

# Optical computer architectures

*The application of optical concepts to next generation computers*

Alastair D. McAulay PhD  
Professor, Department of Electrical and Computer Engineering  
Lehigh University  
February 8, 2004

Chandler Weaver Professor and Chairman  
Dept. of Electrical Engineering and Computer Science  
Lehigh University  
1992-1997

NCR Distinguished Professor and Chairman  
Department of Computer Science and Engineering  
Wright State University  
1987-1992

Original publication:  
John Wiley  
ISBN: 0-471-63242-2  
1991

February 8, 2004

# Contents

<b>I</b>	<b>Background for Optical Computing</b>	<b>1</b>
<b>1</b>	<b>Why Optical Computers?</b>	<b>1</b>
1.1	Electronic Computer Architectures . . . . .	1
1.1.1	Requirements for Future Computers . . . . .	1
1.1.2	Limitations of Current Computer Technologies . . . . .	2
1.1.3	Direction for Computers . . . . .	5
1.2	Why Use Optics in Computers? . . . . .	6
1.2.1	Advantages of Optics . . . . .	6
1.2.2	Introduction to Functional Capabilities of Optics . . . . .	7
1.2.3	Strategy for Evolving Optics into Computers . . . . .	9
1.3	Exercises . . . . .	12
<b>2</b>	<b>Basic Concepts in Optics</b>	<b>15</b>
2.1	Wave Phenomena . . . . .	15
2.1.1	Waves . . . . .	15
2.1.2	Wave Interactions with Media . . . . .	19
2.2	Polarization and Anisotropic Crystals . . . . .	21
2.2.1	Polarization . . . . .	21
2.2.2	Anisotropic Crystals . . . . .	23
2.3	Lenses and Lens Systems . . . . .	26
2.3.1	Lenses . . . . .	26
2.3.2	Optical Lens Systems . . . . .	27
2.3.3	Lens as a Phase Transformation . . . . .	29
2.3.4	Imaging Property of Lenses . . . . .	30
2.4	Coherency . . . . .	31
2.4.1	Temporal Coherency . . . . .	31
2.4.2	Spatial Coherency . . . . .	32
2.5	Exercises . . . . .	33
<b>3</b>	<b>Fourier Optics</b>	<b>37</b>
3.1	Correlation and Convolution . . . . .	38
3.1.1	Correlation . . . . .	38
3.1.2	Convolution . . . . .	38

3.1.3	Fourier Transform Computation of Correlation and Convolution . . . . .	39
3.1.4	Coherent Versus Incoherent Processing . . . . .	40
3.2	Fourier Transforms with Lenses . . . . .	40
3.2.1	1-D Fourier Transform . . . . .	41
3.2.2	2-D Fourier Transform and Frequency Filtering . . . . .	42
3.2.3	Optical Scheme for Coherent Filtering . . . . .	46
3.3	Grating Filters for Addition and Subtraction . . . . .	47
3.3.1	Grating Filters . . . . .	47
3.3.2	Addition and Subtraction with Grating Filters . . . . .	49
3.4	Complex Transform Filters . . . . .	50
3.4.1	Storing Complex Functions on Film . . . . .	50
3.4.2	Using Complex Filters for Convolution and Correlation . . . . .	52
3.4.3	Generating a Complex Filter Optically . . . . .	54
3.5	Holograms . . . . .	55
3.5.1	Equations for Thin Amplitude Holograms . . . . .	56
3.5.2	Thick Holograms for Volume Memory . . . . .	57
3.5.3	Phase Holograms . . . . .	59
3.5.4	Generating a Complex Filter or Hologram by Computer . . . . .	59
3.6	Exercises . . . . .	60
<b>4</b>	<b>Devices for Opto-Electronic Interface</b>	<b>65</b>
4.1	Information on SLMs . . . . .	66
4.1.1	Classification . . . . .	66
4.1.2	Characteristics . . . . .	70
4.1.3	Digital Versus Analog Computing . . . . .	71
4.2	Deformable Mirror Device . . . . .	72
4.2.1	Construction and Addressing . . . . .	72
4.2.2	Modeling . . . . .	75
4.2.3	Converting Phase to Intensity . . . . .	77
4.3	Double Heterostructure Opto-Electronic Switch . . . . .	78
4.3.1	Advantages of Gallium Arsenide . . . . .	78
4.3.2	Device Description . . . . .	80
4.4	Magneto-Optic Spatial Light Modulators . . . . .	81
4.5	Acousto-Optic Devices . . . . .	83
4.5.1	Operation . . . . .	83
4.5.2	Using Acousto-Optic Cells . . . . .	86
4.6	Lasers and Optical Detectors . . . . .	87
4.6.1	Lasers . . . . .	87
4.6.2	Optical Detectors . . . . .	90
4.7	Integrated Optics . . . . .	90
4.7.1	Waveguide Switches . . . . .	91
4.7.2	Applications to Spectrum Analysis and Filtering . . . . .	93
4.8	Exercises . . . . .	93

