimental 113		
5	Fabrication of Periodic Structures	115
5.1	Introduction	116
5.2	Light Beams	116
5.3	Multiple Gratings and the Registration Challenge	118
5.4	Beam Configuration	119
5.4.1	Using Four Beams	119
5.4.2	Using a Single Beam (Phase Mask Lithography)	120
5.5	Pattern Transfer: Material Platforms and Photoresists	122
5.5.1	Negative Photoresists	124
5.5.2	Positive Photoresists	126
5.5.3	Organic–Inorganic Hybrids Resists	128
	Practical Considerations for Interference Lithography	128

5.6.1	Preserving Polarizations and Directions	128
5.6.2	Contrast	131
5.6.3	Drying	132
5.6.4	Shrinkage	133
5.6.5	Backfilling – Creating Inverse Periodic Structures	133
5.6.6	Volume Fraction Control	134
5.7	Closing Remarks	135
	Further Reading	136

Applications 139

6 Photonic Crystals 141

6.1	Introduction	142
6.2	One-dimensional Photonic Crystals	143
6.2.1	Finite Periodic Structures	143
6.2.2	Infinite Periodic Structures	147
6.2.3	Finite versus Infinite Periodic Structures	150
6.3	Two-dimensional Photonic Crystals	151
6.3.1	Reciprocal Lattices and Brillouin Zones in Two Dimensions	152
6.3.2	Band Diagrams and Photonic Band Gaps in Two Dimensions	157
6.3.3	Photonic Band Gaps in Two-dimensional Simple Periodic Structures	160
6.4	Three-dimensional Photonic Crystals	162
6.4.1	Reciprocal Lattices and Brillouin Zones in Three Dimensions	164
6.4.2	Band Diagrams and Photonic Band Gaps in Three Dimensions	168
6.4.3	Photonic Band Gaps in Three-dimensional Simple Periodic Structures	170
	Further Reading	176
	Problems	179

7 Phononic Crystals 183

7.1	Introduction	184
7.1.1	Elastic Waves in Homogeneous Solid Materials	184
7.1.2	Acoustic Waves in Homogeneous Fluid Materials	187
7.2	Phononic Crystals	188
7.3	One-dimensional Phononic Crystals	190
7.3.1	Finite Periodic Structures	190
7.3.2	Infinite Periodic Structures	194
7.4	Two-dimensional Phononic Crystals	198
7.4.1	Vacuum Cylinders in a Solid Background	198
7.4.2	Solid Cylinders in Air	202
7.4.3	Phononic Band Gaps in Two-dimensional Simple Periodic Structures	205
7.5	Three-dimensional Phononic Crystals	207

7.5.1	Solid Spheres in a Solid Background Material	208
	Further Reading	210
	Problems	213
8	Periodic Cellular Solids	215
8.1	Introduction	216
8.2	One-dimensional Hooke's Law	218
8.3	The Stress Tensor	219
8.4	The Strain Tensor	221
8.4.1	Expansion	225
8.4.2	General Deformation	226
8.4.3	Resolving a General Deformation as Strain Plus Rotation	227
8.5	Stress–Strain Relationship: The Generalized Hooke's Law	229
8.6	The Generalized Hooke's Law in Matrix Notation	230
8.7	The Elastic Constants of Cubic Crystals	232
8.7.1	Young's Modulus and Poisson's Ratio	233
8.7.2	The Shear Modulus	235
8.7.3	The Bulk Modulus	237
8.8	Topological Design of Periodic Cellular Solids	238
8.9	Finite Element Program to Calculate Linear Elastic Mechanical Properties	243
8.10	Linear Elastic Mechanical Properties of Periodic Cellular Solids	243
8.11	Twelve-connected Stretch-dominated Periodic Cellular Solids via Interference Lithography	247
8.12	Fabrication of a Simple Cubic Cellular Solid via Interference Lithography	249
8.13	Plastic Deformation of Microframes	250
	Further Reading	252
9	Further Applications	255
9.1	Controlling the Spontaneous Emission of Light	256
9.2	Localization of Light: Microcavities and Waveguides	259
9.3	Simultaneous Localization of Light and Sound in Photonic–Phononic Crystals: Novel Acoustic–Optical Devices	264
9.4	Negative Refraction and Superlenses	268
9.5	Multifunctional Periodic Structures: Maximum Transport of Heat and Electricity	272
9.6	Microfluidics	273
9.7	Thermoelectric Energy	275
9.7.1	Peltier Effect	275
9.7.2	Thomson Effect	276
9.7.3	Seebeck Effect	277
	Further Reading	278

Appendix A MATLAB Program to Calculate the Optimal Electric Field Amplitude Vectors for the Interfering Light Beams 281

Appendix B MATLAB Program to Calculate Reflectance versus Frequency for One-dimensional Photonic Crystals 289

Appendix C MATLAB Program to Calculate Reflectance versus Frequency for One-dimensional Phononic Crystals 297

Index 305