<b>5</b>	<b>Optically Addressable Spatial Light Modulators</b>	<b>97</b>
5.1	Liquid Crystal Devices . . . . .	98
5.1.1	Electrooptic Effect . . . . .	100
5.1.2	Interfacing to Liquid Crystal Devices . . . . .	100
5.2	Self-Electrooptical Effect Device . . . . .	103
5.2.1	SEED description . . . . .	103
5.2.2	Symmetric-SEED . . . . .	105
5.2.3	Interfacing to S-SEED Arrays Using Patterned Mirrors . . . . .	106
5.3	Spatial Light Rebroadcasters . . . . .	108
5.3.1	Electron Trapping Device Description . . . . .	108
5.3.2	Arithmetic Operations . . . . .	110
5.3.3	Application to Template Matching . . . . .	111
5.4	Microchannel Spatial Light Modulator . . . . .	112
5.5	Fabry-Perot Based Optical Transistors . . . . .	114
5.5.1	Principle . . . . .	114
5.5.2	Thin Film Fabry-Perot Devices . . . . .	116
5.6	Devices for Real-Time Holograms . . . . .	116
5.6.1	Photorefractive Crystals . . . . .	116
5.6.2	Four-Wave Mixing or Dynamic Holograms . . . . .	117
5.7	Exercises . . . . .	119

## II Subsystems for Optical Computing 121

<b>6</b>	<b>Optical Interconnections</b>	<b>123</b>
6.1	Interconnection networks . . . . .	123
6.1.1	Use of Networks in Parallel Computers . . . . .	123
6.1.2	Simple Interconnections . . . . .	124
6.1.3	Systolic Arrays . . . . .	126
6.2	Crossbar Switch Interconnection Networks . . . . .	128
6.2.1	Spatial Light Modulator Crossbar Switches . . . . .	129
6.2.2	Polarizing Beam Splitter and Variable Grating . . . . .	132
6.2.3	Holographic Interconnections with 2-D Images . . . . .	136
6.3	Regular Limited Interconnections . . . . .	138
6.3.1	Shuffle Power of Two Interconnections . . . . .	138
6.3.2	Patterned Mirror . . . . .	140
6.3.3	Space Invariant Holographic Interconnections . . . . .	147
6.4	Multistage Interconnection Networks . . . . .	148
6.4.1	Two-by-two Switches for Multistage Networks . . . . .	148
6.4.2	Omega (Multistage Shuffle) Network . . . . .	149
6.4.3	Integrated Optic Crossbar . . . . .	151
6.4.4	Reverse Order Beam Splitter Power of Two Networks . . . . .	152
6.5	Exercises . . . . .	153

<b>7</b>	<b>Optical Memory</b>	<b>155</b>
7.1	Introduction . . . . .	155
7.1.1	Nature of Information Stored . . . . .	156
7.1.2	Associative Versus Random Access Memory . . . . .	156
7.2	Current Memory Management . . . . .	160
7.2.1	Hierarchies . . . . .	160
7.2.2	Cache . . . . .	161
7.2.3	Virtual Memory . . . . .	164
7.3	Optical Word Pattern Matching . . . . .	165
7.3.1	Optical Word Template Matching AM . . . . .	166
7.3.2	Bit-Slice Associative Memory . . . . .	170
7.4	Holographic Memory . . . . .	173
7.4.1	Writing and Reading Holographic Memories . . . . .	173
7.4.2	Optical Beam Deflection Scanning . . . . .	176
7.4.3	Mechanical Scanning . . . . .	178
7.5	Exercises . . . . .	180
<b>8</b>	<b>Optical Logic</b>	<b>185</b>
8.1	Basic Logic Concepts . . . . .	185
8.1.1	Logic Elements and Classification . . . . .	186
8.1.2	Propositional Logic . . . . .	188
8.1.3	Spatial Logic and Optical Logic Gates . . . . .	189
8.2	Logic Programming . . . . .	193
8.2.1	Constructs for Prolog . . . . .	193
8.2.2	Reduction to Normal Form . . . . .	194
8.3	Optical Array Logic with Encoded Inputs . . . . .	195
8.3.1	All Logic Operations in Parallel with Shadow Casting . . . . .	195
8.3.2	All Logic by Correlation with Kernels . . . . .	199
8.3.3	Optical Implementation for Correlation by $2 \times 2$ Kernels . . . . .	202
8.4	Optical Array Logic without Encoding . . . . .	204
8.4.1	All Logic Operations in Parallel with SLRs . . . . .	204
8.4.2	Parallel Logic with Liquid Crystal Devices . . . . .	206
8.4.3	Parallel Logic with Variable Grating LCDs . . . . .	209
8.5	Exercises . . . . .	210
<b>9</b>	<b>Optical Logic Circuits</b>	<b>213</b>
9.1	Approaches to Synthesizing Logic Systems . . . . .	213
9.1.1	Modular Approach . . . . .	214
9.1.2	Sequential Logic Circuits . . . . .	216
9.1.3	Programmable Logic Array Approach . . . . .	217
9.2	Global Interconnection Logic Systems . . . . .	219
9.2.1	Liquid Crystal and Hologram . . . . .	219
9.2.2	Matrix-Vector Crossbar Approach . . . . .	222
9.3	Local Interconnection Logic Circuits . . . . .	227
9.3.1	Symbolic Substitution . . . . .	227
9.3.2	Pattern Logic . . . . .	230

9.4	Regular Interconnection Logic Systems . . . . .	232
9.4.1	Dual-Rail Logic with S-SEEDs and Fan of Two . . . . .	233
9.4.2	Dual-Frequency Logic with SLR-OLCD and Fan of Two . . . . .	238
9.5	Exercises . . . . .	239
<b>10</b>	<b>Optical Arithmetic Computation</b>	<b>243</b>
10.1	Digital Number Representations . . . . .	243
10.1.1	Conventional . . . . .	243
10.1.2	Residue Numbers . . . . .	244
10.1.3	Modified-Sign-Bit . . . . .	244
10.1.4	Floating Point . . . . .	245
10.2	Adder Circuits . . . . .	247
10.2.1	Half Adder Circuit . . . . .	247
10.2.2	Full Adder Circuit . . . . .	248
10.3	Optical Parallel Addition of Words . . . . .	251
10.3.1	Bit Slice Adder with Liquid Crystal Devices . . . . .	252
10.3.2	Optical Bit Slice Adder Using PLAs and Minimum Fans . . . . .	255
10.3.3	Optical Ripple Carry Adder Using Pattern Logic . . . . .	255
10.3.4	Symbolic Substitution Ripple Carry Adder . . . . .	261
10.3.5	Separate Carry Adder Using Symbolic Substitution . . . . .	263
10.3.6	Optical Look-Ahead Carry Adders . . . . .	265
10.4	Optical Parallel Multiplication of Words . . . . .	268
10.4.1	Optical Symbolic Substitution Multiplication . . . . .	268
10.4.2	Optical Digital Multiplication by Analog Convolution . . . . .	269
10.4.3	Optical Wallace Tree Multiplier . . . . .	270
10.5	Optical Division of Words . . . . .	272
10.5.1	Optical Divider Using Convergence-Division . . . . .	272
10.6	Exercises . . . . .	275
<b>11</b>	<b>Optical Matrix Computation</b>	<b>279</b>
11.1	Optical Matrix-Vector Computation . . . . .	279
11.1.1	Computation of Quadratics . . . . .	285
11.2	Systolic Approaches . . . . .	286
11.2.1	Analog Optical Systolic Matrix-Vector Computation . . . . .	286
11.2.2	Digital Optical Systolic Matrix-Vector Multiplication . . . . .	286
11.3	Matrix-Matrix Computations . . . . .	288
11.3.1	Optical Inner Product Computation . . . . .	290
11.3.2	Optical Middle Product Computation . . . . .	291
11.3.3	Optical Parallel Middle Product Computation . . . . .	291
11.3.4	Outer Product Computation . . . . .	293
11.4	Optical Matrix-Vector Sonar/Radar . . . . .	294
11.4.1	Description of Processor . . . . .	294
11.4.2	Optical Implementation . . . . .	298
11.5	Optical Matrix-Vector Expert System . . . . .	299
11.5.1	Concept . . . . .	299
11.5.2	Flow Graph . . . . .	300

11.5.3 Spatial Light Modulator Implementation . . . . .	302
11.6 Exercises . . . . .	305
<b>12 Algorithms for Numerical Computation</b>	<b>309</b>
12.1 Optical Analog to Digital Converters . . . . .	310
12.1.1 Optical Approach Using Table-Look Up . . . . .	311
12.2 Signal Processing Algorithms . . . . .	315
12.2.1 Fast Fourier Transform . . . . .	317
12.2.2 Nonlinear Spectral Estimation . . . . .	319
12.3 Finite Approximation Methods . . . . .	322
12.4 Iterative Methods for Numerical Computation . . . . .	323
12.4.1 Gradient Methods: Steepest Descent, Newton, and Gauss-Newton . . . . .	324
12.5 Solving Large Sparse Linear Equations . . . . .	328
12.5.1 Conjugate Gradient Algorithm Summary . . . . .	329
12.6 Exercises . . . . .	331
<b>III Architectural Models of Computation</b>	<b>333</b>
<b>13 Optical Sequential Machines</b>	<b>335</b>
13.1 Evolution of Construction of Sequential Machines . . . . .	336
13.1.1 The First Programmable computer . . . . .	336
13.1.2 The First Working Programmable Computer . . . . .	338
13.1.3 The First Electronic Computers . . . . .	340
13.1.4 The First Stored Program Computer . . . . .	341
13.2 An Electronic RISC Machine . . . . .	342
13.2.1 Levels of Abstraction . . . . .	342
13.2.2 System Description . . . . .	342
13.2.3 Description of Critical Parts . . . . .	343
13.2.4 Instruction Pipelining . . . . .	344
13.2.5 Stacks . . . . .	347
13.3 Optical RISC Machine . . . . .	348
13.3.1 Critical Parts for Optical RISC Design . . . . .	348
13.3.2 Optical RISC Machine Overall Design . . . . .	356
13.4 Exercises . . . . .	360
<b>14 Optical Dataflow Computers</b>	<b>363</b>
14.1 Principles of Dataflow . . . . .	364
14.1.1 Explanation of Dataflow . . . . .	364
14.1.2 Dataflow Versus Control Flow . . . . .	365
14.1.3 Writing Dataflow Programs . . . . .	367
14.2 Electronic Dataflow Architectures . . . . .	368
14.2.1 Static Dataflow Architecture . . . . .	369
14.2.2 More Parallelism in Dataflow Machines . . . . .	370
14.2.3 Dynamic Dataflow Architectures . . . . .	372

14.3	Optical Static Flow Graph Dataflow Machine . . . . .	373
14.3.1	System Description . . . . .	374
14.3.2	Signal Processing Algorithms . . . . .	375
14.3.3	Optical Matrix-Vector Multiplication . . . . .	380
14.3.4	Optical Conjugate Gradient Algorithm Implementation . . . . .	381
14.3.5	Optical Dynamic Dataflow Machines . . . . .	384
14.4	Optical Prolog Computer . . . . .	386
14.4.1	Prolog and Its Advantages . . . . .	386
14.4.2	System Level Architecture . . . . .	389
14.4.3	Performance Using Simulator . . . . .	391
14.5	Exercises . . . . .	393
<b>15</b>	<b>Optical Cellular Automata</b>	<b>397</b>
15.1	Evolution of the Theory of Computing Machines . . . . .	397
15.1.1	Equivalence of Symbolic and Numeric Computing . . . . .	398
15.1.2	Limitations on What is Computable . . . . .	399
15.1.3	The Universal Computer . . . . .	399
15.2	Theory of Cellular Automata . . . . .	402
15.2.1	Description of Cellular Automata . . . . .	403
15.2.2	Game of Life Illustration . . . . .	403
15.2.3	Implementing Turing Machines as Cellular Automata . . . . .	406
15.2.4	Multiple Setting Transition Rule for Computing . . . . .	407
15.3	Optical Computers Based on Cellular Automata . . . . .	409
15.3.1	Operations Required . . . . .	409
15.3.2	Optical Binary Cellular Automata using Holograms . . . . .	411
15.3.3	Spatial Cellular Logic Array Computers . . . . .	414
15.4	Optical Finite Approximation Machines . . . . .	415
15.4.1	Operations Required . . . . .	415
15.4.2	Optical Implementation . . . . .	416
15.5	Exercises . . . . .	417
<b>16</b>	<b>Optical Linear Neural Networks</b>	<b>421</b>
16.1	Basic Features of Optical Neural Networks . . . . .	422
16.1.1	Massively Parallel Computation . . . . .	422
16.1.2	Learning Simplifies Programming . . . . .	422
16.2	Linear Heteroassociative Memories . . . . .	423
16.2.1	Matrix formulation . . . . .	423
16.2.2	Under and Overdetermined Learning . . . . .	424
16.3	Iterative Learning for Linear Heteroassociative Memory . . . . .	427
16.3.1	Iterative Updating of Weights . . . . .	427
16.3.2	Optical Orthogonalization using Gram-Schmidt . . . . .	429
16.4	Orthogonal Associative Memory . . . . .	429
16.4.1	Principles . . . . .	430
16.4.2	Optical Implementation using SLRs . . . . .	431
16.4.3	Experimental Results for Optical Orthogonal Memory . . . . .	434

16.5 Exercises . . . . .	436
<b>17 Optical Nonlinear Neural Networks</b>	<b>439</b>
17.1 Nonlinear Feedforward Networks . . . . .	439
17.1.1 Single Neuron . . . . .	440
17.1.2 Multilayer Neural Networks . . . . .	441
17.1.3 Implementation . . . . .	445
17.2 Optical Learning . . . . .	449
17.2.1 Photorefractive Device Learning . . . . .	449
17.2.2 Learning with Spatial Light Rebroadcasters . . . . .	450
17.3 Optical Steepest Descent Learning for Nonlinear Networks . . . . .	451
17.3.1 Backpropagation . . . . .	451
17.3.2 Optical Implementation of Backpropagation . . . . .	453
17.4 Optical Gauss-Newton Learning for Nonlinear Networks . . . . .	455
17.4.1 Gauss-Newton Learning Algorithm . . . . .	455
17.4.2 Split-inversion Learning Algorithm . . . . .	457
17.4.3 Optical Implementations . . . . .	459
17.5 Vision Application for Multilayer Neural Network . . . . .	459
17.5.1 Optical Shift, Rotation, and Size Invariance Computation . . . . .	460
17.5.2 Neural Network for Aspect Angle Invariance . . . . .	464
17.6 Exercises . . . . .	464
<b>18 Optical Autoassociative and Self Organizing Networks</b>	<b>469</b>
18.1 Autoassociative Memories Using Nonlinear Feedback . . . . .	469
18.1.1 Nonlinear Correlation Feedback . . . . .	470
18.1.2 Outer Product Nonlinear Feedback . . . . .	472
18.1.3 Feedback Using Angle Holograms . . . . .	475
18.2 Self Organizing Polynomial Networks . . . . .	478
18.2.1 Principles of Polynomial Neural Network . . . . .	480
18.2.2 Application to Pilot Neural Network Advisor . . . . .	481
18.2.3 Optical Implementations of Polynomial Neural Networks . . . . .	482
18.3 Exercises . . . . .	485
<b>19 Conclusion</b>	<b>487</b>
<b>A Conjugate Gradient Method Derivation</b>	<b>489</b>
A.1 Updating Solution and Gradient . . . . .	489
A.2 Searching in Conjugate Directions . . . . .	490
A.3 Computing the Optimum Step Size for Linear Searching . . . . .	493